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Pedestrian evacuation simulation in indoor emergency situations: Approaches, models and tools

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ABSTRACT

Pedestrian evacuation simulation (PES) provides a low-cost and low-risk method to facilitate safety design and emergency management in indoor environment by describing pedestrian evacuation behaviors and predicting evacuation outcomes in what-if scenarios. The area of PES has witnessed rapid growth over the past few decades, but there lacks an up-to-date review of the existing literature that could comprehensively reflect the latest advancements in this area. To address this need, this paper proposes a three-layer analytical framework for synthesizing the abundant literature on PES approaches, PES models and PES tools, and presents a systematic review of the state of the art in the PES area. The findings point out that (1) the use of high-fidelity PES approaches has become more prevalent over time; (2) the adaptability of PES models to different evacuation scenarios is relatively limited; (3) modeling of human behavioral mechanism is the driving force for PES model advancement; and (4) verification and validation are the major challenges for PES tools. Finally, the paper outlines possible directions for future research and discusses specific challenges to address for each direction. This paper is expected to benefit academics and professionals whose work requires the use of PES tools, provoke innovative studies that would push the boundaries of this area, and advance the understanding of pedestrian evacuation behavioral mechanisms and behavioral intervention measures, which would ultimately lead to enhanced human safety in indoor emergencies.

1. Introduction

Humans spend approximately 90% of their time in indoor environments (Klepeis et al., 2001), which comprise public and private buildings, community structures (hospitals, schools, etc.), premises for recreational and/or social activities (cinemas, bars, sports facilities, etc.), and microenvironments, such as public transport (trains, subways, airplanes, etc.) (Viegi et al., 2019). Knowing how to deal with emergency situations and facilitate emergency evacuation is one of the key issues in ensuring human safety in indoor environments. Although there are codes in most countries prescribing the regulatory provisions governing safety design and egress planning in indoor environment, emergency incidents, such as fire, toxic gas leaks and terrorist attacks, that result in major injuries and fatalities are seen every year. One of such recent incidents was the Kyoto Animation fire in Japan in 2019, which killed 36 people and injured another 33 (Baseel, 2020). In the event of emergencies, the ability to rapidly evacuate humans can mean the difference between survival and death, which underpins the criticality and life-saving importance of efficient indoor evacuation.

With the development of computing technologies, pedestrian evacuation simulation (PES) provides an effective method to describe pedestrian evacuation behaviors and predict evacuation outcomes. The PES simulates pedestrians' motions and behaviors during the evacuation process, on the premise of considering various crucial factors affecting emergency scenarios and evacuation process, in a virtual space created by computers (Şahin et al., 2019). Compared with other methods, such as evacuation drills (Peacock et al., 2012) and animal experiments (Shiwakoti et al., 2011), the PES can investigate the safety conditions of a given space with relatively low cost and risk by producing what-if scenarios of possible emergency events (Şahin et al., 2019). The outputs of PES can reflect the dynamics of the evacuation process and quantify the evacuation outcomes, measured by metrics such as evacuation time, individual density distribution and possible fatalities (Haghani, 2020). These outputs can be used to identify evacuation bottlenecks in structures (Şahin et al., 2019), improve building safety designs (Cristiani and Peri, 2019, 2017; Helbing et al., 2005; Kirik et al.,

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2018), facilitate the development of evacuation plans (Albi et al., 2016; Aleksandrov et al., 2019; Lu et al., 2017a; Yuan et al., 2018), and so on.

The earliest PES models can date back to the 1970 s (Hirai and Tarui, 1975; Okazaki, 1979), and the research on pedestrian dynamics has an even longer history. The explorations of pedestrian movement characteristics and analytical formulae based on empirical data (Fruin, 1971; Henderson, 1974, 1971; Predtechenskii and Milinskii, 1978) formed the keystones of PES studies. The key simplifications adopted by PES nowadays, such as the representation of human body using the three-circle model (Thompson, 1994) and the description of space using grids (Galea and Perez Galparsoro, 1994) or continuous planes and links (Thompson, 1994), were mostly developed in the 1990 s (Ronchi, 2020). Since then, the area of PES has seen remarkable advancements, with continuous shifts of research paradigms and rapid increase of published works in the past several decades. A holistic review of this area, which is currently lacking in the literature, would benefit academics and professionals whose work requires the use of PES tools, provoke innovative studies that would push the boundaries of this area, and advance the understanding of pedestrian evacuation behavioral mechanisms and behavioral intervention measures, which would ultimately lead to enhanced human safety in indoor emergencies. A number of prior studies have attempted to summarize and assess the existing literature in the area of PES from different angles (Dong et al., 2020; Gwynne et al., 1999a; Kuligowski, 2005; Kuligowski et al., 2010; Martinez-Gil et al., 2017; Radianti et al., 2013; Schadschneider et al., 2009; Zheng et al., 2009). However, there still lacks an effective way to synthesize the abundant literature on PES that examines a myriad of challenges, ranging from the representation of hazardous spatial environments with desirable computational efficiency to the development of high-fidelity human behavioral rules, from diverse philosophical, methodological, technical and practical perspectives. This has become a barrier to gain a deep understanding of the state of the art in this area. In addition, the PES is an active area that witnesses an increasing number of published works each year. As such, an up-to-date review is needed to comprehensively reflect the latest advancements in this area.

To address the above needs, this study proposes an analytical framework for assessing the existing PES literature. The framework comprises three interconnected layers that examine prior research on PES approaches, models and tools, respectively. The term “PES approach” is employed to represent the general paradigm of establishing analogies between real evacuation scenes and abstract entities, and simplifications from real human behaviors to hypothetical mathematical equations or rules; the term “PES model” is employed to represent a concrete implementation of the PES approach under certain evacuation scenarios characterized by certain type of space, type of emergency and characteristics of individuals; and the term “PES tool” is employed to represent engineering and computational means that implement the PES models for the purpose of quantifying evacuation performance and representing the dynamics of the evacuation process to facilitate practical applications. The proposed analytical framework posits that the PES approach is the foundation and theoretical basis of PES models and tools, and its evolution is usually driven by the accomplishments from other fields such as computational science. The evolution of PES approaches in turn has driven the transformation of PES models in the past decades from concerning a homogeneous crowd composed of individuals that follow uniform behavioral rules to heterogeneous individuals that exhibit autonomous decision-making and diverse behavioral patterns. As such, a considerable amount of research has focused on the refinement of the models in terms of individuals’ decision-making mechanisms and their interactions with the environments and among themselves. Meanwhile, prior studies that aimed to transform the advancements of PES research into practical uses mainly focused on developing enabling tools for practitioners. These studies largely relied on the latest PES models that acted as the core processor of the PES tools. Distinguishing the above three layers of PES research and synthesizing the existing PES literature using the proposed analytical framework is vital for understanding the fundamental pillars and driving forces behind the historical and ongoing evolution of the PES area, and predicting the directions where future breakthroughs are likely to occur.

This study has the following specific objectives: (1) to synthesize the latest accomplishments in the area of PES and assess various research efforts based on the proposed analytical framework; (2) to depict the evolution of the PES area and the current research trends that are getting the most attention; and (3) to identify limitations of the existing literature and lay out possible directions for future research. By achieving the above objectives, this study aims to make the following contributions to the existing body of knowledge: (1) based on a holistic review of the literature on PES, the findings will serve to advance the understanding of the state of the art in this area, and demonstrate where literature is still lacking and further research is needed; (2) the proposed analytical framework not only enables a synthetic review of the existing literature on PES and revelation of the factors that drive its evolution in the past decades, but also provides a useful perspective for scrutinizing the continued efforts in this area; and (3) the informed discussions about the gaps in the literature and possible direction for future research are expected to inspire more studies that may lead to further accomplishments in this area.

2. Methodology

The *Web of Science Core Collection* database was used to search for relevant academic publications in the area of PES. To yield a comprehensive set of search results that could reflect the current trends in this area and their changes over time, the search did not set any restriction on the year of publication. With respect to the document type, it was restricted to journal articles. After various attempts, the search statement “TI = (egress or evacuat*) AND TI = (simulat* or model*) AND TS = (emergency)” was used, where TI and TS stand for title and topic (topic contains title, abstract and author keywords) respectively, and AND stands for a search operator, according to the search syntax of *Web of Science*.

The results returned from the above search contained a number of irrelevant publications that needed to be filtered. The filtering was manually done by reviewing the title and abstract, as well as the full text when necessary. To be considered relevant, a qualified publication had to meet all of the following criteria: (1) it should focus on evacuation simulation, rather than hazards simulation or evacuation plan assessment and optimization (for comprehensive reviews of optimization models, see (Haghani, 2020; Vermuyten et al., 2016)); (2) it should focus on evacuation behaviors during emergencies, rather than pedestrian dynamics under normal conditions (for comprehensive reviews of the pedestrian dynamics field, see review papers authored by Bellomo and Dogbe (2011) and Duives et al. (2013) and the book by (Cristiani et al., 2014)); (3) it should focus on pedestrians only, rather than drivers; and (4) it should be relevant to indoor environments (for a comprehensive review of pedestrian behaviors in broad urban environments, see (Papadimitriou et al., 2009)). After the filtering was conducted, in order to avoid missing non-indexed materials with high relevance and impact, the authors continued to enrich the search results, by using the snowballing technique (Wee and Banister, 2016).

As a result, a total of 235 publications were included in the search results, which are reviewed in detail in Section 3. It is noteworthy that, beyond these publications, the authors have also reviewed a range of additional materials, including publications discussing pedestrian dynamics, empirical evacuation experiments, and principles of computer simulation, as well as user manuals by PES tool vendors, fire safety-related standards and technical reports, and so on. These materials did not meet all of the above criteria to be included in the search results; however, they were beneficial for comprehensive review and thorough discussions of the state of the art of the PES area that are presented in the following sections. A preliminary bibliometric analysis of publications in the search results, as illustrated in Fig. 1, shows that the amount of

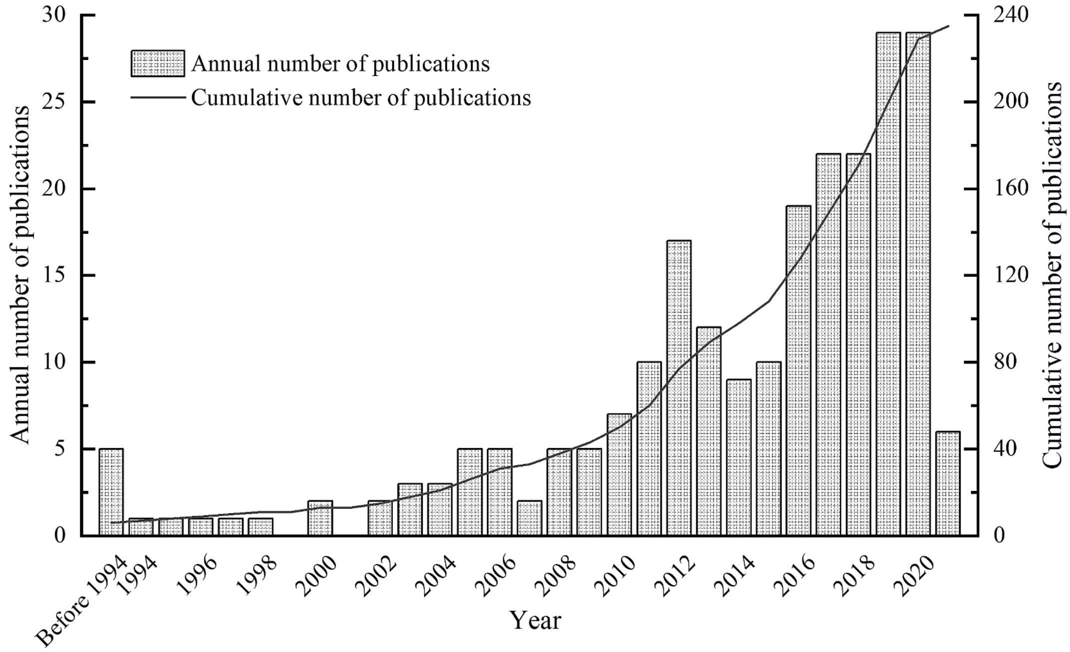

Fig. 1. The statistics of annual publications.

works published in this area remained at a relatively low level until 2009, after which a rapid increase was observed. The top five countries/regions where corresponding authors were from, as shown in Fig. 2a, were China (104), United States (32), Germany (9), Spain (8) and United Kingdom (8). The top five sources of publications, as shown in Fig. 2b, were the following journals: *Physica A: Statistical Mechanics and its Applications* (36), *Safety Science* (18), *Simulation Modeling Practice and Theory* (12), *Fire Safety Journal* (12) and *Fire Technology* (9).

3. Review of pedestrian evacuation simulations

This section provides a systematic review of prior studies in the area of PES. Based on the simulation approaches they adopted, these studies are categorized into four groups, including macroscopic approach-based PES, social force (SF)-based PES, cellular automata (CA)-based PES and agent-based modeling (ABM)-based PES. Studies in each group are reviewed in a separate subsection below, which examines the PES approach, PES models developed using this approach, and PES tools that implement these models. With respect to models, this review focuses on their attributes, functions and the purposes they serve. The mathematical formulations of the models, which are reviewed in (Eftimie, 2018), are not examined in detail in this review. With respect to tools, only those which are classic or widely-used and whose information is publicly accessible are included in this review. In addition to the information obtained from relevant academic articles, vendor websites, developer communities (e.g. Github) and tool user manuals, the authors also tested a few tools and consulted with the developers or vendors in order to obtain additional first-hand knowledge about the tools.

3.1. Macroscopic approach-based PES

3.1.1. The macroscopic approaches

Macroscopic approach is a general term for a class of PES approaches that consider all evacuees as homogeneous and neglect their individual characteristics and decisions, based on the assumption that the number of pedestrians is large enough for them to be described by locally averaged quantities (Cristiani et al., 2014). For representation of the geometry of evacuation sites, macroscopic approaches generally use a network, in which the whole geometry is divided into multiple nodes connected by arcs. Nodes represent rooms, lobbies or intersection points, while arcs represent corridors, hallways, stairways or connections between intersection points (Hamacher and Tjandra, 2002). The

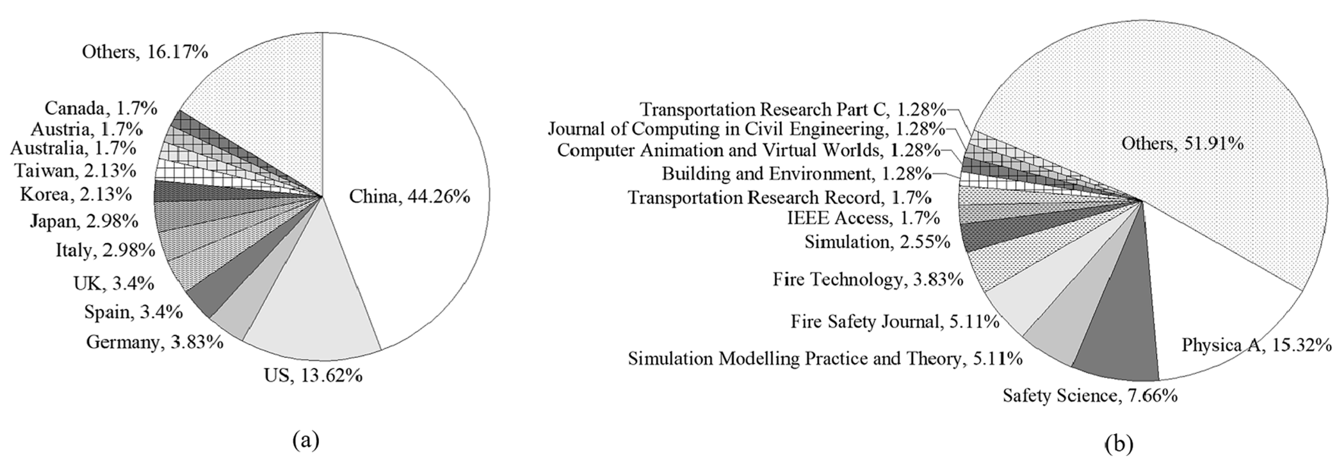

Fig. 2. (a) The country and region distribution of corresponding authors; (b) The journal distribution of publications.

network is used to model supply points (locations that house evacuees) and demand points (exits or safety locations), as well as paths that transfer supplies to demands. Each node is characterized by the number of evacuees it houses and its capacity, which is the upper bound of the number of evacuees allowed to stay in the node simultaneously. Each arc is characterized by its flow volume, travel time and flow capacity, where the flow capacity determines the number of evacuees allowed per unit time to traverse the arc.

In macroscopic approaches, evacuees are modeled as "flow" that travels through the arcs. The volume and route choices of the flow can be modeled based on two different principles, namely optimization and simulation. Under the "optimization" principle, macroscopic approaches mainly determine which path each individual should follow in ideal scenarios, by using graph-theory based mathematical methods to achieve certain optimization objectives, such as shortest path (Fahy, 1991), minimum cost (Yamada, 1996) and quickest path (Kagaris et al., 1999). In contrast, the "simulation" principle aims at simulating the probable behavior of individuals or crowds by modeling their observed behavioral characteristics, so as to reproduce the properties of individuals or crowds in the evacuation process. Macroscopic approaches based on optimization algorithms are not covered in detail in this review, because these approaches do not fully comply with the definition of PES. They ignore the spontaneity and randomness of behaviors of evacuees, and the results are based on how the evacuees should behave in an ideal scenario instead of how they are most likely to behave in reality. For a comprehensive review of optimization approaches, see (Hamacher and Tjandra, 2002).

The only widely known macroscopic PES approach based on the "simulation" principle is the fluid dynamic approach. First proposed by Henderson (1971, 1974) and Predtechenskii and Milinskii (1978) and later on enhanced by Helbing (1998), this approach considers pedestrian dynamics as flows of fluids, for they share certain properties from the macroscopic perspective. In Helbing's work (Helbing, 1998), the pedestrians are distinguished into different groups, representing crowds with different intended movement directions. Each group is mainly characterized by its spatial density, mean velocity and velocity variance. The motion of the groups and the interaction between the groups are both calculated based on fluid dynamics equations. This approach is suitable for simulating the jamming situations in which the crowd flow is dense. However, the actual evacuation situations do not always conform with the hypotheses of the fluid dynamic approach (Hughes, 2002), and the fluid dynamic equations are complex and highly nonlinear, which limits the flexibility of this analogy of fluid in practical applications.

3.1.2. Macroscopic approach-based models

The following review of macroscopic models mainly focuses on simulation models, including a few hybrid models of simulation and optimization, in which optimization algorithms are used to determine individuals' route choices and simulation plays an important role in representing individual interactions and crowd behaviors.

For simulation models, Hughes (2002) derived the equations of motion governing the two-dimensional flow of multiple crowds, by introducing the concepts of high-density (subcritical) and low-density (supercritical) flow regimes. In another study (Hughes, 2003), he developed a continuum model to describe crowds as "thinking fluids'' by hypothesizing that individuals were commonly willing to reach the destination as a crowd and seek to minimize their estimated travel time, but would avoid being extremely gathered when densities were excessively high. Colombo and Rosini (2005) proposed a continuum model to describe typical characteristics of evacuee flows, such as crowd overcompression and accidents of falling caused by a crowd jam.

A number of hybrid models were developed to study the interactions among evacuees. For instance, Luh et al. (2012) simulated the disorder and blocking phenomena caused by stress and competitive behaviors. Their study bridged the gap of modeling the blocking effect at a macroscopic level by driving pedestrian movements with an acceleration or deceleration force. Guo et al. (2011) proposed a model that refined the representation of space as finer hexagonal cells in combination with the so-called potential map to simulate the interactions of crowds when they pass through a bottleneck. In the potential map, each cell was assigned with a potential value according to the route distances to exits, which served as the basis of route choices of evacuees. Hybrid models were also used to study the influence of the environment on evacuees' route choices. One example was the routing model developed by Stubenschrott et al. (2017), which considered both individuals' different degrees of familiarity with the infrastructure and their personal preference in the calculation of the optimal paths. Another example was the study conducted by Hashemi and Karimi (2016). They introduced the accessibility indices, which formed a weighted graph of the entire geometry in the routing algorithm, to describe the accessibility of indoor spaces, a key factor for the routing requirements of disabled individuals during emergency evacuation.

3.1.3. Macroscopic approach-based tools

Since most of the contemporary PES tools are based on microscopic approaches for their better simulation accuracy, the following review mainly focuses on several macroscopic tools that were once widely used and integrated the "simulation" approach in their processing mechanism. Tools that implemented the optimization models only, such as EVACNET4 (Kisko et al., 1998) and EESCAPE (Kendik, 1983, 1986), are not included in this review.

A well-known macroscopic PES tool is EXITT (Levin, 1989). It takes individuals' behavioral responses towards hazards (fire and smoke) into account. Specifically, compared with optimization tools, EXITT improves the simulation of behavior of individuals by considering the impacts of various factors, including age, sex, smoke conditions, smoke detector and alarm, capabilities of the individuals, and so on. Influenced by these factors, the individuals may take different actions in the simulation, including evacuating, investigating the fire, alerting others, and rescuing others. The behavioral (or decision) rules used by EXITT are developed based on data from investigations of real fire incidents. Additionally, EXITT is the first PES tool to incorporate fire hazards data, by connecting to the fire simulator HAZARD I (Bukowski et al., 1987). Another once widely used macroscopic PES tool is EXIT89 (Fahy, 1991; Fahy et al., 1995). It integrates the queueing analysis of EVACNET and the behavioral rules of EXITT. By considering the variation of mobility among individuals with different physical conditions (e.g. disabled people tend to move slowly) or under different scenarios (e.g. the crowd density influences individuals' walking speed), EXIT89 is suitable for

Table 1
Features of macroscopic approach-based PES tools.

Tools	Accessibility	Space representation	Simulation mechanism		
			Behavior	Movement flow	Movement direction
EXITT	Proprietary - commercial	Coarse	Rule-based deterministic behavior	SD	Flow-equation
EXIT89	Proprietary - scholarly	Coarse	Rule-based deterministic behavior, stochastic	SR	Flow-equation

Note: SR = Specification required (users are required to specify speeds values on their own), SD = Specified speed values based on secondary data.

simulating the evacuation of high-density crowds from large buildings.

A major limitation of the macroscopic PES tools is that they are all based on the node-arc representation of the geometry, with which it is difficult to capture the inherent randomness of human behavior and more detailed and microscopic interactions between individuals (e.g. clogging), leading to inaccuracies in movement prediction (Hamacher and Tjandra, 2002).

Table 1 compares the macroscopic PES tools in terms of three features, namely accessibility, space representation and simulating mechanism. "Accessibility" assesses whether the tool is open-source or proprietary (commercial or scholarly); "space representation" assesses the granularity of geometry representation; and "simulation mechanism" assesses the pedestrian behavioral rules adopted in the tool, including what behavioral rules the pedestrians follow ("behavior"), how the pedestrian movement speed is specified ("movement flow"), and how the direction of pedestrian movement is determined ("movement direction").

3.2. SF-based PES

3.2.1. The SF approach

The SF approach regards each pedestrian as a Newtonian particle, which is subject to forces and acts through acceleration or deceleration behaviors. The earliest force-based PES approach can date back to the mathematical model proposed by Hirai and Tarui (1975) and the magnetic model proposed by Okazaki (1979). Hirai and Tarui (1975) considered that individuals are subject to a force to form a group and move forward, a force exerted by the environment around the individual, and a random force, while Okazaki (1979) regards individuals as positive magnetic charge, being attracted by exits (negative magnetic charges) and repelling other individuals. The widely used concept of SF, which refers to a vectorial quantity that describes the concrete motivation to act, was formally conceptualized by Helbing and Molnár (1995). They proposed to use the SF to represent the effect of the environment and the crowd on the behavior of each individual. In a follow-up study, Helbing et al. (2000) further improved the SF approach by considering the impact of "panic" on the individuals. "Panic" is assumed as a particular form of collective behavior occurring in situations of scarce or dwindling resources in Helbing et al's research, a definition of "panic" that was later on adopted by a number of SF models.

According to the SF approach proposed by Helbing et al. (2000), the crowd behavior is controlled by a mixture of socio-psychological and physical forces, which includes a driving force $m_i\left(v_i^0(t)e_i^0(t)-v_i(t)\right)/\tau_i$, an interaction force f_{ij} between individual i and individual j, and an interaction force f_{iW} between individual i and wall W. The change of velocity of individual i at time t can be determined based on the following acceleration equation:

$$m_i\frac{dv_i}{dt}=m_i\frac{v_i^0(t)e_i^0(t)-v_i(t)}{\tau_i}+\sum_{j(\neq i)}f_{ij}+\sum_{W}f_{iW} \tag{1}$$

where m_i, v_i, v_i^0 and e_i^0 denote the mass, instantaneous velocity, desired speed of and preferred direction of individual i, respectively, and τ_i denotes a certain characteristic time interval.

There are two particular effects in panicking evacuation crowds associated with collisions caused by high-density crowds, including a "body force" counteracting body compression, and a "sliding friction force" impeding relative tangential motion. The two effects, as well as social repulsive force (the repulsive effect produced by territorial effect), constitute the interaction force. When the sliding friction force is large enough, the famous Fast Is Slow (FIS) phenomenon can be observed (Helbing et al., 2000). Additionally, panic can also affect the desired speed v_i^0 and the preferred direction e_i^0 in equation (1). Compared with other approaches, the SF approach is relatively simplistic and effective for describing pedestrian movements, thus it is often combined with other approaches to develop hybrid PES models.

3.2.2. SF-based models

As aforementioned, the total social force that drives pedestrian behaviors consists of three different forces. Accordingly, the existing SF-based PES models can be divided into three groups based on the specific force being examined in each model.

The first group of models focuses on improving the modeling of the driving force. For instance, Zainuddin and Shuaib (2010) proposed an SF-based model with enhancement of the decision-making capability of independent pedestrians during the evacuation process. Two attributes of pedestrians were taken into account, including their independence level on others and the ability to assess the crowdedness of an exit. To make the simulated pedestrians more intelligent, the same researchers modified the above model in a follow-up study (Shuaib and Zainuddin, 2017), by introducing a rush parameter and a prediction factor. The rush parameter represents the individual's assessment of the desired speed, which can reflect the panic level under emergencies to a certain extent. The prediction factor represents the individuals' forecast of the future status (e.g., whether clog or not) of their chosen exits. In another study, Han and Liu (2017) introduced an information transmission mechanism to calculate the driving force in the SF-based model. Compared with the model proposed by Helbing et al. (2000), the movement directions of pedestrians are decided by the information obtained from their neighbors, instead of the location information of the nearest exit. In addition, several studies extended Helbing's model and allowed SF-based models to simulate the evacuation process in scenarios where multiple exits are accessible (Wang et al., 2016) and emergency signs are visible (Yuan et al., 2018). The exits and emergency signs in the models provided a preferred direction (a vital parameter in driving force expression) that was attractive to the individuals. Andrés-Thió et al. (2021) modified Helbing et al.'s model and included a self-stopping mechanism to limit the amount of pushing between individuals. As a result, the FIS effect disappeared, which suggested that when individuals stay calm and do not push others, the evacuation process could be accelerated.

The second group of models focuses on improving the modeling of the interaction force among individuals. For instance, to avoid oversimplifying the contact force, Lin et al. (2016) developed an SF-based model in which they used the Hertz contact model (Hirshfeld et al., 1997) to represent the contact force between two spherical particles. Meanwhile, an anisotropic feature was added into the repulsive force among individuals to measure the intensity of pedestrians' reactions to different directions. Hou et al. (2014) developed an SF-based model to simulate the force between trained leaders and followers in a smoky room, in which trained leaders knew exactly the location of exits. However, the model could only simulate straight evacuation routes in simple spaces (e.g., a blank room). To address this limitation, Li et al. (2016) combined the above model with a trace model, which could simulate the following behavior in complex evacuation routes (e.g., zigzag paths). The impatience of followers was also considered in this model. In addition, several studies introduced a group force into SF-based models. A group refers to a group of individuals who have social relationship or/and navigate together (Hien et al., 2017). For instance, B. Liu et al. (2018) defined four relationships in the crowd, namely family, friends, colleague and no-relation, by extracting the coordinates of the crowd through video data. In a follow-up study, different group relationships based on kinship were identified using a cluster algorithm (Liu et al., 2019a). Both of the above models established the group force based on the identified relationships among the individuals. Zhang et al. (2018) developed an SF-based model for simulating earthquake evacuation. The model could simulate different types of individuals, including leaders, group members and disorganized pedestrians. The disorganized pedestrians would tend to gather into groups that were within their horizons. In another SF-based model for earthquake scenarios, individuals' emotional intensity affected by the earthquake was considered in the interaction force between the leader and other individuals (Liu et al., 2019b).

The third group of models focuses on improving the modeling of the interaction force between the individuals and environments. For instance, Han et al., (2017) extended Helbing's model (2000) by introducing a force between individuals and multiple obstacles in the space. Zhang et al. (2012) developed an SF-based model that could be applied in spaces with complex interiors. Li et al. (2021) proposed another SF-based model that considered the constraining effect of the ground topography on stair movement based on the height map. Terrorist attacks are another type of scenario considered in prior research. One such study carried out by Liu (2018) proposed an SF-based model that introduced an interaction force between terrorists and victims for simulating the evacuation of victims caught in terrorist attacks. Wan et al. (2014) considered the force between pedestrians and sudden toxic gas source in a biological and chemical terrorist attack. Their SF-based model incorporated the Gaussian puff model, which was used to calculate the concentration of instantaneous toxic gas sources.

3.2.3. SF-based PES tools

There are four publicly accessible SF-based PES tools. Simwalk PRO (Simwalk, 2020) and PTV Viswalk (PTV group, 2020a) are two flexible general-purpose commercial software packages that are developed for modeling pedestrian walking behavior and crowd analysis and have wide applications in building evacuation simulation. PTV Viswalk can connect to Vissim (PTV group, 2020b), a traffic flow simulation software, which enables researchers to investigate evacuations from indoor environment to outdoor environment. Pedsim and FDS + Evac are two free SF-based PES tools. Pedsim (Gloor, 2020) is a microscopic pedestrian crowd simulation library plus several helper applications. Using this tool requires a C++ compiler and certain level of computer science knowledge. FDS + Evac (Korhonen and Hostikka, 2009) is developed and maintained by VTT Technical Research Centre of Finland (VTT, 2020). Implemented as part of the Fire Dynamics Simulator (FDS), FDS + Evac runs on a command prompt window, and its simulation results can be visualized with the support of Smokeview (Forney, 2013).

The above tools are further compared in Table 2 based on the following five features, namely accessibility, hazard scenario, input, representation and visualization. "Hazard scenario" assesses which hazard scenario the tool is developed for; "input" assesses the supported input format for hazards and space modeling; "representation" assesses the granularity of geometry modeling and human body modeling; and "visualization" assesses the availability of computer graphics for visualizing simulation outcomes.

3.3. CA-based PES

3.3.1. The CA approach

CA approach is a general term for a class of approaches for modeling pedestrian evacuation. As a grid dynamical simulation approach in discrete space, time and states, the CA approach usually involves the concepts of cells, states of cells and evolution rules. Given the initial state of each cell, the whole model updates at a certain time interval, and each cell may change its state based on its own and adjacent cells' states. The major advantage of the CA approach is its high computational efficiency since its simple structure is well suited for simulation on parallel computers (Bandini et al., 2001). Despite its simplicity, the important qualitative features of pedestrian behaviors in the evacuation, including jamming, lane formation (Burstedde et al., 2001) and "panics" (Kirchner and Schadschneider, 2002), can all be modeled using the CA approach. It is noted that although "panic" was often simulated in PES models, there lacks a universally adopted definition of panic, and panic behaviors in PES models are largely subject to the interpretation of modelers (Haghani et al., 2019). Whether panic often occurs in case of emergencies and whether it is supported by empirical evidence is still questionable (Haghani et al., 2019; Rogsch et al., 2010). Regardless of such debates, this review does not intend to define this concept but to reflect how it was interpreted in various contexts in prior studies.

Depending on how they extend the above basic framework of the CA approach, current CA-based PES approaches can be generally classified into the lattice gas (LG) approach and the field-based approach. According to the LG approach, each individual has a preferred direction, and is more likely to proceed towards the preferred direction, while the transition probabilities towards other directions are set to be lower (Muramatsu et al., 1999). The dynamics of the LG approach are based on a succession of two steps in turn, namely collision and propagation. At the collision step, the individuals interact with each other, and their new preferred directions are determined. At the propagation step, the individuals move to the next locations according to their transition probabilities.

On the other hand, the field-based approach describes individuals' behavioral principles with the concept of "field". Among its several variations, the most widely used form of field-based approach is the floor field (FF) approach proposed by Burstedde et al. (2001). This approach assigns values of static field and dynamic field to each cell. The static floor field is correlated with the distance of a cell to any exit (higher when closer to exits), and is used to describe the tendency of individuals to walk along the "shortest path" (e.g., (Kirik et al., 2011)). In contrast, the dynamic floor field is correlated with the "trace" produced by evacuees. The more individuals pass by, the higher dynamic field one cell gains (it may diffuse to adjacent cells or decay over time). The dynamic field is often used to describe the herding behavior of crowds, which refers to a tendency of individuals to follow the crowd or, more specifically, to imitate the action of the majority (Haghani et al., 2019), under emergency situations. As such, a cell with a strong dynamic field at present implies that it is preferred by individuals in previous moments. A map of field values of all cells is updated at each time interval, and each individual chooses to move to the adjacent cell with the highest total field value if this cell is available for transition. Additionally, efforts were made to improve the representation of pedestrians and space in the field-based approach, by introducing density fluctuations and improving spatial relations (Wąs et al., 2006; Wąs and Lubás, 2013).

3.3.2. CA-based PES models

Depending on the type of approach used in model development, existing CA-based models can be broadly categorized as LG-based models and field-based models. For LG-based models, since Marconi and Chopard (2002) proposed a 2-dimentional LG-based model that

Table 2
Features of SF-based PES tools.

SF tools	Accessibility	Hazard Scenario	Input		Representation		Visualization
			Hazards input	Space input	Space	Human body	
SimWalk Pro	Proprietary - commercial	NSS	N/A	DWG, IFC	Continuous	Circle	2D/3D
PTV Viswalk	Proprietary - commercial	NSS	N/A	DWG, IFC	Continuous	Circle	3D
Pedsim	Open-source	NSS	N/A	XML	Continuous	Particle	2D
FDS+Evac	Open-source	Fire	FDS fire data	TXT	Continuous	Three-circle model	N/A

Note: NSS = no specified scenario, N/A=not applicable.

contained extra rules (herding behavior and friction) for the collision step, later studies mainly focused on improving the modeling of the interactions between the individuals and environments. For instance, Helbing et al. (2003) simulated the evacuation of students from a classroom and focused on the spatial dependence of their escape times on the initial positions and dynamic situation of congestion. Isobe et al. (2004), Nagai et al. (2004) and Cao et al. (2015) studied the effect of exit configuration (quantity and location) on the escape-time distribution in a low-visibility room. Li et al. (2008) introduced a parameter "exit bias" to account for the impact of familiarity of individuals with different exits on their evacuation decisions. Ma et al. (2012) developed an LG model to simulate evacuation in a high-rise building, by taking the usage of elevators and refugee floors into account. Fang et al. (2016b) simulated civil aircraft evacuation using a finer grid LG model, in which the effect of seat area and the hesitation of individuals before leaving exits were considered.

Several other studies aimed at improving LG-based models by describing the interactions among individuals more accurately. For instance, Wąs (2005) proposed an LG model that related the state of each individual to the crowd density in the individual's proximity, which allowed the model to consider the influence of both the pressure among individuals and their strategic abilities. Guo et al. (2012, 2013) developed a heterogeneous LG model that introduced local population density, partial evacuation intensity and critical force of injury (casualty would happen if local repulsion force exceeds the critical force) to simulate human interactions in high-density crowds. Hybrid models were also developed to simulate various human interactions. Examples include the models developed by Song et al. (2006) and Guo and Huang (2008), which introduced the social force concept into LG-based models to represent various interactions, such as extrusion, repulsion and friction.

As for the existing field-based models, they can be classified into two groups, including those that focus on interactions between the individuals and environments, and those that focus on interactions among the individuals. One example of the first group is the model developed by Yang et al. (2009). It included extra dynamic information of buildings (e.g., fire alarm and light signal) in the calculation of dynamic field, and was used to study the impact of building information on the evacuation efficiency. Li et al. (2019) developed an extended cost potential field model, which introduced a novel visibility function to describe the impact of poor vision, psychological tension and special contexts on evacuation efficiency. Ding et al. (2017a) studied the fatigue factor that could impact the transition speed of evacuees during evacuation from high-rise buildings. Based on the FF model and genetic algorithm, they also studied the influence of mixed evacuation choices of using elevators and stairs in a high-rise building on evacuation time (Ding et al., 2017b). Zheng et al. (2019) proposed a FF model for simulating the evacuation from a flooded underground station. Different behaviors of individuals evacuating from floods, such as moving to higher places and holding support objects, were modeled using different floor fields.

Regarding the field-based models that investigated the interactions among individuals, one of their focuses is the interactions that may have negative impact on the evacuation efficiency (friction effect). For example, Kirchner et al. (2003) introduced the concept of friction parameter, which was used to distinguish competitive and cooperative movements, in aircraft evacuation simulation. Schultz et al. (2007) introduced repulsion potentials, friction effects, and pathfinding/guidance algorithms to simulate evacuation in airports. Tanimoto et al. (2010) established a field-based model that used game theory to simulate the collision effect. Their simulations showed that collision could be reduced by placing an obstacle ahead of the exit. Another focus of this group of field-based models is the group behavior. For instance, Köster et al. (2011) developed a field-based model for simulating group formation within crowds, based on the assumption that pedestrians prefer walking abreast and communicating when the path is free. The model was validated with an experiment of classroom egress. Similarly, Lu et al. (2017) developed a FF model by incorporating the leader–follower rule in group behaviors, which allowed individuals to change direction when necessary to access an alternate exit route. Pereira et al. (2017) introduced the route change probabilities and group fields into their FF model, which made groups of individuals more likely to remain close to each other during evacuation. Chen et al. (2019) explored children's behavior in evacuation. They pointed out that children tended to stop and wait for group members, and showed in simulation that this group behavior and their tendency of playing while evacuating had a significant negative impact on evacuation time. Furthermore, hybrid models with multiple types of social forces were also proposed to simulate interactions among individuals. For instance, Yang et al. (2004, 2005) introduced five types of forces into their model to describe the interactions among individuals, and used this model to simulate the effects of attraction in each group of evacuees. Similar work was also reported by (Song et al., 2006), in which various behaviors such as arching, clogging and "faster-is-slower" were observed. Chen et al. (2020) combined the field-based model with social forces, and found that the more unevenly individuals were distributed in a room, the more significantly the evacuation time would be affected by social forces.

3.3.3. CA-based PES tools

There are three publicly accessible CA-based PES tools, including STEPS (Mott Macdonald, 2020), PedGo (TraffGo HT, 2013) and EXODUS (Owen et al., 1996). STEPS can model interactions between evacuees and 3D moving vehicles as well as within evacuees. Compared with other CA-based tools, STEPS is featured by its intuitive 3D modeling environment and outputs for simulating evacuations from complex multi-level facilities. PedGo simulates the route choices of evacuees according to the potential map, and models hazards (e.g. smoke, fire or floods) by blocking rooms at stochastically defined times for denoting that these spaces are unavailable due to the hazards. EXODUS comprises a suite of software packages tailored to building, maritime, rail and aircraft environments. First released in 1996, it is now one of the most widely used tools in the market. It simulates the interaction between evacuees and various fire hazards, such as heat, smoke and toxic (narcotic and irritant) gases.

The above tools are further compared in Table 3, based on the following features: accessibility, input, simulation mechanism and visualization.

3.4. ABM-based PES

3.4.1. The ABM approach

The earliest form of the ABM approach can date back to political economist Thomas Schelling's segregation model (Schelling, 1971) in the 1970 s. An agent-based model consists of a system of agents (autonomous decision-making entities (Bonabeau, 2002)), their environments (supplying agents' perceptions and enabling their actions) and the interactions among agents (Bandini et al., 2009). One critical feature of the ABM is that the system is decentralized, where no global system behavior would need to be defined (Borshchev and Filippov, 2004). The ABM is a bottom-up modeling approach, which describes individual-level interactions among agents. However, it can capture higher-level emergent phenomena, such as herding behavior and traffic jam, as a result of agents and their interactions (Bonabeau, 2002). Agents can represent various types of entities, such as humans, vehicles, corporations, infrastructures and so on. Each agent is set with unique attributes to realistically represent a few characteristic features of the entities.

Agents' autonomy, social ability, reactivity, pro-activity, cooperation, learning ability and adaptivity (Laughery, 1998) allow the ABM to simulate the complex behavior of humans in emergency situations, therefore making the ABM an effective and increasingly used approach for PES. There are three advantages of ABM as an evacuation simulation approach, including its capability to capture emergent phenomena, its natural description of a system, and its flexibility to tune the complexity

Table 3
Features of CA-based PES tools.

CA Tools	Accessibility	Input		Simulation mechanism		Visualization
		Hazards input	Space input	Decision-making rule	Movement speed	
STEPS	Proprietary - commercial	FDS, CFAST	DXF, IFC	Implicit	SR	2D/3D
Exodus	Proprietary - commercial	FDS	DXF, IFC, SFM	Rule-based deterministic behavior	PO	2D/3D
PedGo	Proprietary - commercial	CFAST	DXF	Implicit	SR	2D/3D

Note: Implicit means behaviors are not represented directly by rules, PO = Specified speed values based on primary observation, SR = Specification required.

of the agents (Bonabeau, 2002). Specifically, emergent phenomena during evacuation, such as queueing, competition and herding behaviors, can be captured, thus the ABM can be used to predict the collective behavior of the crowd. Second, ABM makes the evacuation simulation seem closer to reality compared with other PES approaches. With the ability to learn and memorize, agents can show adaptive behaviors to dynamic environments. Last but not the least, ABM can describe agents with different levels of aggregation (e.g., individual, group, crowd) (Bonabeau, 2002), and can be easily combined with other methods, such as fuzzy logic, genetic algorithm and so on, to adjust agents' behaviors and decision-making rules.

3.4.2. Agent-based PES models

A number of agent-based PES models have been proposed in recent years, which can be generally divided into three groups, according to whether their major contribution is related to the modeling of agents' perception and decision-making mechanisms, their interactions with the environment, or their interactions with each other.

Simulating the perception and decision-making of agents in emergencies is challenging since the cognitive processes of perception and decision-making are not simply logic rule-based (Joo et al., 2013). Lee et al. (2010) proposed an extended belief-desire-intention (BDI) model to improve the simulation of agents' perception and decision-making processes. In this model, an agent would identify available options based on its assessment of the environment, and make a decision according to its preference value and choice probability of each available option. However, this model could not simulate human reactions to dynamic environments. To address this limitation, Joo et al. (2013), Busogi et al. (2017) and Hassanpour and Rassafi (2021) incorporated the affordance theory, which allowed an agent to make decisions based on various affordance values perceived from a dynamic environment. Yuksel (2018) adopted the NEAT (Neuroevolution of augmenting topologies) algorithm in his model to train autonomous agents, which could learn how to change and improve their behaviors (e.g., obstacle detection and collision avoidance) during evacuation through the evolution of ANNs (artificial neural networks). Niu et al. (2018) combined membrane computing with ABM and proposed a bio-inspired simulation model. In their model, each agent would choose its next step based on its knowledge base, which was updated continuously according to the interactions of the agent with the surrounding environment and the neighbor agents. Sharma et al. (2008, 2018) incorporated the fuzzy logic approach in their agent-based model and constructed a membership function for speed, which could model uncertainty in behavior that resulted from panic and stress. Agents would produce three levels (low, medium and high) of speeds depending on their levels of panic or stress, and their evacuation time would be affected accordingly. Zhou et al. (2016) embedded a fuzzy logic-based model in their agent-based model. The fuzzy inference system used information from individuals' perception as well as their prior experiences and knowledge to determine their turning angle and movement speed. Schröder et al. (2015) considered the perception process of fire-related effects with a smoke sensor and modeled the decision-making process based on the cognitive map (Kuipers, 1983, 1978; Tolman, 1948) in their agent-based model. Similarly, Andresen et al. (2018) modeled the decision-making process of those who own no or limited information about the environments, and proposed a representation of partial spatial knowledge using cognitive maps in their agent-based model.

The second group of models focuses on improving the modeling of agents' interactions with the environment. A number of models were developed to examine the evacuation in different types of space, which is a key environmental factor that determines the characteristics of the space and in turn influences agents' interactions with the environment. For instance, Wagner and Agrawal (2014) developed a configurable evacuation model for a concert venue setting, such as a stadium or an auditorium. Their model allowed users to specify customized environments with any number and arrangement of seats, pathways and exits. Liu et al. (2014) simulated the process of releasing seat belts, egressing from seats, and opening emergency exit doors in an aircraft PES model. Due to the growing number of emergency incidents in schools, several studies also developed agent-based models to examine the evacuation of students under different classroom layout scenarios (e.g., different arrangements of desks and numbers of exits) (Delcea et al., 2020; Liu et al., 2016). For regular buildings, Chu et al. (2015b) considered the impact of different arrangements of exit signs in their agent-based model. In another agent-based model proposed by Chu and Law (2019), the agents would choose different escape routes based on their knowledge and familiarity with the building instead of simply following the shortest path.

Another factor that has major influence on the agent-environment interactions is the characteristics of hazards in the environment. Accordingly, prior studies have examined a few variables that are associated with the hazards and may influence the agents' behaviors. The first such variable is the physiological harm. Shi et al. (2009) introduced individuals' physical fitness and mobility into an agent-based model to measure the physiological harm caused by flames, high temperatures, and high concentrations of smoke and toxic gases. Li et al. (2020) developed an indoor evacuation model to simulate the dynamic influences of heat, temperature, toxic gas and smoke particles on evacuees' mobility and health conditions, as well as fire risk-informed navigation decision making. Another variable is the dynamic spatial accessibility. For instance, Nguyen et al. (2013) simulated human evacuation behaviors with the effect of smoke diffusion on the visibility of space in their agent-based model. Tan et al. (2015) developed an agent-based model that considered the fact that some evacuation paths would be blocked when fire rolling shutters were activated and smoke and flames were spreading. A third variable is the psychological impact. For instance, Cimellaro et al. (2017) modeled the psychological impact to evacuees caused by hazardous environments. They established the relationship between the intensity of earthquake and the agents' anxiety level in an agent-based model, and evaluated the evacuation time when agents were under different anxiety levels.

The third group of agent-based PES models focuses on improving the simulation of interactions among agents. Pan et al. (2006) were among the first researchers to consider human social behavior in agent-based models. They built an agent-based framework for modeling agent's social behaviors based on three critical factors in the social structure, namely social identity, personal spaces and social proof, and investigated a few emergent phenomena, such as competitive, queuing and herding behaviors. Based on Pan et al.'s work, Chu et al. (2013, 2015a) further proposed a three-level agent-based model, in which human behaviors in evacuation were influenced by individual experience, social group and crowd interactions. Based on the perceived information and its traits, an agent would show a type of behavior chosen from a set of predefined behaviors by reasoning through the rules of the behavioral models. von Sivers et al. (2016) built a social identity model based on empirical evidence from the London bombings on July 7th, 2005, and proposed in their model an algorithm for modeling helping behavior during evacuation. In the agent-based model developed by Chen and Wang (2021), individuals were modeled to exhibit peer-seeking behavior with a tendency to evacuate in social groups during emergencies. In addition, prior research pointed out that evacuees tend to follow others in smoky, dark or unfamiliar environments, in the hope that others have already found a way out (Albi et al., 2016). Therefore, the role of leaders and their relationship with followers are a critical factor to be considered in PES models. There are two types of leaders. The first type are authorities, such as building staff and stewards, who could calm the evacuees and assist or lead them to evacuate, as modeled in several prior studies (Chu and Law, 2019; Liu et al., 2016). The other type are evacuees who are familiar with the environment and whose behaviors are influential on others. For instance, Fang et al. (2016a) developed a leader–follower model, in which each agent could decide to follow or become a leader when the conditions warranted it. Colangeli et al. (2018) and Richardson et al. (2019) proposed agent-based models for modeling the interactions between active agents that have knowledge about the spatial layout and passive agents that do not have the spatial knowledge in smoky environments with limited visibility. In general, the existence of leaders could accelerate the evacuation process (von Schantz and Ehtamo, 2020), and provides the possibilities to control the pedestrian flows with bottom-up approaches during emergencies (Albi et al., 2016) and improve the design of evacuation plans (Cristiani and Peri, 2019; Zhou et al., 2019).

The emotion contagion among humans during evacuation is also considered as a critical factor in several agent-based models (Liu et al., 2018c; Ta et al., 2017). For instance, Zhou et al. (2020) and Zou and Chen (2020) proposed emotion contagion models that were drawn upon the OCEAN (openness, conscientiousness, extroversion, agreeableness, neuroticism) personality trait in the psychological domain. When the cumulative value of a kind of emotion of an agent exceeded an infection threshold, the agent's emotion state would change, and its path planning and behavioral patterns would be influenced by the current emotion state. Taking a step further, Tsai et al. (2011) proposed an airport evacuation model that could simultaneously consider the influence of emotional contagion and kinship. Hien et al. (2017) developed another agent-based model, in which three attributes of groups, including the time to wait for a missing follower, the minimal distance of maintenance of group and the time to search for other social group members, would affect agents' emotions.

3.4.3. ABM-based PES tools

Both general-purpose and specialized tools have been developed and used for agent-based PES simulation. The general-purpose ABM tools that have been used for PES simulation include MASON (Trivedi and Rao, 2018), Anylogic (Busogi et al., 2017), Netlogo (Wagner and Agrawal, 2014) and GAMA (Ta et al., 2017). These tools are more widely used than specialized modeling tools, but users have to define the attributes of agents and set the evacuation rules by themselves. As for the specialized tools, users are only required to fill in the values of a set of pre-defined attributes. One example is Simulex (Thompson et al., 1997; Thompson, 1994), which uses multiple distance maps to assess travel distances and find optimal evacuation routes in a building. It was also the first tool to introduce the three-circle model for human body representation, which is now used in various other PES tools. MassMotion (Oasys, 2020), Pedestrian Dynamics (Incontrol, 2020) and Pathfinder (Thunderhead Engineering, 2014) are another three commercial ABM-based PES tools, which are featured with continuous spatial structure and compatibility with BIM (building information modeling) software. The software development kit in MassMotion provides users with direct access to its engine for customizing the behaviors of individuals and creating connections to other software tools. Pathfinder is one of the most widely used PES tools (Lovreglio et al., 2020). It allows users to connect families, coworkers and other socially-related individuals into groups. It also provides representation of wheelchairs and hospital beds for agents with special mobility needs, and can simulate assist behaviors during evacuation. In addition to the above commercial tools, there are another two tools developed by academics. They are SAFEgress (Chu, 2015) and AvartarSim (Sharma, 2009). SAFEgress is implemented using a tiered decision-making process that allows the agents to exhibit individual, group and crowd behaviors. Moreover, it can simulate group dynamics and social interactions observed in real-life evacuation incidents. AvartarSim combines the genetic algorithm with neural networks and fuzzy logic to model the learning and adaptive behavior of agents during evacuation.

The above ABM-based PES tools are further compared in Table 4, based on the following five features: accessibility, input, representation, intelligence of agents, and visualization. "Intelligence of agents" assesses whether the agents possess learning abilities and social relationships.

4. Discussions

4.1. PES approaches: Use of high-fidelity approaches has become more prevalent over time

Bibliometric analysis is conducted in this review to analyze prior PES publications in terms of the use frequency of different approaches over the years. The result, as visualized in Fig. 3, illustrates the annual number of published PES models that used the four different PES approaches. The figure suggests that models based on the CA and ABM approaches account for the majority of existing PES models, and that the ABM approach has gradually become more prevalent over time.

The different properties of the four PES approaches may help explain such trends. Specifically, these approaches are compared in three aspects, namely the computational efficiency, the granularity in modeling individuals and environments, and the fidelity in describing evacuee decision-making mechanism and behavioral characteristics, as discussed in detail below.

The computational efficiency is an important performance indicator of PES, particularly in the early stage of PES research when the computing power was generally limited and the computability was a primary concern for computer programs. The macroscopic approach is the most computationally efficient PES approach, thanks to its simplified representation of the pedestrian flow and space layout. As for the CA approach, since its fundamental updating mechanism sets that each cell can only be influenced by the status of adjacent four cells (instead of all surrounding individuals and environments), its computational load grows linearly with the number of evacuees. Meanwhile, ABM approach is the most computationally intensive, as most of the interactions between every two individuals (or objects) need to be calculated, which leads to a power growth of the computational load as the number of individuals and objects in the model increases. However, due to the remarkable advancement of computing power, the computational efficiency has become less of a concern. This can explain the scarcity of works using the macroscopic approach and the rapid increase in ABM-related works in recent years.

The granularity in modeling individuals and environments is another important performance indicator of PES. Macroscopic approaches usually cannot precisely describe spatial environment in detail and hardly involve descriptions of individuals; therefore, the scope of its application tends to be limited to large-scope or relatively homogenous scenarios. The CA approach allows the assignment of at most one individual to each grid, which prevents this approach from reflecting evacuation scenes with high-density crowd (Pelechano and Malkawi, 2008). For instance, the maximum crowd density that buildingExodus and PedGO

Table 4
Features of ABM-based PES tools.

ABM tools	Accessibility	Input		Representation		Intelligence of agents		Visualization
		Hazards input	Space input	Space	Human body representation	Learning	Social relationship	
Simulex	Proprietary - commercial	N/A	DXF, IFC	Discrete	Three-circle model	N/A	N/A	N/A
MassMotion	Proprietary - commercial	N/A	DXF, IFC	Continuous	Circle	N/A	N/A	2D/3D
Pedestrian Dynamics	Proprietary - commercial	N/A	DXF, IFC	Continuous	Circle	N/A	N/A	2D/3D
Pathfinder	Proprietary - commercial	Fire data	DXF, IFC	Continuous	Convex polygon/ Circle	N/A	As, SE, LF	2D/3D
SAFEgress	Proprietary - scholarly	N/A	TXT	Continuous	Three-circle model	Yes	SE, SGM, LF, Au	2D
AvartarSim	Proprietary - scholarly	N/A	TXT	Continuous	Circle	Yes	SE	2D

Note: N/A=not applicable; As = Assist behavior; SE = Stay and evacuate together; LF = Leader-follower behavior; SGM = Search group members; Au = effect of authorities.

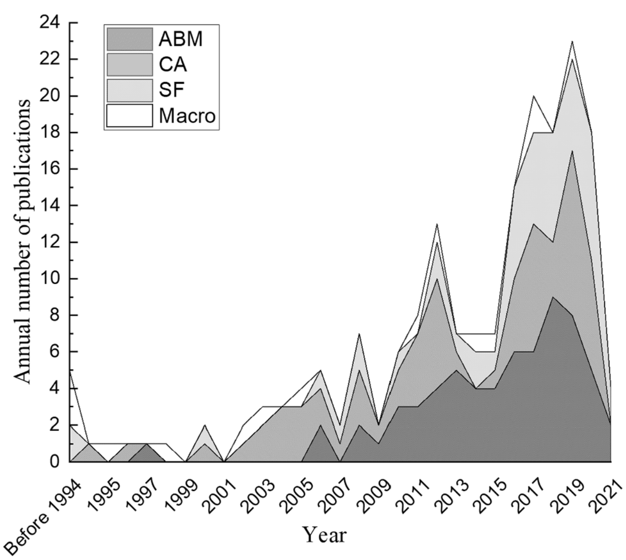

Fig. 3. Bibliometric analysis of 177 published PES models surveyed in this review (note: a few publications used two different PES approaches and are counted twice in the plot).

(both CA-based tools) can simulate is apparently below the threshold for causing serious congestions (Rogsch et al., 2009). In addition, due to the restrictions of basic rules of the CA and SF approaches, models using these two approaches have limited granularity in terms of representation of heterogeneous evacuees. The prospect of the CA approach largely depends on whether the basic CA conceptual framework can be improved to make up for its endogenous shortcomings (discretized, homogenous, implicit behavioral rules), so as to support more accurate simulation of more complicated scenarios. The ABM approach, meanwhile, does not set fixed rules on modeling space and other objects, thus providing modelers with flexibility in the selection of specific methods (e.g. continuous or discrete). With regard to evacuee modeling, ABM is an approach that models each agent as an autonomous decision-making entity and allows modelers to define a wide range of ad-hoc attributes of the agents.

The third important performance indicator of PES is the fidelity in describing evacuees' decision-making mechanism and behavioral characteristics. Fidelity here refers to the apparent realism of the PES approach, but it is noted that higher fidelity does not necessarily mean better simulation outcomes (Schadschneider et al., 2009). Individuals are modeled as homogenous entities making no autonomous decisions in the macroscopic approach. The SF approach is suitable for simulations where various kinds of interaction forces need to be described precisely. However, Henein and White (2007) argued that the omission of several real-world parameters, such as perception process, strength and force thresholds of injury, by the SF approach limited the accuracy of the simulation results. Moreover, the assumptions adopted by the SF approach related to wayfinding strategies are usually oversimplified, especially in scenarios where the geometries are complicated and multiple evacuation routes exist. The CA approach can be modified by setting various update rules to describe behavioral characteristics, however, it still bears limitations when used to model non-adaptive effects (e.g., falling, injury) in high-density crowds and information exchange and exploration in large-scale buildings (Pelechano and Malkawi, 2008). These limitations are rooted in the homogeneity assumption in the basic thinking of the approach. Compared with other approaches, the flexibility of ABM approach allows agents to gain situational awareness, adapt to dynamic environments, and make informed evacuation decisions. The characteristics of agents, including autonomy, social ability, reactivity, pro-activity, cooperation, learning ability and adaptivity (Laughery, 1998), lead to considerable potential of the ABM approach, which makes it likely to be the most prevalent PES approach in the future.

4.2. *PES models: Adaptability to various scenarios is relatively limited*

Evacuation scenarios may vary significantly, depending on three key attributes, including type of space, type of emergency and characteristics of individuals. These attributes may have critical impact on the evacuation process and outcomes (SFPE, 2019). Take space type as an example, individuals' evacuation behaviors are likely to be different between e.g. public gathering places and residential buildings, due to their different levels of familiarity with the spatial layouts; the difference in spatial complexities between e.g. shopping malls and office buildings may also influence individuals' wayfinding decisions and therefore should be modeled using different route choice algorithms. The type of emergency is another important impact factor. For instance, the dynamic spatial accessibility and confined visibility are critical factors to model in fire evacuation scenarios, while the physical health condition is one of the most concerned factors when modeling evacuation in toxic gas evacuation scenarios. As for the characteristics of individuals, their age and physical condition may impact their mobility, as reflected by parameters such as step width, step length and coefficient of friction in the simulation models (Ronchi et al., 2019). In addition, their experiences, job duties and social roles may impact their behavioral goals and patterns (Colangeli et al., 2018; SFPE, 2019).

Considering the significant diversity of the evacuation scenarios, PES should be adaptable to different scenarios to make sure that the major attributes of studied scenarios and their possible impacts on evacuation are properly considered. However, such adaptability is rather limited among existing PES models, as evidenced by the following observations about the current PES literature. First, among all PES models surveyed in this review, approximately 39.0% of them (69 out of 177) did not provide any specifics about the evacuation scenarios, in terms of the types of space, emergency and evacuees, as if the models they proposed were one-fit-all PES solutions. Among those studies that did specify the evacuation spaces they aimed to address, approximately 65.8% (52 out of 79) focused on buildings, while other types of space where evacuation could occur, such as transportation hub (e.g., metro stations and airports) and premises for recreational and/or social activities (e.g., concert halls, stadiums and theaters), have largely remained understudied. Similarly, approximately 59.2% (29 out of 49) of the surveyed models that specified emergency types focused on fire, followed by earthquake (14.3%, 7 out of 49) and toxic gas (10.2%, 5 out of 49), while other possible types of emergency, such as explosion and terrorist attacks, were rarely investigated. As for the type of evacuees, only a small fraction of the surveyed models (12.4%, 22 out of 177) examined specific groups of evacuees, such as children, seniors and disabled people, despite that these people usually face higher risks during evacuation due to their limited mental or physical capabilities and hence deserve more attention.

In summary, generic PES models may not be directly applicable to different evacuation scenarios, due to unique challenges resulting from specific attributes of the scenarios. This requires that existing PES models be made more configurable and adaptable, so that they can better simulate the evacuation processes and outcomes under various scenarios.

4.3. PES models: Modeling of human behavioral mechanism is the driving force for advancement

The evolution of PES models can be separate into four stages, which are featured with hydraulic models, ball bearing models, deterministic or stochastic rule-based models, and adaptive pedestrian models, respectively (Castle and Longley, 2008). Most early-stage models were limited to the modeling of physical movement of humans and rarely looked into the modeling of human behavior. As a result, these models were prone to produce unrealistic and inaccurate results (Kuligowski, 2008). Having realized this limitation, contemporary PES models usually aim to incorporate fine-grained and realistic modeling of human behavioral mechanism so as to reflect the autonomous and adaptive behavioral patterns of evacuees and produce accurate prediction of the evacuation process and outcomes.

Kuligowski (2008) proposed that the behavioral mechanism of evacuees includes four cognitive processes, namely perception, interpretation, decision-making and action. Among them, the perception and decision-making processes have drawn the most attention in prior PES studies. Regarding the perception process, individuals constantly receive physical and social cues from the environment and other individuals (SFPE, 2019). Over the years, the improved modeling of the perception process has remarkably benefited the PES models. Most of early-stage models oversimplified the perception process of physical cues and usually simulated the perception process by setting humans not to collide with obstacles and hazards. To limit the visual perception range for a more realistic simulation, the cone of vision was introduced into PES models (Chu, 2015), which could stipulate the direction and scope of vision. It is also vital to guarantee the impermeability and opacity of obstacles when modeling the perception process of humans (Cristiani and Peri, 2017). Meanwhile, the modeling of audio perception process was introduced to detect the audio cues, a sensory capability that individuals in earlier PES models did not possess. The refinement of visual perception and the introduction of audio perception have motivated and enabled the investigation of effects of various physical cues and social cues, which pushes PES models towards adaptive pedestrian models, and provides crucial clues for the development of behavioral intervention measures. For instance, the modeling of the perception of social cues, such as authority-given cues (Jafer and Lawler, 2016) and communication from others (Wang et al., 2015), promoted the modeling of interaction behaviors with other individuals, adding to the types of interaction behaviors that can be captured in PES models; the modeling of the perception of dynamic physical cues (Joo et al., 2013; Nguyen et al., 2013) made it possible to model the adaptive behaviors on conditions of local information and surrounding environment.

As for the modeling of the decision-making process, its influence on the improvements of PES models is also evident. In the early-stage hydraulic models, the evacuation of flow only followed the laws of physics and decisions were modeled to be made only on the basis of physical influences (Gwynne et al., 1999b). In ball bearing models, functions (e.g., magnetic equation or social force equation) were introduced to improve the modeling of human behavior. Yet, all individuals were considered identical and affected by the functions in the same way (Castle and Longley, 2008). These homogeneous models largely limited the modeling of the complexity of evacuee behaviors. To address this limitation, rule-based models were developed, which allowed for deterministic or stochastic decisions to be taken by individuals, according to predefined sets of rules. More recently, various decision-making theories in the social science domain (e.g., affordance theory) and computational frameworks in the computer science domain (e.g., genetic algorithms, BDI model) have begun to be applied to PES models, which enables agents to make decisions adaptively and sensitively. With the extension of the modeling framework of decision-making process, psychological and social factors could be well integrated into PES models. The incorporation of individual emotions further advances the modeling of individualized and heterogeneous decision-making process. Meanwhile, the modeling of social behaviors, such as following a leader (Colangeli et al., 2018; Hou et al., 2014; Richardson et al., 2019), waiting and searching for group members (Li et al., 2015), and helping others (von Sivers et al. 2016), enriches the behavioral space of individuals in the model, which further improves the fidelity of the evacuation simulation.

In addition, a few studies have pointed out that the shape of individuals is also an important factor that influences human behavioral mechanisms and patterns and therefore should be properly modeled. To this end, several representations of the human body shape, such as the three circles (Thompson, 1994), and more recently, the ellipse (Wąs et al., 2006; Wąs and Lubás, 2013), spheropolygon (Alonso-Marroquín et al., 2015, 2014) and spherocylinder (Chraibi et al., 2011; Hidalgo et al., 2017), have been introduced in prior studies to substitute the simple circle representation. The spheropolygon model reproduces the human body shape in two-dimensional space and enables the calculation of stress in crowds. The spherocylindrical model increases the degree of freedom and allows for more realistic descriptions of competitive behavior compared with the simple circle model. As for the three-circle model, recent studies have shown that its structure is advantageous for describing various emerging behaviors in high-density scenarios, such as actively squeezing to pass through a bottleneck by rotation (Song et al., 2019), movements on stairs (Qu et al., 2014) and overtaking behavior in dense crowds (Liu et al., 2018b).

In summary, the extent to which the human behavioral mechanism is considered and the levels of granularity and sophistication at which it is modeled is what differentiates prior PES models from different stages of evolution. The improvement of the modeling of human behavioral mechanism, for which there is still considerable room for further exploration, is likely to continue to drive future advancement of the PES models.

4.4. PES tools: Verification and validation are the major challenges

PES tools are widely applied in the performance-based safety design of indoor environments such as buildings and aircrafts, as well as the emergency management planning of crowd gathering places such as metro stations. The credibility is one of the most critical criteria for developing and evaluating a PES tool. The main principles necessary for establishing credibility of PES tools include the processes of verification and validation (ISO, 2015).

The process of checking that a tool does what it is planned to do is known as verification (Gilbert and Troitzsch, 2005). In the verification process, it is essential to "debug" the simulation carefully by using a set of test cases. However, there is a lack of universally recognized verification standards for PES tools in varying contexts, although the IMO (International Maritime Organization) made an initial effort by proposing the *guidelines for evacuation analysis for new and existing passenger ships* (MSC/Circ.1238) (IMO, 2016), which were later adopted and modified for buildings by NIST (National Institute of Standards and Technology) in the United States (Ronchi et al., 2013). Meanwhile, to make the verification process easier, it is also desirable to have a system that can automatically run the test suite and record the outputs (Gilbert and Troitzsch, 2005), and such a system is still yet to be developed.

According to ISO (International Organization for Standardization) 16730–1 (ISO, 2015), validation is defined as the process of determining the degree to which a calculation method is an accurate representation of the real world from the perspective of the intended uses of the calculation method. Ideally, a PES tool should be validated with evacuation data from historical emergency incidents. However, access to such real data that relates to a full range of possible behaviors and scenarios representing real-life evacuation processes has always been a major challenge, and there is a scarcity of successful validation efforts of such kind. Alternatively, researchers have attempted to use certain characteristics of pedestrian movements, which are usually extracted from empirical evidence collected in experiments, to validate PES tools. For instance, Kretz et al. (2008) used the empirically observed linear dependence between pedestrian flow and bottleneck width as a criterion to validate an SF-based PES tool. Similarly, the well-known fundamental diagram that describes the dependence relations between the velocity (or flow) and density of pedestrians (Seyfried et al., 2005, 2010) has been used for validating PES tools at the macroscopic level (Martinez-Gil et al., 2017; Schadschneider and Seyfried, 2009). In addition, a few developers of PES tools, such as STPES (Mott Macdonald, 2020), collected data from evacuation drills to substitute data from real emergency incidents and compared their data with parallel simulations. However, participants in drillings typically know that they are not exposed to real emergency situations and are therefore prone to yield biased data (Gwynne et al., 1999a). Moreover, even if real-life emergency evacuation data were somehow made available, it would still be difficult, if not impossible, to extract information about implicit or subjective factors (e.g., psychological and social factors) from the data. Such information, however, is critical input to PES tools for replicating the real-life emergency events and validating the tool. Therefore, finding a feasible and effective approach for validating PES tools remains a major challenge that deserves future efforts.

4.5. Directions for future research

The above review has outlined many of the issues the area of PES currently faces. There remain a number of fundamental challenges to which no clear solutions exist. These challenges need to be addressed in the near future in order for PES to evolve into a more mature scientific field and better serve relevant professions. The recommendations for future research are summarized as follows.

4.5.1. The adaptability of PES to various scenarios should be improved

The above review has revealed that the adaptability of PES to various scenarios is relatively limited. Most existing models oversimplified the interaction between the environments and humans, and hazards data except fire data can barely be imported into existing PES tools. Future research could look into the following efforts to improve the adaptability of PES models and tools: (1) create more links between hazards simulation tools and PES tools that would enable simultaneous and coordinated simulations. Existing PES tools such as Exodus and Pathfinder are able to integrate fire simulation; nevertheless, to the authors' best knowledge, linking simulators of other hazards, such as floods and earthquakes, with PES tools has yet to be achieved. More importantly, evacuees' behaviors can impact the hazards (e.g., firefighting behavior may impact spreading of fire and smoke), therefore, bi-directional data exchange and simultaneous simulation between PES tools and hazards simulators are necessary to capture such reciprocal effects; (2) build more configurable and adaptable PES models to better simulate the evacuation process and outcomes under various scenarios. Models targeting specific scenarios are likely to be more prevalent and applicable in the future; and (3) investigate how various hazards in the environments, such as fire, smoky and adversaries, affect human behaviors and how such effects can be modeled in PES. The consideration of such effects in the literature has thus far mostly concerned evacuees' emotions and physical health, while the possible effects on their perceptual capabilities, mobility, wayfinding goals and route choices deserve further investigation.

4.5.2. The modeling of behavioral mechanism of individuals should be advanced

As aforementioned, the advancement in the modeling of the behavioral mechanism of individuals has been the driving force for the evolution of PES models. Future improvements of PES are likely to continue to depend on how the modeling of human behavioral mechanism can be enhanced.

For the modeling of the human perception process, the improvements could be done in the following two aspects: (1) enrich the types of perceived information in the models by, for instance, extending the modeling of individuals' sensory capabilities from vision and hearing to other senses such as haptics and smelling; and (2) consider various psychological effects associated with individuals' stress status on their perception capabilities, for instance, the amount of information perceived by evacuees can be influenced by the arousal level of their emotions in an emergency (Nilsson et al., 2009).

The modeling of the human decision-making process also could be improved. Specifically, future research could look into the following issues: (1) consider human-building-emergency interactions (Zhu et al., 2020) and model their multi-way interactions, e.g., individuals may choose to fight adversaries instead of hiding or running way, which would influence the emergency situations; (2) consider various social effects associated with individuals' social statuses and roles, e.g., males are found to be more likely to help females during an emergency (Tong and Canter, 1985); (3) apply advanced artificial intelligence algorithms to improve agents' intelligence, so that they can learn from their memory and others' experiences and adapt their own behaviors.

The interpretation process, which has rarely been explored in the existing PES literature, also deserves attention. This process could be considered in the following aspects: (1) model the interpretation and reasoning mechanism for processing the perceived information, particularly when the information is vague, incomplete or inconsistent; and (2) model the interpretation process about perceived risks to self or others, for instance, an individual is likely to perform protective actions in order to begin the evacuation process when s/he interprets the current situation as a risk (Kuligowski, 2008).

It is noteworthy that the pursuit of the above directions calls for close interdisciplinary collaboration among researchers from a spectrum of domains, such as engineering, computer science, psychology and sociology.

4.5.3. Innovative methods are needed to verify and validate PES models and tools

Improving the credibility of PES models and tools would largely promote the application of PES in practice and maximize their values for safety planning and emergency management. Although a few organizations and researchers have made efforts to define suitable verification and validation tests and procedures over the years (IMO, 2016; ISO, 2015; Rogsch et al., 2014; Ronchi et al., 2013), verifying and validating the PES tools have largely remained a major challenge. There is an urgent need for innovative methods to address this challenge. For verification, one possible way to solve the problem is to incorporate the stochastic process in the PES models and generate human location and human traits under a certain probability. The incorporation of a stochastic process and use of repeated simulations could exclude accidental factors and improve the reliability of the results (Au, 2005). For instance, the IMO guidelines (IMO, 2016) specified that 500 simulation runs should be performed when a convergence dose not occur and their 95th percentile represents the predicted evacuation time value when doing evacuation analysis of ships. As for validation, access to data about human evacuation behaviors at real emergency scenes is the key to calibrating and validating PES tools. This calls for vital collective actions among researchers in this area to establish open datasets suitable for PES validation, an initial effort of which can be found in (Deere et al., 2020). In addition, Kretzschmar et al. (2014) proposed that the Turing test could be a potential method to validate PES tools, by asking human subjects to distinguish real human trajectories from the trajectories generated by simulations. Human subjects may rely on the observation of certain qualitative characteristics of collective effects, such as jamming, density waves, lane formation, oscillations and patterns at intersections (Schadschneider et al., 2009), to make their assessment. It should also be noted that future validation methods might be further inspired by innovations in other fast-growing areas of research, such as virtual reality (Dickinson et al., 2019; Lu et al., 2017b), automatic trajectory extraction (Boltes et al., 2010), pattern recognition, and so on. It is hoped that research advancements in these fields will allow the collection and interpretation of more realistic evacuation behavioral data that can be used for PES validation.

5. Conclusions

PES has been widely used to examine crowd evacuation behaviors during indoor emergency situations and facilitate safety design and emergency management in indoor environments. This paper proposes a three-layer analytical framework for synthesizing existing literature on PES approaches, models and tools, and presents a systematic review of the state of the art in this area. It was found that PES approaches with high simulation fidelity are getting more prevalent over time, and that the adaptability of existing PES models to different evacuation scenarios is relatively limited. The review also revealed that the modeling of human behavioral mechanisms, particularly the cognitive processes of perception and decision-making, has been the driving force for the advancement of PES models. As for the PES tools, the review indicated that their verification and validation remain a major challenge. Lastly, directions for future research are discussed accordingly, including improving the adaptability of PES to various scenarios, advancing the modeling of human behavioral mechanisms, and finding innovative methods for verifying and validating PES models and tools. The informed discussions are expected to inspire more studies that may lead to further breakthroughs in this area.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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