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Minireview

A review of cellular automata models for crowd evacuation

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HIGHLIGHTS

- Research paradigm of CA models is summarized.
- CA models are classified into lattice gas, floor field and other field-based models.
- Three main challenges of cellular automata models for evacuation are presented.
- Typical simulation scenarios and research issues are concluded.
- The advantages and disadvantages of CA models are discussed.

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ABSTRACT

With the increasing of risk potential in crowded places, evacuation management becomes practically important to ensure the safety of crowds. The studies of crowd evacuation in normal or emergency situations have become a hot topic. Due to the distinct advantages of high efficiency, strong scalability and simple implementation, cellular automata models (CA) have become one of the most widely-used models for evacuation. However, the practical requirements of evacuation propose some important challenges for CA models, for example, to accurately characterize both position and velocity of individuals, to depict environments and accidents, and to describe human behaviors. In the last 20 years, there are many studies aiming at resolving the above challenges. Starting from the challenges mentioned above, this paper tries to give a review of CA models, specially used for crowd evacuation. Firstly, we give an overview of CA models for evacuation, and put forward research paradigm, modeling framework and classification of CA models. The models used for evacuation are classified into three kinds of categories, i.e. lattice gas model, floor field model, and other field-based models. The last category includes potential field model, electrostatic-induced potential field model, cost potential field model, etc. Then, three main challenges of CA models for evacuation are presented, and the improvements for each type of challenge are summarized. Typical simulation scenarios and research issues are further proposed. Finally, the advantages and disadvantages of CA models are illustrated from the aspects of implementation, performance, scalability, accuracy and applicability.

Contents

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1. Introduction

With the increasing of group activities and the frequent occurrence of accidents, a significant risk potential often exists in crowded places. Therefore, how to evacuate from the dangerous places becomes practically important to ensure the safety of crowds. In the past several decades, crowd evacuation has been conducted by a lot of researchers. Among crowd evacuations, designing reasonable building facilities, grasping the least time to evacuate and taking correct guidance measures could be effective to minimize casualties and losses. However, in order to realize the above three aims, it is necessary to model crowd movement and behavior as possible as accurately. Within either continuous or discrete spaces, evacuation models usually take crowd or individual as a research object, and then to simulate the evacuation process under normal or emergency situations. On the one hand, evacuation models are the basis for studying the movement of crowd and the evolution of crowd's behavior. On the other hand, they provide a theoretical support for assessing the ability of evacuation, formulating emergency plans, and making emergency decision in safety management.

According to modeling scales, evacuation models can be classified into macroscopic, microscopic and mesoscopic models [1,2]. Macroscopic models regard the crowd as the research object. They analogize the crowd movement to fluid and approximate the individual movement to streamline. The fluid dynamics is used to describe the trend of crowd velocity and density with time in the form of partial differential equations. Mesoscopic models treat the crowd as a compressible gas formed by individuals. By appropriately modifying the theory of gas dynamics, a statistical model of crowd is established to depict the probability distribution of individual position and velocity. The individual in the microscopic models can be considered as the research object and the crowd can be regarded as a multi-particle system. The individual velocity and position are depicted by either ordinary differential equations or related rules. Although macroscopic models have a high computational efficiency, they cannot reflect the interaction and heterogeneity among individuals and are only suitable for simulating large-scale crowd. Microscopic models have a relatively lower computational efficiency, but the movement is described in a more accurate and natural manner. Mesoscopic models can capture non-equilibrium physical phenomena that are not available in microscopic models, but they are often difficult to find numerical solutions. From the way of avoiding collision on operational level [3], microscopic models can be divided into force-based models (e.g. social force model [4], centrifugal force model [5]), grid-based models (e.g. cellular automata model [6]) and velocity-based models (e.g. RVO model [7]). Among these models, cellular automata models (CA models) only require relatively less amount of calculation than other continuous space models, but still give sufficiently arcuate prediction if presuming an appropriate grid size as well as time-discrete size. Therefore, CA models attract lots of interests and have become one of the most widely-used models for evacuation.

In the past decades, some review articles summarized the existing evacuation models, and proposed classification and assessment methods. According to modeling scales, Bellomo et al. reviewed the models for vehicle traffic and crowd evacuation, and mainly focused on the identification of research perspectives [1]. From the view angle of dynamics, Dogbe classified evacuation models into three kinds of categories, i.e. microscopic models, macroscopic models and gas dynamic models [2]. Gwynne et al. reviewed 22 kinds of evacuation models relying one of the following three objectives, i.e. optimization, simulation and risk assessment. It also classified the models from the perspectives of simulation space, research objects and whether to consider behavior [8,9]. Kuligowski et al. reviewed 30 kinds of evacuation models [10]. Based on characteristic information the models can be classified to help users select the appropriate model for specific objective. For the case of building evacuation, Zheng et al. summarized seven kinds of models and compared the advantages and disadvantages of each model [11]. They concluded that it is important to combine multiple models and to consider more psychological factors. Duives et al. summarized crowd movement models and proposed a set of model evaluation methods according to the accuracy and applicability of models [12]. Radianti et al. classified crowd models into five kinds of categories, i.e. physics–mathematics crowd models, human behavior and decision making, software simulations for crowd evacuation, integrated virtual crowd simulations and crowd for human-centric sensing and decision support [13]. Vermuyten et al. reviewed the optimization models for pedestrian evacuation and classified them according to the type of problems to be studied, the level of model realism and the techniques of modeling [14]. Wijermans et al. proposed an integrated crowd management framework INCROWD and summarized 237 articles as a representative sample of crowd models from the framework view, the type of models, and the involved subsystems [15]. Ibrahim et al. summarized the intelligent evacuation management systems and classified evacuation models into four typical branches, namely fuzzy logic, neural network, probability map model and genetic algorithm [16].

The evacuation process in normal or emergency situations is strongly characterized by non-linearity, fluidity, openness, self-adaptation and self-organization, which can be regarded as a typical complex system. Scientists generally study the evolution of complex systems from the perspective of individual movement and evolution. It is known that CA models are a kind of dynamics system, in which the time, space and state are discrete, and the spatial interaction and time causality are local. It is easy to describe the interaction between cells, and does not need to set up or solve the complex differential equations. Hence, it is suitable for simulating the evolution process of crowd evacuation. However, CA models are based on discrete space–time and only set simple motion rules. The description of environment, and human position, velocity and behavior is inaccurate. Therefore, there are many studies focus on the improvement of classical CA models. Based on CA models, Goldengorin et al. proposed some improvements on evacuation software by considering the geometry of obstacles for pedestrian flow modeling and adding Hopfield network for traffic flow modeling [17]. Pelechano et al. took two commercial software, namely EXODUS and STEPS, as an example to explain the limitations of CA models, including grid size, fatigue factor, route selection, uneven use of stairwells and limitation in stairwells [18]. They identified the important defects of CA models used for high-rise buildings, such as the ability to explore partly known environment, the depict of body-to-body contact and the ability to communicate with others. Sirakoulis summarized the achievements of his research team on CA models, which touches electrostatic-induced potential fields, automated obstacle avoidance, follow-the-leader CA models, anticipative crowd management tools and CA-based robot crowd evacuation [19,20]. Wąs et al. depicted two dominant approaches of CA models, i.e. lattice gas models and floor field models [21]. They listed the optimization ways of floor field models, such as finer grid discretization, constructing proxemic floor field, modifying neighborhood types, optimizing calculation method of static floor field, adding individual behaviors, building complex scenes, etc.

The practical requirements of evacuation propose three kinds of challenges for CA models, namely, how to accurately characterize both position and velocity of individuals, how to depict environments and accidents, and how to describe human behaviors. According to the above reviews, Goldengorin [17] and Pelechano [18] analyzed several software based on CA models. They mainly considered the geometry of obstacles to depict the environment more accurately. Pelechano pointed out some limitations of CA models related to the description of human behavior [18]. Sirakoulis summarized research results of his team, including some improved models about human behavior. It involved obstacle avoidance behavior and follow-the-leader behavior [19,20]. Wąs did a review of CA models and summarized some improved approaches [21]. The improvements of discrete rules of space, including finer grid discretization and modifying neighborhood types have been described in their study. In addition, both human behavior and complex scenes have also been considered. However, the existing reviews mostly summarized defects and limitations of CA models or summed up the improved approaches for models. They have not provided a corresponding and holistic analysis of model's defects and existing improvement methods. It should be noted that the improvements of models should be mainly intended to solve the existing problems occurred in practical applications, and the models should simulate evacuation process as possible as accurately. Therefore, a clear analysis of models' defects and a deep understanding of the corresponding solutions are important for a comprehensive understanding of CA models for crowd evacuation. Starting from some main challenges faced by CA models, this paper summarizes most of the related articles. It explains the important improvements and contributions of existing researches in the face of the above-mentioned three kinds of challenges. Some interesting problems and potential solutions for CA models are also to be proposed. The major contributions are listed as follows:

- *The research paradigm on evacuation is summarized from the aspects of model design, research issues and simulation scenarios.*
- *Based on the coupling mechanism, CA models for evacuation are classified into lattice gas models, floor field models and other field-based models, such as potential field model, electrostatic-induced potential field models and cost potential field models.*
- *Three main challenges of CA models in the field of evacuation are presented, and the related improvements for each type of challenge are reviewed.*
- *Typical simulation scenarios and research issues of CA models for evacuation are concluded.*
- *From the aspects of implementation, performance, scalability, accuracy and applicability of the model, the advantages and disadvantages of CA models are discussed.*

This paper is organized as follows. Section 2 gives a brief overview of CA models for crowd evacuation and proposes the research paradigm, modeling framework and classification of CA model for evacuation. Section 3 presents three main challenges of CA models for evacuation and summarizes the related improvements for each type of challenge. Section 4 proposes typical simulation scenarios and research issues of CA models. At last, a brief conclusions and further problems are given in Section 5.

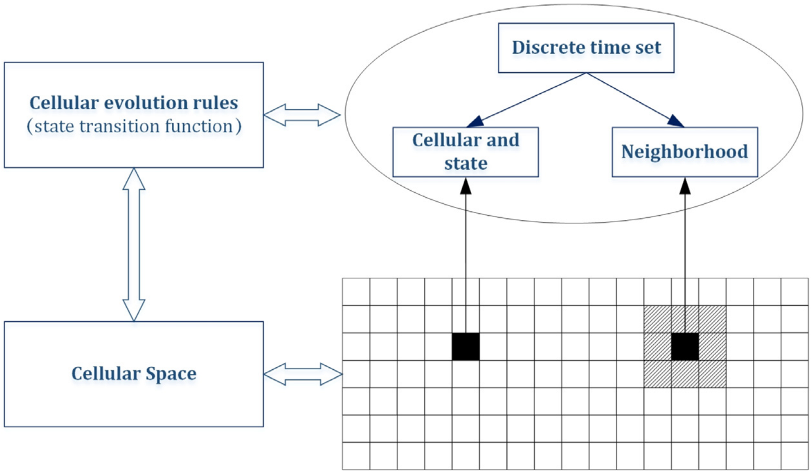


Fig. 1. Schematic diagram of cellular automata.

2. Overview of cellular automata models for evacuation

2.1. Cellular automata

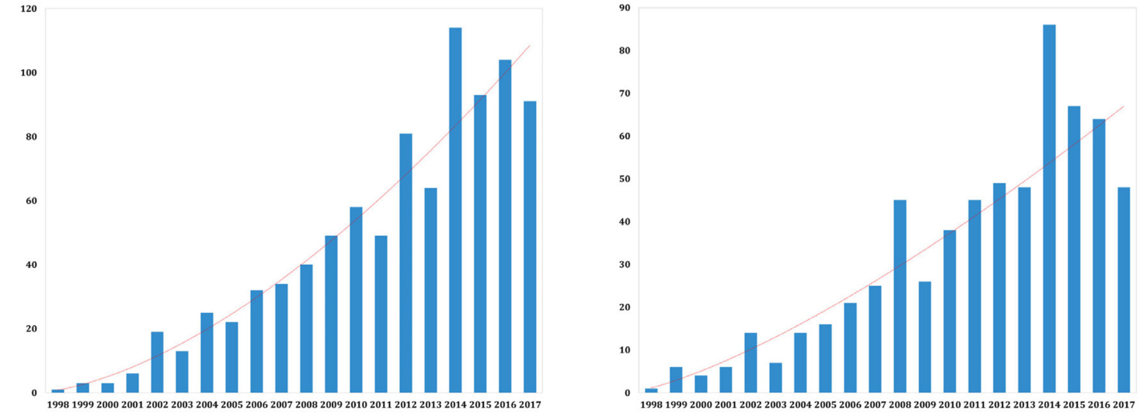
In the 1950s, Von Neumann proposed the concept of cellular automata. Unlike other kinds of dynamic models, cellular automata model (i.e. CA model) is not defined by a fixed physical formula or function but set by a series of rules. According to certain local rules, CA model is a dynamical system defined in a discrete space consisting of cells with limited states. It evolves on a discrete time dimension based on its own and adjacent cellular states. Therefore, it has the ability to simulate the spatial–temporal evolution of complex systems. CA model is a kind of grid dynamic model, in which the time, space and state are discrete, and the spatial interaction and time causality are local. Its main components include cells, cellular space, cellular state and cellular state evolution rules. Fig. 1 is the schematic diagram of CA [22]. CA can be regarded as a methodological framework for studying the movement and evolution of complex systems. It has been widely used in various fields of complex systems, such as physics, economics, biology, and computer science. Due to the local rules and fitness for simulating crowd movement and evolution process, it has also been applied to the field of evacuation.

2.2. Quantitative summary on cellular automata models for evacuation

It is known that *Web of Science* Core database (WOS) and *Engineering Village* database (EV) are two commonly-used databases. In this paper, we choose WOS and EV as databases to search the studies on CA models for evacuation. The combination of topics such as '*crowd*', '*pedestrian*', '*evacuat**', '*dynamic*', and '*flow*' was used to search related works of evacuation from 1998 to 2017 in both WOS and EV databases. By keyword screening and manual screening for words related with CA models, a total of 977 and 670 articles in WOS and EV database are strongly associated with CA models. A statistical analysis of the search results can give a general trend of the number of CA articles published annually, as shown in Fig. 2. The number of CA articles published in international journals and conferences is shown in Fig. 3. Due to the large number of journals and conferences, only several representative journals and conferences in recent years are listed in Fig. 3.

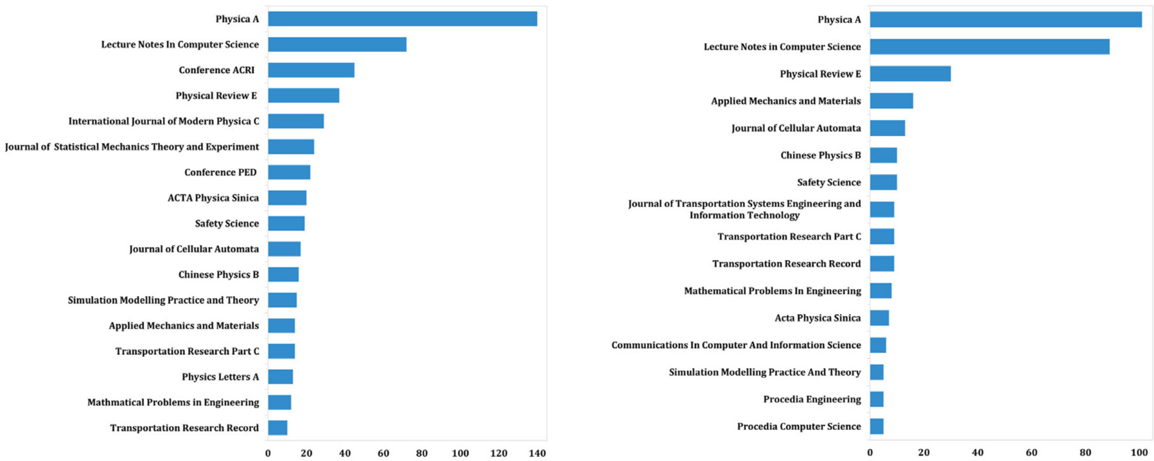
From Fig. 2, CA models began to gradually applied to pedestrian dynamic from 1998, and the number of relevant articles is increasing year by year. After the year of 2010, it has already been an important topic in the field of evacuation. A maximum number of articles had been published in 2014.

From Fig. 3, CA-based articles are generally published in the journals of physics, computer science, transportation science and applied mathematics. Representative physical journals include '*Physica A*', '*Physica Review E*', '*International Journal of Modern Physics C*', '*Acta Physica Sinica*, *Chinese Physics B*', etc. Representative journals or conferences of computational science include '*Lecture Notes in Computer Science*', '*Simulation Modelling Practice and Theory*', '*Communications in Computer and Information Science*', etc. Because crowd evacuation is a mainly research issue in the field of public safety, numerous articles have been published in public safety journals, like the journal '*Safety Science*'. Specialized journals and conferences related to cellular automata, such as '*Journal of Cellular Automata*' and '*ACRI*' (International conference on cellular automata for research and industry) have also published relevant articles. In addition, 'PED' (International conference on pedestrian and evacuation dynamics), which is a well-known conference for studying pedestrians and evacuation dynamics, have also published many evacuation articles based on CA model.



(a) *Web of Science* Core database **(b)** *Engineering Village* database

Fig. 2. The number of articles on CA models published annually in evacuation domain.



(a) *Web of Science* Core database **(b)** *Engineering Village* database

Fig. 3. Statistics of journals/conferences of cellular automata models in evacuation domain.

2.3. Research paradigm of cellular automata models for evacuation

For crowd evacuations, three main aspects should be generally considered, i.e. what are the research issues, how to establish appropriate models to solve these issues, and how to set up appropriate simulation scenarios. Therefore, Fig. 4 summarized the research paradigm of CA models for evacuation from the three aspects of model establishment, research issues and simulation scenarios. This will also serve as an overall framework for this article, which is the basis for the following sections.

Model establishment. In Section 2.1, some main components for CA models are introduced, such as cells, cellular space, cellular state and cellular state evolution rules. How to perform state transition according to the state of itself and neighbors in discrete time and space is the first problem to be solved. Therefore, time discrete rules, space discrete rules and state update rules need to be considered. In this paper, a general framework of CA models for evacuation is described in detail in Section 2.4. In addition, when state is updated, the main influence factors need to be analyzed, and a reasonable coupling mechanism should be set up for multiple factors. According to coupling mechanism, CA models are divided into three kinds of categories. Based on the framework of CA models, Section 2.5 will propose the classification of CA models for evacuation. Based on the particularity for the characterization of human movement and behavior in evacuation domain, three major challenges of CA models are to be presented. For each kind of challenges, we introduce the related works and the improvements in Section 3.

Simulation scenarios. In order to show the effectiveness of the proposed models, simulation scenarios are necessary to set up in a practical manner. Based on the scale of space environment and crowd, simulation scenarios are roughly

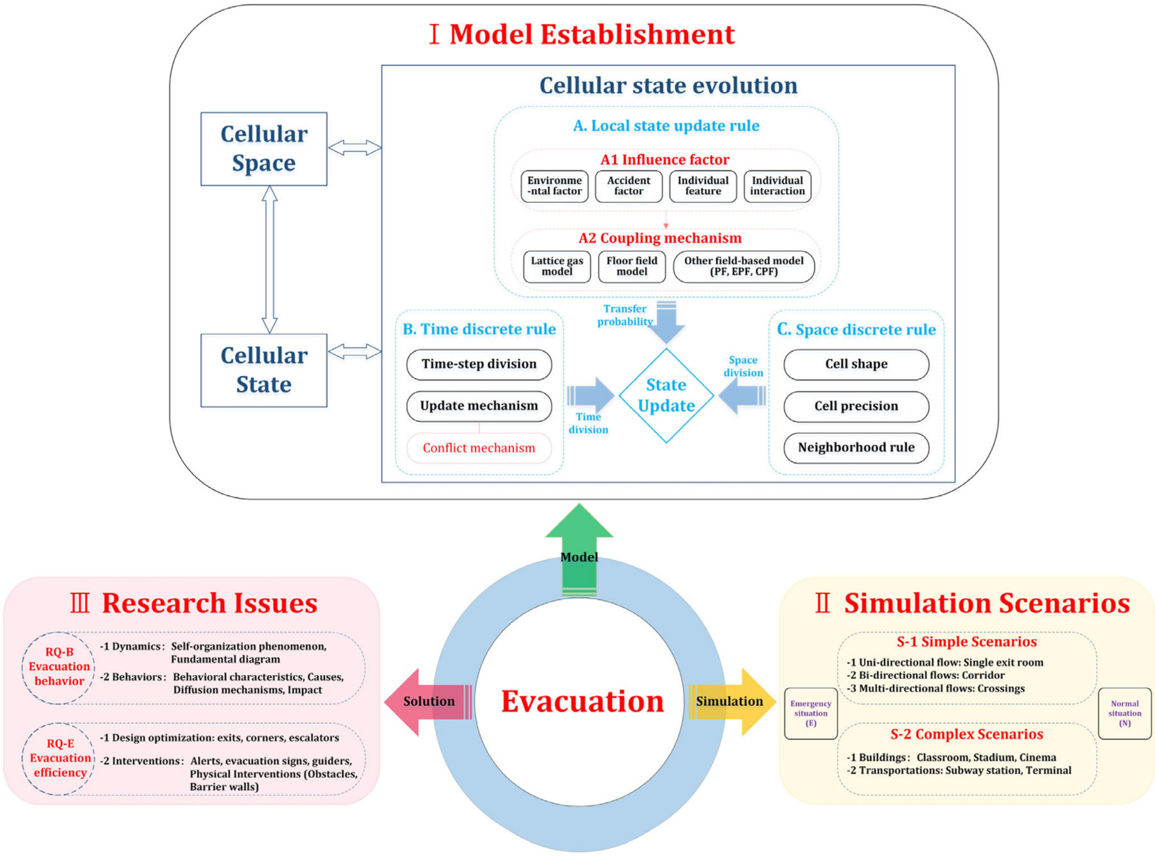


Fig. 4. Research paradigm of cellular automata models for evacuation.

classified into two kinds of types, i.e. simple scenarios and complex scenarios. Simple scenarios are scenes with small-scale space, simple spatial structure, small-scale crowd, simple behavior and simple pedestrian flow. They may be parts of real scenes or simple representations abstracted from real scenes. Simple scenarios can be composed by one or several basic motion, such as uni-directional flow, bi-directional flow, and multi-directional flow, which were proposed by Duives [12]. However, complex scenarios are generally dependent on real scenes with a large space, complex spatial structure, large-scale crowd, complex behaviors and variable pedestrian flows. They are used to study the dynamic and behavior features of people in real scenes, which can be a practical accepted tool for assessing the effects of evacuation policies and plans. The typical simulation scenarios of CA models for evacuation are to be discussed in Section 4.

Research issues. Starting from the established models and simulation scenarios, some interesting issues should be considered. The researches on evacuation mainly consider two kinds of issues, i.e. evacuation efficiency and evacuation behavior. The former aims to study the efficiency for crowd evacuation by optimizing the building designs and intervention measures. The goal of the latter is to accurately reproduce and predict human's behavior, and to adopt corresponding intervention strategies to avoid the occurrence of disasters during evacuation. In this paper, some typical research issues of CA models for evacuation are to be discussed in Section 4.

2.4. General framework of cellular automata models for evacuation

In the literature, crowd evacuation based on CA models is generally studied on a discrete space–time system. Therefore, it is necessary to discretize space and time firstly. The commonly-used CA models can divide the space into square cells, and each cell occupies an area of 40 cm $*$ 40 cm [6]. Each cell can either be empty or be occupied only by one pedestrian or obstacle. The update time are discrete, and individuals can generally move only one step for each time-step. Moreover, local state update rules also need to be considered when designing CA models. That is, it should consider how to determine the next movement direction of individual by the state of itself and neighboring cells. Here, a general framework of CA models for evacuation is shown in Fig. 5. The principle of designing models should concentrate on the setting of cellular state evolution rules, such as time discrete rule, space discrete rule, and local state update rule.

(1) Space discrete rule. Because CA models are defined on discrete space with cell being the basic unit, the main task of space discrete is to select a reasonable cell shape. The widely-used shape of cell is square [6]. Hexagon [23] and

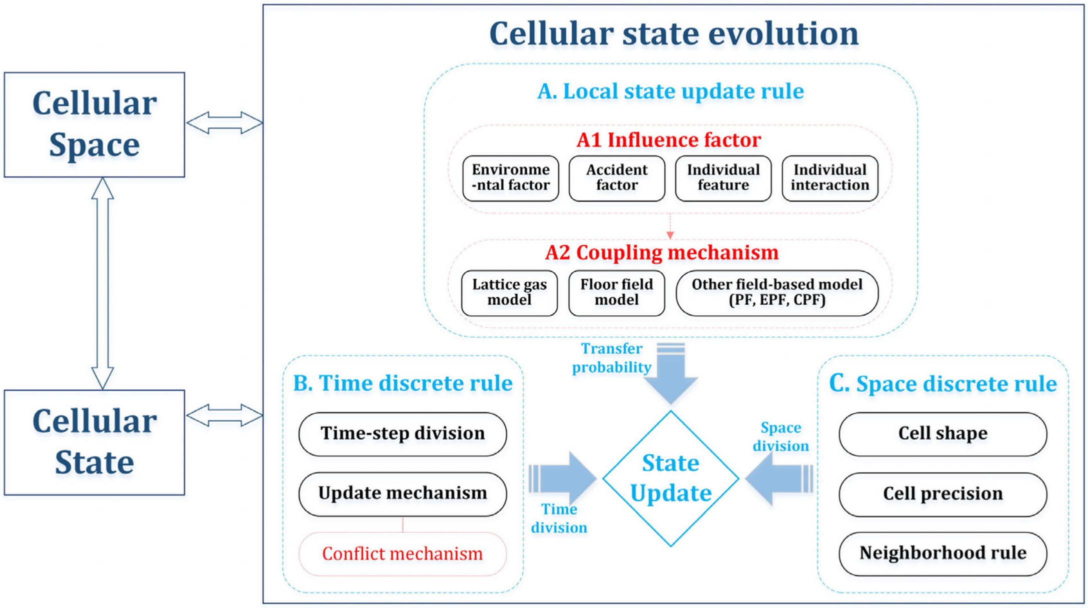


Fig. 5. The framework of cellular automata models for evacuation.

voronoi diagram [24] have also been adopted in some studies. The models with square grid were simple and intuitive, especially suitable for computer programming. However, they cannot accurately simulate the phenomenon of isotropy. That is, the diagonal direction is different from the horizontal direction. The models with hexagonal grid can overcome the isotropy problem. But it is hard to express directly in computer programming. Voronoi diagram can be used to calculate pedestrian density. The number of neighborhoods is not fixed, which is helpful to describe complex problems. However, due to the grid structure which is not fixed, the value of static floor field is hard to compute. For each kind of cell shapes, it is also necessary to design a suitable size of cells. A standard way is to make every cell only accommodate a single individual [6]. Either larger or smaller cell sizes are also considered in some studies [25,26]. In order to update the rule, each cell should consider its neighbors. Either von Neumann neighborhood [6] or Moore neighborhood [27] could be appropriate neighborhood rules.

(2) Time discrete rule. Because the CA models are based on discrete space, update intervals and time-steps should be first given. Divide the whole time into equal time intervals Δt. Then, the moment Δt, 2Δt, …, $n\Delta t$ are called the first, second, …, nth time-steps, respectively. Individuals can only update their location and status at each time-step. The appropriate update mechanism should be further considered, either synchronous updates [6] or asynchronous updates [28]. Synchronous update refers to the status of all individuals being updated simultaneously. Asynchronous updates are made by each individual in turn. If the synchronous update mechanism is adopted, it can bring conflicts during the update, i.e. multiple individuals choose the same cell at one time-step. So, it is necessary to introduce the mechanism to deal with the conflicts. In the literature, selecting winner in conflict randomly [29], introducing friction parameter [30] or friction function [31] to represent the probability that no one moves, or describing conflict based on game theory [32] could all be effective. In the following section, the various conflict mechanisms are to be described in detail.

(3) State update rule. To study the emergence of collective phenomena and movement patterns throughout the evacuation, the most important thing for CA is to set a series of local state update rules. In general, it consists of two kind of steps, i.e. selecting influence factors and setting coupling mechanism.

In the literature, influence factors can be classified into the following four categories. (i) Environmental factors, which mainly include scene factors and crowd factors on local behavioral decisions. Typical scene factors are spatial structure [33], exit width [34], barrier wall [35], elevators [36], etc. Typical crowd factors are crowd distribution [37], crowd density [38], etc. (ii) Accident factors, which describe the impact of accidental hazard sources on local behavioral decisions. Fire and smoke [29,39] are often considered in the literature. (iii) Individual characteristics, which describe the effects of individual movement characteristics, behavior characteristics and empirical factors on local behavioral decisions. The movement characteristics include acceleration [40], steering [31], front-watching [41], right-hand walking preferences [42]. Behavior characteristics include agitated [25], impatient [43], fear [44], aggressive [45], etc. Empirical factors include familiarity [46], etc. (iv) Individual interaction, which describe the influence of interactions between individuals and information communication, including forces [47], small groups [48], information process [49] and communication [50].

Table 1
The considered factors to design cellular automata models.

Factors			Introductions
A State update rules	A1 Influence factors	A1-1 Environmental factors	① Scene factors (spatial structure, exit width, barrier wall, elevators, etc.) ② Crowd factors (crowd distribution, density, etc.)
		A1-2 Accident factors	① Fire (Smoke, Visibility, etc.) ② Smoke (Visibility, etc.)
		A1-3 Individual characteristics	① Movement characteristics (acceleration, steering, sideways, right-facing preferences, etc.) ② Behavior characteristics (forward-looking, inertia, anxiety, radicalism, panic, etc.) ③ Empirical factors (familiarity, etc.)
		A1-4 Individual interaction	① Individual interaction (forces, small groups, etc.) ② Information communication (information exchange, etc.)
	A2 Coupling mechanism	A2-1 Lattice gas model	Introduce drift probability D.
		A2-2 Floor field model	Introduce potential fields, including static floor field and dynamic floor field.
		A2-3 Other field-based models	① PF (Potential field model) ② EPF (Electrostatic-induced potential field model) ③ CPF (Cost Potential field model)
B Time discrete rules		B-1 Time division B-2 Update mechanism B-3 Conflict mechanism	Normal (N), Sub-step (S). Synchronous update (S), Asynchronous update (A). Original (O), Random selection (S), Friction parameter (F), Friction function (FF), Game theory (GT).
C Space discrete rules		C-1 Cell shape C-2 Cell precision C-3 Neighborhood rule	Square (S), Hexagons (H), Voronoi diagram (V). Normal (N), Finer (F), Coarsely (C). von Neumann neighborhood (VN), Moore neighborhood (M).

Then, the coupling mechanism of influence factors should be considered. Two most classical used methods are lattice gas model [28] and floor field model [6,51]. In lattice gas models, each individual has a preference direction at each moment. The strength of drift in preference directions is set as D. When calculating the transition probabilities of all available directions, the probability of all directions is equally divided except for adding probability D in the preference direction. The other widely-used method is floor field model. It established the concept of floor fields to describe the willingness to walk from shortest distance and the herding behavior [6]. Based on the floor field model, the studies have extended some other factors by establishing fields, such as the anticipation to avoid collision [52], the communication among crowd [50], etc. The transition probabilities for each pedestrian are determined by the fields, which are coupled by the framework of multinomial logic models.

In addition, there are many other field-based methods that use the concept of potential fields, which is similar to floor flied model. However, the expression approach of influence factors and the coupling mechanism are different. Potential field model (PF [53]) used the concept of potential, which reflected the total effect of the route's distance, congestion, and capacity to compute the transition probability in each timestep. Electrostatic-induced potential field model (EPF [54,55]) was based on the virtual potential field generated by electric charges at selected positions to attract or repel the pedestrians. Negative charges were usually placed at exits and generated attractive forces upon pedestrians. Positive charges were usually placed at obstacles or walls and generated repelling forces. Then, it used Coulomb's Law to compute the attractive or repelling forces. Cost potential model (CPF [56]) considered the travel time and non-adaptive cost when moving to neighbor cells. It proposed the concept of cost potential to represent the travel cost from the present position to target position and expected to minimize the value of cost potential when making decisions. Table 1 lists the factors to be considered when designing CA models.

2.5. Classification of cellular automata models for evacuation

According to the coupling mechanism (A2) in Table 1, CA models for evacuation can be classified into lattice gas model, floor field model and other field-based models.

(1) Lattice gas model

In 1999, Muramatsu et al. proposed lattice gas model (LG), which is also known as a drift random walk model [28]. It utilizes the framework of CA and regards the individual as a particle. Each individual has a preference direction at each moment, and the individual movement process is simulated by the drift probability. If the drift strength of preference direction is set as D, the number of neighbor cells who are not occupied is set as n. Then, the transition probability of preference direction is $p = D + (1 - D)/n$ and the transition probabilities of other direction are $p = (1 - D)/n$.

Recently, many improvements of lattice gas models have been proposed. The modification of local state update rule (A), time discrete rules (B) and space discrete rules (C) were mainly considered. According to the framework of CA models in Fig. 5, the relative researches on lattice gas model are summarized as shown in Table 2. They are mainly compared and analyzed from the following four aspects, namely local state update rule (A), time discrete rule (B), space discrete rule

Table 2
Summary and comparison of researches on lattice gas model.

No	Ref.	A Local status update rules			B Time discrete rule			C Space discrete rule			V
		A1 Influence factor		A2	B-1	B-2	B-3	C-1	C-2	C-3	
		Cate.	Specific	Co.M.	T.S.	U.M.	C.M.	C.S.	C.P.	N.R.	
1	Muramatsu et al. [28]	Null	Null	LG	N	A	N/A	S	N	V.N.	C
2	Muramatsu et al. [57]	Null	Null	LG	N	A	N/A	S	N	V.N.	C
3	Muramatsu et al. [58]	Null	Null	LG	N	A	N/A	S	N	V.N.	C
4	Ma et al. [36]	A1-1	Ultra H.E.	LG	N	A	N/A	S	N	V.N.	C
5	Guo et al. [59]	A1-1	Density	LG	N	S	RP	S	N	M	C
6	Isobe et al. [60]	A1-2	Visibility	LG	N	A	N/A	S	N	M	C
7	Nagai et al. [61]	A1-2	Visibility	LG	N	A	N/A	S	N	V.N.	C
8	Cao et al. [62]	A1-2	Visibility	LG	N	S	EO	S	F	M	V
9	Isobe et al. [41]	A1-3	Front watch	LG	N	A	N/A	S	N	V.N.	C
10	Fukamachi et al. [63]	A1-3	Turn & sidle	LG	N	A	N/A	S	N	V.N.	C
11	Yue et al. [42,64]	A1-3	Right-hand	LG	N	S	R	S	N	M	C
12	Song et al. [65]	A1-4	Force	LG	N	S	F	S	F	M	C
13	Guo et al. [66]	A1-4	Force	LG	N	A	N/A	S	N	M	C
14	Maniccam [23]	Null	Null	LG	N	A	N/A	H	N	V.N.	C
15	Fang et al. [67]	Null	Null	LG	N	A	N/A	S	F	V.N.	C
16	Weng et al. [68]	Null	Null	LG	N	A	N/A	S	F	V.N.	V
17	Shi et al. [69]	Null	Null	LG	N	S	GT	S	N	V.N.	C

Notes: Cate. (Category): A1-1 Environmental factor; A1-2 Accident factor; A1-3 Individual feature; A1-4 Individual interaction.
Specific: Ultra H.E.—Ultra high-rise building evacuation.
Co.M. (Coupling mechanism): LG—Lattice gas model; FF—Floor field model.
T.S. (Time step): N—Normal.
U.M. (Update mechanism): A—Asynchronous Update; S—Synchronous Update.
C.S. (Cell shape) : S—Square; H—Hexagonal.
C.M. (Conflict mechanism): N/A—Not Applicable; F—Friction; R—Random; GT—Game theory; RP—Relative probability; EO—Experimental observation.
C.P. (Cell precision) : N—Normal precision; F—Finer precision.
N.R. (Neighbor Rule): V.N.-Von Neumann neighborhood; M—Moore neighborhood.
V (Velocity): C—Constant velocity; V—Variable velocity.

(C) and velocity. Each study listed in Table 2 will be described in detail in Section 3. Based on the challenges faced by CA models, this paper will introduce the improvements of lattice gas model.

Unfortunately, it learns from Table 2 that there exist scarce works on lattice gas model in recent years. On the one hand, the lattice gas model makes decision based on biased probabilistic, and is only suitable to scenes with simple geometric. On the other hand, the lattice gas model is far less scalable than the floor field model based on potential fields when extending the influence factors.

(2) Floor field model

In 2001, Burstedde et al. first proposed the floor field model (FF) based on a two-dimensional CA framework [6]. They simulated the pedestrian flow and successfully reproduced the classical self-organizing phenomenon. Kirchner et al. proposed the calculation methods about the static floor field and dynamic floor field [51]. The static floor field was used to describe the individual tendency to walk from the "shortest distance", and the dynamic floor field was used to describe the herd behavior of the individual under panic conditions. The transition probabilities for each pedestrian are determined by both the static and dynamic floor fields, which are coupled by the framework of multinomial logic models. The transition probability for each pedestrian is usually calculated as

$$p_{ij} = N\xi_{ij} \exp(k_D D_{ij} - k_S S_{ij})(1 - \phi n_{ij})$$

where p_{ij} is the probability that pedestrians move to cell (i, j), N is a normalization factor for ensuring $\sum_{i,j} p_{ij} = 1$, k_S is the sensitivity parameter for the SFF weighting S_{ij}, k_D is the sensitivity parameter for the DFF weighting D_{ij}, $\xi_{ij} \in \{0, 1\}$ is the obstacle parameter, $n_{ij} \in \{0, 1\}$ is the occupancy parameter, and $\phi \in \{0, 1\}$ is the parameter weighting n_{ij}.

Recently, the floor field model has become one widely-used class of CA models for evacuation. The existing researches generally introduced some influence factors (A1) by establishing potential fields. The anticipation field [52] described the anticipation to avoid collision. Force field [70] depicted the interaction force between pedestrian. Inertial field [71] expressed the tendency of pedestrians to continue the current route. Direction visual field [72] represent the congestion in the direction of visual field. Multi-information communication field [50] reflected the transition of information among pedestrians. In addition, some studies also modified the time discrete rules (B) and space discrete rules (C). According to the framework of CA models in Fig. 5, the relative researches on floor field model are summarized as shown in Table 3. They are mainly compared and analyzed from the following four aspects: local state update rule (A), time discrete rule (B), space discrete rule (C) and velocity. Each study listed in Table 3 will be described in detail in Section 3. Based on the challenges faced by CA models, this paper will introduce the improvements by related researches on floor field model.

From Table 3, most of the existing researches are based on the floor field model. The main optimization way is to introduce related influence factors, including environment factors (A1-1), accident factors (A1-2), individual characteristics

(A1-3) and individual interaction (A1-4). The calculation methods of static floor field (SFF) and dynamic floor field (DFF) are also modified for different application scenarios. In response to the conflicts (B-3) caused by synchronous update, scholars have proposed many methods to resolve, such as friction parameter, friction function and game theory. In addition, there were also some studies which divide the cellular space more finely (C-2) to improve the shortcoming, that the accuracy characterization of velocity and position in CA models.

(3) Other field-based models

Except for the classic lattice gas model and floor field model, there are many other kinds of models within the framework of CA. They used the concept of potential fields, mainly including potential field model (PF), electrostatic-induced potential field model (EPF) and cost potential field model (CPF).

Potential field (PF). Guo et al. proposed a pedestrian route choice algorithm by taking into account the factors such as route distance, pedestrian congestion and route capacity to simulate the closed areas with internal obstacles [53]. They calculated the potential of lattice $p_{i_0j_0}$ by considering the distance, congestion and capacity of route. Then, the transition probability can be computed as follow:

$$P_{(i,j)\to(i_0,j_0)} = Nexp(-\varepsilon(p_{i_0j_0} - \min_{(i_1,j_1)\in A_{ij}} \{p_{i_1j_1}\}))(1 - o_{i_0j_0})$$

where N is a normalization factor, ε is a sensitivity parameter for scaling the difference of potentials, A_{ij} is the set of lattices which are neighbors of lattice (i, j) and unoccupied by a pedestrian, wall or obstacle, and $o_{i_0j_0}$ is the parameter to judge whether the neighboring lattice site (i_0, j_0) is occupied by a pedestrian, obstacle or wall.

Electrostatic-induced potential field model (EPF). Georgoudas et al. proposed a CA model with the electrostatic-induced potential fields generated by charges at selected positions [54]. The EPF can provide the essential knowledge of the whole route. Based on the electrostatic-induced potential fields model, Georgoudas et al. proposed a framework of expected crowd management system to avoid blocking [55]. It used the Coulomb's Law to compute the attractive or repelling forces and used the form of the following formula:

$$\vec{F}(\vec{r}) = \frac{q}{4\pi\varepsilon_0}\sum_{i=1}^{N}\frac{Q_i(\vec{r}-\vec{r}_i)}{\left|\vec{r}-\vec{r}_i\right|^3} = \frac{q}{4\pi\varepsilon_0}\sum_{i=1}^{N}\frac{Q_i}{R_i^2}\widehat{R_l} = q\hat{E}(\vec{r})$$

where Q_i and $\vec{r}_i$ represent the magnitude and the position of the ith charge respectively, $\widehat{R_l}$ is the unit vector in the direction of $\vec{R}_i = \vec{r} - \vec{r}_i$, i.e. a vector pointing from charge Q_i to charge q, R_i is the magnitude of $\vec{R}_i$, i.e. the distance between charges Q_i and q, and $\vec{E}$ is the corresponding electric field.

Cost potential field model (CPF). *Zhang et al.* firstly proposed the concept of cost potential field by considering the travel time and non-adaptive cost when moving to neighbor cells [56]. Each individual is expected to minimize the value of cost potential field when making decisions. It defined the cost potential value as $\tau(x, y, t)$ at the tth timestep for cell (x, y),

$$\tau(x, y, t) = \frac{1}{v_e(\rho(x, y, t))} + g(\rho(x, y, t))$$

where $1/(v_e(\rho(x, y, t)))$ is related to the traveling time, and $g(\rho(x, y, t))$ represents the discomfort of pedestrians.

Jian et al. presented a perceptible potential field used in uncrowded cells to reflect the pedestrians' desire of minimizing their travel costs and an aggregated force field used in crowded cells to depict much stronger interaction between pedestrians for pedestrian navigation in low-visibility or complex geometries [98]. *Guo et al.* [99] and *Li et al.* [100] proposed an extended cost field CA model by considering the psychological characteristics of crowd during emergency and introducing behavior variant quantitative formulas to express behavior changes caused by stress.

3. Challenges of cellular automata models for evacuation

Note that CA models are based on the discrete time and space, and the setting of rules is relatively simple. However, the realistic evacuation processes are dependent on continuous time and space. During the process of evacuation, the environment is complex and variable, and the human's behavior is unpredictable. Therefore, these actual characteristics will raise some challenges for CA models.

3.1. Challenge 1: How to accurately characterize both position and velocity of individuals?

It is noted that the discrete space and the fixed velocity are necessary in most kinds of CA models (e.g. Lattice gas model [28], Floor field model [6]). The accurate characterization of the position and velocity of individuals during the practical evacuation processes is important to study the evolution of the global evacuation phenomenon. If there is a lattice to move for each pedestrian, acceleration to each pedestrian's free-flow velocity is achieved instantaneously in CA models. The coarse discretization of space limits the choice of direction, and influences space requirements and the handling of speed [101]. In the meanwhile, pedestrians are assumed to move within a static environment, where the paths towards the exits do not change over time [18]. These all do not match the characteristics of the crowd evacuation in

Table 3
Summary and comparison of relevant papers about floor field model.

No	Ref.	A Local status update rules					B Time discrete rule			C Space discrete rule			V
		A1 Influence factor				A2	B-1	B-2	B-3	C-1	C-2	C-3	
		Cate.	Specific	SFF	DFF	Co.M.	T.S.	U.M.	C.M.	C.S.	C.P.	N.R.	
1	Burstedde et al. [6]	Null	Null	–	–	FF	N	S	O	S	N	V.N.	C
2	Kirchner et al. [51]	Null	Null	E	HoB	FF	N	S	O	S	N	V.N.	C
3	Xu et al. [72]	A1-1	View & Density	E	HoB	FF	N	S	–	S	N	V.N.	C
4	Nishinari et al. [33]	A1-1	Obstacles	D	HoB	FF	N	S	F	S	N	V.N.	C
5	Varas et al. [27]	A1-1	Obstacles	V	HoB	FF	N	S	R	S	N	M	C
6	Huang et al. [73]	A1-1	Obstacles	H	HoB	FF	N	S	O	S	N	V.N.	C
7	Alizadeh [37]	A1-1	Crowd distr.	New	HoB	FF	N	S	R	S	N	M	C
8	Liu et al. [38]	A1-1	Crowd density	E	HoB	FF	N	S	O	S	N	V.N.	C
9	Zheng et al. [35]	A1-1	Barrier wall	*m*V	HoB	FF	N	S	FF	S	N	V.N.	C
10	Peng et al. [74]	A1-1	Multi-exits	V	–	FF	N	S	F	S	N	V.N.	C
11	Zhao et al. [75]	A1-1	Multi-exits	E	HoB	FF	N	S	O	S	N	V.N.	C
12	Wei et al. [34]	A1-1	Wide exit	New	HoB	FF	N	S	–	S	N	–	C
13	Tang et al. [76]	A1-1	Rail station	E	HoB	FF	N	S	–	S	N	M	C
14	Georgoudas et al. [77]	A1-1	Auto-obstacle av.	M	HoB	FF	N	S	–	S	N	M	C
15	Zhu et al. [78]	A1-1	Multi-obstacle	M	HoB	FF	N	S	–	S	N	V.N.	C
16	Zheng et al. [79]	A1-2	Fire	D	HoB	FF	N	S	F	S	N	V.N.	C
17	Georgoudas [80]	A1-2	Fire spreading	–	HoB	–	N	S	–	S	N	M	C
18	Yang et al. [29]	A1-2	Fire & View	–	Null	FF	N	S	R	S	N	V.N.	C
19	Zheng et al. [39]	A1-2	Fire & Smoke	New	New	FF	N	S	F	S	N	M	C
20	Kirchner et al. [40]	A1-3	Accelerate	E	HoB	FF	N	S	F	S	N	V.N.	V
21	Kirchner et al. [81]	A1-3	Max velocity	–	HoB	FF	N	S	New	S	F	V.N.	V
22	Yanagisawa et al. [31]	A1-3	Steering	D	HoB	FF	N	S	FF	S	N	V.N.	V
23	Fu et al. [82]	A1-3	Multi-velocity	E	HoB	FF	N	S	New	S	N	–	V
24	Fu et al. [83]	A1-3	Velocity match	H	HoB	FF	N	S	New	S	N	M	V
25	Tanimoto et al. [84]	A1-3	Conflict	V	HoB	FF	N	S	GT	S	N	V.N.	C
26	Zheng and Cheng [32]	A1-3	Conflict	M	HoB	FF	N	S	GT	S	N	V.N.	C
27	Guo et al. [85]	A1-3	Exit choice	–	–	FF	N	S	R	S	N	V.N.	C
28	Xie et al. [25]	A1-3	Agitated	H	HoB	FF	S	S	RP	S	C	V.N.	V
29	Was et al. [86]	A1-3	Social distance	–	–	FF	N	A	Null	S	F	M	C
30	Guo et al. [87]	A1-3	Modified DFF	E	HeB	FF	N	S	R	S	N	V.N.	C
31	Nicolas et al. [43]	A1-3	Impatient	E	–	FF	N	S	–	S	N	V.N.	C
32	Huang et al. [88]	A1-3	Neigh. behavior	E	HoB	FF	N	S	GT	S	N	M	C
33	Guan et al. [44]	A1-3	Fear index	–	–	FF	N	S	GT	S	N	M	C
34	Pereira et al. [89]	A1-3/4	Route change	E	HoB	FF	N	S	–	S	N	M	C
35	Kaji et al. [90]	A1-3	Personal space	New	Null	FF	N	S	–	S	F	–	V
36	Hrabak et al. [45]	A1-3	Aggressive	E	HoB	FF	N	A	–	S	N	M	V
37	Suma et al. [52]	A1-3	Anticipation	E	HoB	FF	N	S	O	R	N	V.N.	C
38	Liu et al. [71]	A1-3	Inertia	E	HoB	FF	N	S	O	S	N	V.N.	C
39	Song et al. [70]	A1-4	Force	M	–	FF	N	S	O	S	N	V.N.	C
40	Henein et al. [91]	A1-4	Swarm force	–	HoB	FF	N	S	–	S	N	V.N.	C
41	Guo et al. [47]	A1-4	Force	–	HoB	FF	N	S	–	S	F	V.N.	C
42	Leng et al. [92]	A1-4	Exclusion	New	Null	FF	S	A	–	H	N	–	V
43	Zhao et al. [93]	A1-4	Attractive	E	HoB	FF	N	S	R	S	N	V.N.	V
44	Lu et al. [48]	A1-4	Small group	E	HoB	FF	N	S	–	S	N	V.N.	C
45	Lu et al. [94]	A1-4	Small group	E	HoB	FF	N	S	R	S	N	V.N.	C
46	Vihas et al. [95]	A1-4	groups	E	HoB	FF	N	S	R	S	N	V.N.	C
47	Yang et al. [96]	A1-4	Kin behavior	–	–	FF	N	S	–	S	N	V.N.	C
48	Henein et al. [49]	A1-4	Info. process	E	HoB	FF	N	S	–	S	N	V.N.	C
49	Wang et al. [50]	A1-4	Communicate	E	HeB	FF	N	S	F	S	N	M	C
50	Hu et al. [97]	Null	3D-CA	M	–	FF	N	S	R	S	N	V.N.	C
51	Kirchner et al. [30]	Null	Null	E	HoB	FF	N	S	F	S	N	V.N.	C

Notes: Cate. (Category): A1-1 Environmental factor; A1-2 Accident factor; A1-3 Individual feature; A1-4 Individual interaction.
SFF: M—Manhattan metric; E—Euclidean metric; V—Varas method; H—Huang's method; D—Dijkstra algorithm.
DFF: HoB—Homogeneous bosons model; HeB—Heterogeneous bosons model.
Co.M. (Coupling mechanism): LG—Lattice gas model; FF—Floor field model.
T.S. (Time step): N—Normal; S—Time slice.
U.M. (Update mechanism): A—Asynchronous Update; S—Synchronous Update.
C.M. (Conflict mechanism): N/A—Not Applicable; F—Friction parameter; FF—Friction function; R—Random; GT—Game theory; RP—Relative probability; EO—Experimental observation.
C.S. (Cell shape): S—Square; H—Hexagonal.
C.P. (Cell precision): N—Normal precision; F—Finer precision.
N.R. (Neighbor Rule): V.N.—Von Neumann neighborhood; M—Moore neighborhood.
V(Velocity): C—Constant velocity; V—Variable velocity.

realistic environment. The original CA models are two-dimensional, while pedestrians sometimes may move in a three-dimensional space if the evacuation scenario in a multi-story building is considered. Since the degree of freedom for pedestrian's movement is high, the inaccuracy characterization of pedestrians' position and velocity may be obtained. Therefore, how to obtain the accurate characterization of both position and velocity remains one challenge for CA models for evacuation.

For this kind of challenge, the possible solution is to improve the accuracy of space discretization, and to modify the update mechanism and frequency, which make it infinitely approximate a continuous state. The differential expression of the velocity can be achieved by walking multiple cells per timestep or using the time subsets to update. It makes models depict more closely to real situations. In the literature, the recent progress on this challenge rely strongly on the modification of time discrete rules and space discrete rules.

(1) The modification of space discrete rules

The improvement of cell shape. The optimization of the shape of cell is one commonly used kind of space discrete rules, which makes the characterization of both position and velocity more accurate. Note that most of CA models adopt the shape of a square cell [6,28]. In this case, it is difficult to accurately depict the pedestrian's action of walking along the diagonal direction. In addition, the walking time and displacements of pedestrians between diagonal walking and straight walking are different, which results in different velocities of pedestrians. However, in realistic scenes, the velocity and displacement of pedestrians between diagonal walking and straight walking should be identical. To ensure the homogeneity of each direction, CA models on the basis of hexagon cells was proposed. Using hexagonal lattice, Maniccamextended the lattice gas model to study the critical density, which has a phase transition from freely moving state to jammed state [23]. It was found that the critical density of hexagonal model was greater than that of original square model. For the floor field model, Hartmannadopt the hexagonal lattice for adaptive path finding in microscopic simulations of pedestrian dynamics [102]. Based on a regular hexagonal cell, Leng et al. proposed an extended floor field model to simulate the pedestrian dynamic features in corridor, and revealed the relationship among density, velocity and flow via fundamental diagrams [92].

The improvement of cell precision. Song et al. [65], Guo et al. [66] and Fang et al. [67] divided the cell finely, and regarded multiple cells as a pedestrian to simulate the velocity and size of pedestrian in a more realistic manner, which can reproduce more self-organization phenomena. Combining a multi-grid evacuation model with finer grid, Cao et al. simulated the evacuation feature in a room without visibility [62]. Kaji et al. combined the high-precision multigrid method with floor field model and reproduced Hagen–Poiseuille flow features [90]. Therefore, the finer discretization of space could bring a more accurate representation of position and interaction in crowd.

Note that all pedestrians walk with the same velocity in classical CA models, i.e. move one cell per each time step. Recently, multi-velocities have been successfully realized by improving the precision of cells. Kirchner et al. found the irrationality for all pedestrians shares the same velocity [81]. He increased the discrete precision of space to represent differential maximum velocities of individuals. Weng et al. proposed a small-grid lattice gas model to simulate different desired walk velocities, and studied the relationship between evacuation time and some parameters, such as update interval, the number of moving grids per step, and individual walk velocity [68]. Yuan et al. proposed an indirect algorithm to model the behavior of a crowd consisting of people with different movement velocities [103]. Guo et al. developed a mobile lattice gas model by adopting mobile positions of eight lattices around each pedestrian, and made pedestrians differentiated by moving step size [66]. This kind of model gives a more accurate description of moving distance and evacuation time. Based on the floor field and social distance model, Was et al. presented a non-homogeneous and asynchronous CA model by improving the accuracy of grid, and used the shape of ellipse representing individual to depict the density of pedestrians in a more detailed way [86]. Guo et al. proposed a cellular automaton model with finer discretization of space and higher walking velocities to simulate the evacuation from a single exit room [26].

The improvement of three-dimensional space. Hu et al. found the two-dimensional CA simulation result differs a lot from the reality for the reason that the ladder in three-dimensional space has major impact over velocity [97]. He proposed a three-dimensional CA model with ladder factor, and defined the calculation formula for transition probability based on floor field, position vacancy degree and group attraction.

(2) The modification of time discrete rules

The time discrete rules such as time-step division mechanism, update mechanism and conflict mechanism have also been optimized to depict different velocities of pedestrians in crowd evacuation. By modifying the model update at different time-step intervals, Weng et al. proposed a cellular automaton model without step back, and simulated pedestrian movement with different walk velocities [104]. Bukáček et al. introduced the concept of adaptive time span into floor field model to realize the expression of heterogeneous desired velocity. In this kind of model, there was a specific time sequence unique for every agent, which determined the moments when agent is activated to actualize his position [105]. Fu et al. established a multi-velocities floor field CA model by introducing the velocity ratio. In this kind of model, the time step is decided by the max velocity, and in each timestep pedestrians with fast desired velocity should move with a higher possibility [82].

In comparison with the synchronous update in the original floor field model, the asynchronous update mechanism has been widely used in the literature [45,86,92]. Bandini et al. compared different types of asynchronous update schemes in CA models, and proposed an ontology on how to classify them [106]. The implications of different update schemes have been presented by introducing a simple CA based model and testing it by adopting different update schemes.

Moreover, it should be noted that the synchronous update could bring conflicts during the update, i.e. multiple individuals choose the same cell at a time step. The conflicts caused by asynchronous update could heavily affect the accurate characterization of individual velocity and position. Therefore, how to deal with the conflicts remains important. In the original model, individual can be selected randomly. Kirchner et al. introduced the friction parameter μ to represent an internal and local pressure among pedestrians, i.e. introducing the probability μ that no one moves [30]. Based on Kirchner's method, Yanagisawa et al. introduced the concept of friction function to solve the conflict problem [31]. In addition, random method [27,29] and relative probability method [25] were useful to resolve the conflicts. Game theory can be also introduced to determine the individual's behavioral decisions in conflict [32,44,69,84,88]. By defining two strategies of cooperation and competition, they established the game-theory-based models of conflict between individuals. When both choose to cooperate, two individuals will pass in order. When both choose to compete, the two will be locked in a stalemate and unable to move. When one chooses to compete and the other chooses to cooperate, the competitor will win in the conflict and the cooperator will stay in place.

3.2. Challenge 2: How to depict environments and accidents?

In actual evacuation scenarios, there are a variety of environments. The empty and unobstructed squares, or complex subway stations. Sometimes, pedestrians evacuate on the ground, and there are also cases that require evacuation by stairs and elevators. In recent years, various accidents have occurred frequently, which has led to the increase of emergency evacuation. The sarin gas attack of Tokyo in 1995 and the subway arson of Daegu in 2003 both caused serious damage. Because environments are variable and accidents often happens during the evacuation processes, the reasonable characterization of environmental and accident factors in the evacuation process is very important problem. It implies that the above two kinds of factors should be introduced into CA models for evacuation.

(1) Environmental factors

For the lattice gas models, scene factors or crowd factors can be introduced in CA models. Adding the description of elevator into lattice gas model, Ma et al. proposed a quantitative elevator aided ultrahigh rise building evacuation model to simulate both pedestrian movement and elevator transportation in the process of evacuation [36]. Based on the mobile lattice gas model (MLG), Guo et al. developed a heterogeneous lattice gas model, whose update rule depends on the local population density and the crowded degree of exit [59].

For floor field models, the static floor field represents the environment information of simulation scenarios. Individuals can obtain the location of exits and internal structure through static floor field, and select walking routes according to the distance to exits. The original floor field model, proposed by Kirchner, uses either Manhattan metric or Euclidean metric to calculate static floor field [51]. This kind of metric method is suitable for simple scenes with convex boundaries but without internal obstacles. For complex scenes with internal obstacles, the original distance calculation method has inherent limitations, and some improved algorithms have been proposed. Nishinari et al. used the Dijkstra algorithm to calculate the static floor field, and introduced the repulsive potential to the wall to depict behaviors on the corner or bottleneck more accurately [33]. However, the Dijkstra algorithm has high computational complexity, and consumes a lot of resources when simulating a large scene. Varas et al. proposed an approximation method of Dijkstra's algorithm, which sets the value of cell on exit position to 1 and searches for the Moore neighborhood range from the cell [27]. If the value of a certain cell is N, then the horizontal and vertical directions in the neighborhood are assigned as $N+1$, and the diagonal direction is assigned as $N+\lambda$. Based on the shortest feasible distance to the exit, Huang et al. [73] proposed an improved algorithm, which is similar to Varas' algorithm. The difference is that the shortest feasible distance to exit is calculated for all neighbor cells in each time step in Huang et al. [73], while the decision is made only according to the neighbor's current values in Varas et al. [27].

In addition to the influence of the distance to exits, both scene and crowd factors have an important impact on individual behavior decisions. Alizadeh proposed a dynamic CA model by introducing factors such as the location and width of exit, location of obstacles, ambient light and crowd distribution [37]. Liu et al. considered the influence of crowd density on the decision of exit choices, and corrected floor field model [38]. Zheng et al. used the modified Varas' method to calculate the static floor field in the scenario with a barrier wall, and optimized the model by considering the crowd density, exit distance and geometry of the barrier wall [35]. Peng et al. established a multi-layer static floor field to describe the attraction of multiple exits to individuals, and studied the congestion of a T-shaped intersection [74]. Zhao et al. proposed an improved CA model to simulate the evacuation behavior from a room with multiple exits by considering the capacity of exit [75]. Xu et al. proposed a direction visual field based on original floor field model, and simulated the pedestrian evacuation behavior from a room with multiple exits by considering the jamming degree of exit in the direction of vision [72]. Based on the concept of virtual reference point, Wei et al. established a new static floor field to simulate the evacuation process from a room with wide exit [34]. This method solved the low export utilization rate problem that the original floor field model has when simulating the wide exit. Tang et al. improved the floor field model to describe the behavior of pedestrians at high-speed rail station [76]. Based on the generation of a virtual field along obstacles, Georgoudas et al. proposed a CA model with auto-defined obstacle avoidance approach [77]. Each obstacle defines a field around it according to its shape and position, which affects a pedestrian that reaches it by guiding him to move along the axis of the obstacle, towards the direction of increasing field values. Considering the unique attribute in the multi-obstacle space, Zhu et al. established an extended floor field model to simulate the evacuation process from a classroom [78].

In the literature, environmental factors were mainly related to scene factors and crowd factors. For scene factors, the influence of obstacles, exit and special construction facilities on the evacuation process has been extensively explored. Scenarios with moderate spatial environment and crowd density have often been fully considered, while special scenes such as confined space and extra-large space have been rarely involved.

(2) Accident factors

In the literature, accident factors mainly include fire or toxic gas, and the models should be extended to describe the spread of either fire or smoke and to study the influence on the visual range. Yang et al. introduced some factors such as locational hazard level, fire hazard level and pedestrian visual range into the CA model, and mainly simulated the crowd evacuation process in a fire [29]. Isobe et al. proposed an extended lattice gas model (i.e. Many-particle system) by introducing the visibility factor [60]. They studied the evacuation process from a room full of smoke according to simulation and experiments. Nagai et al. extended the lattice gas model to simulate evacuation process from a multi-exit classroom without visibility [61]. They also explored the effect of different exit distribution on evacuation efficiency by simulation and experiment. Zheng et al. proposed an extended CA model which introduced the fire floor field to study the impact of fire spread on pedestrian evacuation [79]. Georgoudas et al. used a two-dimensional CA model to simulate the evacuation process of a crowd responding to fire spread and successfully simulated the fire spreading and crowds' movements while approaching the fire [80]. Cao et al. established a multi-grid evacuation model for the room without visibility based on the typical evacuation features (e.g. preference of choosing left-hand side direction and following behavior) [62]. Zheng et al. proposed an extended floor field model which divided the pedestrian movement into three phases: normal walking, walking and crawling [39]. The fire floor field and smoke floor field were respectively established to describe the influence of fire and smoke diffusion on the evacuation dynamics.

3.3. Challenge 3: How to describe human behavior?

In the process of evacuation, human behaviors are complex, which are another crucial factor to influence the formation of self-organization and the efficiency of evacuation. Therefore, how to understand and describe human behaviors is a big challenge during the process of evacuation. In the past decades, the improvement of CA models by considering human behaviors mainly dealt with whether to interact between individuals.

(1) Non-interactive individuals

Individual movement characteristics, behavior characteristics and empirical factors have already been introduced into CA models so that the pedestrians' movement can be described in a more realistic manner. The extension of individual movement characteristics mainly focused on behavioral habits, such as the differential expression of walk velocities and walk habits like turning or right-side walking. Kirchner et al. introduced the mechanism of acceleration into floor field model to distinguish competitive and cooperative behavior, and simulated the competitive behavior at the aircraft's emergency exit [40]. Kirchner et al. realized the differential representation of maximum walking velocities by increasing the lattice precision to describe individual movement more realistically [81]. They simulated the evacuation process in the corridors and room with single exit to explore the effect of spatial cohesion and maximum walking speed on model attributes. Isobe et al. considered the characteristics of movement and behavior such as, front watching effect and back step in the lattice gas model [41]. They studied the counter flow in the open boundaries. Based on turn and sidle on lattice gas model, Fukamachi et al. studied the behavior of walkers sidling through the crowd in the counter flow of pedestrian [63]. Yanagisawa et al. used the friction function to solve the conflict phenomenon arising from the update in floor field model [31]. In addition, for the velocity-declining phenomenon on corners caused by inertia, they introduced the steering cost to simulate the competitive behavior at the exit in a room with single exit. Yue et al. [42,64] added the right-hand parameters to the extended lattice gas model (i.e. dynamic parameters model) to describe the right-hand walking preference of pedestrians, and studied the direction split and pedestrians' walking habit effect of bi-direction pedestrian flow. Fu et al. established a multi-velocity floor field model to simulate the pedestrian's movements with a small change of speed and travel path due to fatigue or injury [82]. Based on the extended floor field model, Fu et al. studied the velocity matching effect and explored its effect on pedestrian's velocity–density–flow fundamental diagram [83].

Moreover, the introduction of behavior characteristics such as herding, conflict, panic, anxiety and choice preference gives the particles more human attributes, which is of great significance models. By improving calculation method of static floor field and introducing game theory, Tanimoto et al. established an improved CA model to solve the conflict behavior at the exit [84]. Based on floor field model, Guo et al. proposed a logic-based exit choice model to study the evacuee's exit choice behavior in rooms with internal obstacles and multiple exits [85]. Zheng and Cheng combined the conflicting game with CA model, and integrated rational factors, congregation effects and conflict costs into the study of dynamic conflict behavior in crowd evacuation [32]. By establishing the inertial floor field, Liu et al. extended the floor field model to take into account the compliance and perceptual inertia of the evacuees to the emergency evacuation signs [71]. Xie et al. proposed an alternative floor field model by incorporating the agitated behavior and elastic characteristics of pedestrians [25]. A parameter revising the transition probability of pedestrians is introduced to describe agitated behavior. To characterize elasticity of pedestrians, it is assumed that a cell can hold more than one pedestrian in crowd condition. Suma et al. proposed the anticipation floor field as an extension of floor field model to describe the behavior of avoiding conflict through pre-judgment when the pedestrian is conscious or unconscious [52]. Guo et al. proposed a floor field model based on heterogeneous bosons to solve the boson interference problem of dynamic floor field, and eliminated the interference of bosons released by individuals themselves to route choice [87]. Combining the snowdrift game theory with CA, Guan et al. considers two important factors of fear index and cost coefficient to simulate the interaction between pedestrians in crowd evacuation [44]. Based on microscopic statistics of the distribution of individual escape time series, Nicolas et al. developed a minimal cellular automaton model to afford the semi-quantitative reproduction of the experimental "microscopic" statistics [43]. Meanwhile, they introduced a process about social contagion of impatient behavior and studied the relevance to statistical micro-behavior. Huang et al. proposed a behavior-based CA model involving environmental characteristics and neighbors' behaviors, and studied the relationship between evacuation time and influenced factors, such as degree of emergency and cooperation enthusiasm [88]. With two extensions including route change probabilities and group fields, Pereira et al. proposed an extended CA model, which can be applied to emergency evacuation [89]. Integrating the multi-grid method and static floor field, Kaji et al. developed the improved cellular automaton model to study the personal space of pedestrian and reproduce the Hagen–Poiseuille flow feature [90]. Hrabak et al. studied the influence of pedestrians' heterogeneity such as velocity, aggressiveness and sensitivity to occupation on the microscopic characteristics of pedestrian flow [45].

Although the existing researches have already considered individual movement characteristics, behavior characteristics and empirical factors, most works must satisfy the assumption of homogeneity of crowd. However, the actual crowd is heterogeneous, and structural characteristics of crowd in different scenes are also different. The effect of heterogeneity needs to be carefully considered when building models. At the same time, CA models only describe adaptive movements of pedestrians, but there are few studies focusing on individual non-adaptive movements.

(2) Interactive individuals

The interactions between individuals include physical interaction like interaction force, and information interaction like exchanging information. In the literature, factors such as force, small group, kin relationship and information transmission have been widely studied.

The physical interaction in crowd was described mainly by introducing the concept of force. By extending the concept of force, Song et al. constructed a new discrete model based on lattice gas model, which is called multi-grid model [65]. Song et al. introduced forces to CA model and demonstrated that the interaction forces between pedestrians (e.g. repulsive force, friction force and attractive force) are the basic causes of complex behavior in the evacuation process [70]. By introducing the crowd forces into floor field model, Henein et al. proposed a swarm force model and demonstrated the necessity of force in crowd models by differences qualitative and quantitative results, in comparison to Kirchner's model [91]. Combining lattice gas model and social force model, Guo et al. proposed a mobile lattice gas model, in which the interactions between either pedestrians, or pedestrians and walls, are determined by the distance and step length of pedestrian [66]. Considering the asymmetric, accumulative and transferable interaction among pedestrians in high-density crowd, Guo et al. proposed an improved floor field model by discretizing the space into smaller cells [47]. In this work, the interaction between pedestrians is described by their own inertia. Zhao et al. proposed an improved two-dimensional CA model with attractive force and discussed the effects of two kinds psychology of spatial follow and direction follow on the evacuation efficiency [93]. Fang et al. improved the precision of cell by setting the occupied space of each cell to 0.1 m $*$ 0.1 m, so that each pedestrian occupied 5 $*$ 5 cells [67]. They described the nearest exit choice behavior by adding the biased direction and biased force. Based on coarse-grained cells, Xie et al. proposed an optimized floor field model and made each cell accommodate multiple pedestrians to describe the elasticity between pedestrians [25]. Based on hexagonal cells, Leng et al. proposed an extended floor field model and used pedestrian exclusion to replace the dynamic floor field to simulate the pedestrian dynamics in the corridor scene [92].

The information interaction was also widely considered, such as small group, kin relationship and information transmission. Considering small groups, Lu et al. proposed an extended floor field model suitable for group walking behavior by introducing the leader–follower walking pattern [48,94]. The characteristics of group walking behavior were successfully captured and the walking process was predicted. Vihas et al. developed a CA-based model by incorporating follow-the-leader technique as its driving mechanism and introduced the flocking formations of individuals during mass collective motion [95]. Yang et al. proposed a two-dimensional CA model with the extension of kin behavior to simulate the process of evacuation and reproduced many intriguing phenomena such as incoherence, jamming, gathering, backtracking and waiting [96]. Pereira et al. introduced the small group effect into CA model for emergency evacuation [89]. Henein et al. extended behavior factors such as information processing and communication into CA model and studied the influence of human behavior on physical movement [49]. Wang et al. proposed a multi-information communication field as an extension of the CA model and described the processes for which an evacuation assistant disseminates the information of each exit route using the strategy and evacuees receive, cognize and react to the multi-information [50]. Boukas et al. proposed a novel approach using a mobile robot to attract the attention of evacuees heading towards saturated exits and guide them to less blocked ones [107]. It relies on the CA crowd evacuation model and provides estimation for the evolution of the evacuation process, along with content rich information. In addition, it is subsequently utilized to plan a robot trajectory that is required for the redirection of evacuees to an alternative less crowded exit.

4. Simulation scenarios of cellular automata models for evacuation

Based on space environment element and crowd element, simulation scenarios of CA models will be classified into simple scenarios and complex scenarios. In general, simple scenarios are scenes with small-scale space, simple spatial

Table 4
Comparison between simple scenarios and complex scenarios.

Scenarios	Space environment		Crowd			Situation
	Scale	Structure	Scale	Behavior	Flow	
Simple scenarios	Small	Simple	Small	Simple	Simple	Normal/Emergency
Complex scenarios	Large	Complex	Large	Complex	Complex	Normal/Emergency

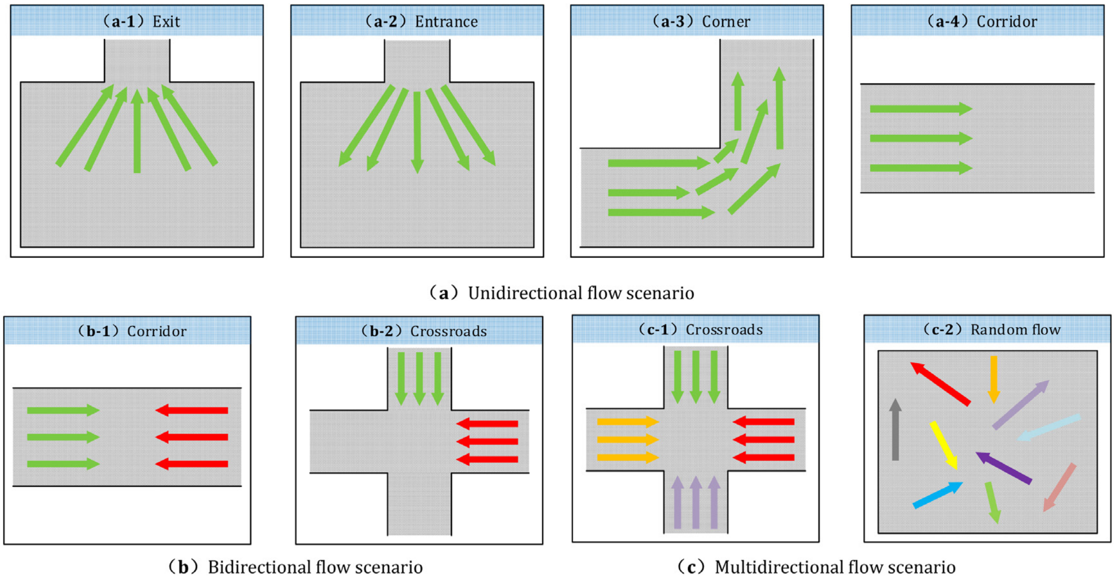


Fig. 6. Base cases of pedestrian flow in simple scenarios.

structure, small-scale crowd, simple behavior and simple pedestrian flow. They may be parts of real scenes or simple representations abstracted from real scenes, e.g. room with a single exit [51,65,84,91], corridors [41,63,81], crossing [58], etc. They are just used to study typical mechanisms and phenomena, which have a large gap with real scenes. However, complex scenarios are generally dependent on real scenes with a large space, complex spatial structure, large-scale crowd, complex behaviors and variable pedestrian flows, e.g. school [48,78,108], train stations [109,110], shopping malls [96] and stadiums [86]. Elements of simulation scenarios can be abstracted as space environment element, crowd element and situation element. Here is a comparison of simple and complex scenarios, as shown in Table 4.

For simulation scenarios, both evacuation behavior and evacuation efficiency can be studied in CA models. The evacuation behavior refers to the behavior or phenomenon inherent in the evacuation process under either normal or emergency conditions. It is to analyze the characteristic behavior of crowd in the process of evacuation by focusing on the causes or impact of behaviors on evacuation, such as exit choice behavior [40,67,75], kinship behavior [96] and follow-up behavior [93]. The evacuation efficiency often refers to the building design and intervention measures, which can be used to propose a design proposal that is most conducive to evacuation. The evacuation efficiency can be improved by optimizing the building design such as the width, number and position of exits [27,37,73,111]. In addition, interventions measures such as obstacles [84], barrier walls [35], evacuation signs [71,112], and guiders [50,55] were also useful to improve the evacuation efficiency.

(1) Simple scenarios. Duives et al. proposed eight distinct motion base cases and further classified them into unidirectional flow, bidirectional flow and multidirectional flow [12], seen in Fig. 6. Simple scenarios can be composed of one or several basic motion in eight motion base cases, and the movement direction of pedestrian flow is relatively simple. The most typical simple scenarios can be directly obtained from eight cases include: room with single exit, long corridor, corner, crossroad, etc.

(1-1) Room with single exit.

The room with single exit is one of the most typical scenarios in evacuation research [33]. When many pedestrians try to leave from the room at the same time, the exit will be a bottleneck because of the limited width of exit. From empirical data, it can be found that typical self-organization phenomena such as clogging effect and arching effect will appear before the exit [6]. Therefore, it must be guaranteed that the designed CA models can reproduce these self-organization phenomena.

The exit of room can be regarded as a classical bottleneck, and high-density areas are prone to occur in the vicinity. Therefore, in addition to considering the attraction of exit to pedestrians, it is also necessary to consider the interaction between pedestrians or pedestrians and obstacles. By introducing friction parameters to express the local forces among pedestrians, Kirchner et al. finally successfully reproduced the clogging and arching behavior before the exit of room [30]. Nishinari et al. introduced a repulsive potential for the wall to describe the behavior of pedestrians away from obstacles, and more realistically portrays the clogging and arching near the exit [33]. Based on a finer lattice, song et al. introduced the concept of force, and each pedestrian occupies multi-grids instead of one. The influence of active and passive factors was extended to portray the process of evacuation, and the formation of arching phenomenon during evacuation was observed [65]. Combined with lattice gas and social force model, Guo et al. proposed a method to determine the interaction between pedestrians or pedestrians and walls through distance and pedestrian movement steps [66]. Based on particle field, Henein et al. introduced the concept of swarm force into floor field model, which was able to describe force breaks within the crowd. Finally, it successfully reproduced faster-is-slower effect in a room with single exit [91].

The behavior of pedestrians in the room with single exit is relatively simple, so most of the research issues were related to the following behavior or evacuation efficiency. Zhao et al. studied the effects of two kinds of psychology (i.e., directional GWC and spatial GWC) on the process of evacuation in different room sizes and structures [93]. Cao et al. investigated the preference of choosing left-hand side direction and following behavior in the process of blind evacuation [62]. Tanimoto et al. studied the effects of obstacles before exit on evacuation efficiency [84]. Zheng et al. studied the effect of setting barrier wall on evacuation efficiency [35]. Yamamoto et al. [111] and Xie et al. [25] discussed the effect of exit width on evacuation efficiency.

(1-2) Long corridor.

The long corridor is another research hotspot for evacuation. A typical example of real life is the transfer channel of subway station. The pedestrian flow in corridor can be regarded as parallel flow. According to the direction of flow, it can be classified into two types, i.e., unidirectional flow and bidirectional flow (counter flow).

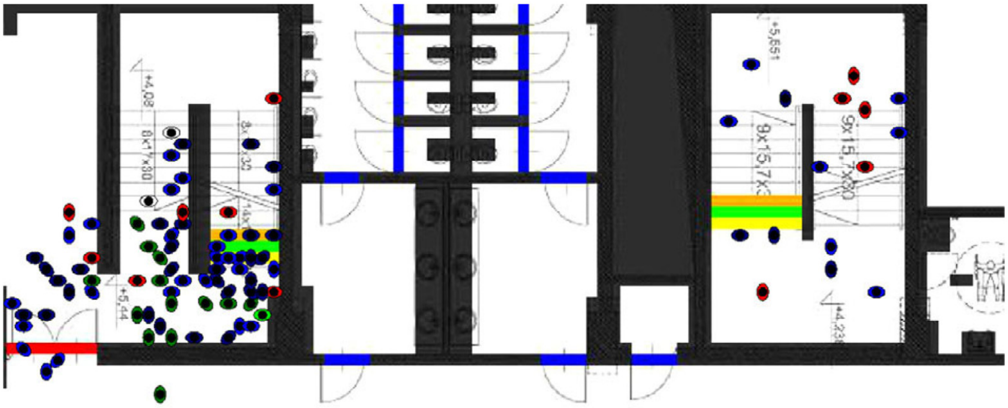
All pedestrians in unidirectional flow keep moving in the same direction, which walk from one side of corridor to the other. The relevant researches of unidirectional flow focused on describing the heterogeneous velocities of pedestrians, and strived to reproduce typical behaviors, such as overtaking behavior. Based on a multi-velocity floor field CA model, Fu et al. classified the motion state into normal state and tactical overtaking state, and study the decision process of overtaking [113]. The effects of tactical overtaking ratio, free velocity dispersion, and visual range on fundamental diagram, conflict density, and successful overtaking ratio were discussed.

In the corridor scene with bidirectional flow, two groups of pedestrians moving in opposite directions. Due to the opposite direction of motion, it is prone to conflict and congestion. As the focus research for corridor scenes, the most typical self-organizing phenomenon of bidirectional flow is lane formation. Therefore, relevant researches generally focused on the critical density of jamming transition, and tried to reproduce the typical self-organization phenomenon, such as lane formation. Muramatsu et al. proposed a lattice gas model with biased walking to mimic the counter flow in corridor, and found the jamming transition occurred at a critical density [28]. They explored the dependence of transition points on the strength of drift. Through experimental observation, Isobe et al. introduced front watching effect and back step mechanism to lattice gas model, and accurately describing the dynamic features of the counter flow and the formation of jamming transition [41]. Fukamachi et al. investigated the influence of the sidle effect on counter flow, and extended LG model by considering turn and sidle [63]. The model can be classified into three types: face-to-face, sidle, turn-and-sidle. The results show that the critical density of turn-and-sidle is higher than face-to-face, so that this model is conducive to avoiding congestion. Yang et al. studied the influence of pedestrians' right-moving preference on the critical density of jamming transition. The study found that right-moving preference will be more effective when the density is below critical value [114]. Burstedde et al. proposed the floor field model, which will lead to an effective attraction of identical directional pedestrians while different pedestrian species separate. The model successfully reproduced the formation of lane [6]. By adding leader–follower walking model, Lu et al. introduced kinship behavior, and found that the small groups hinder the lane formation and make the pedestrian flow unstable [94]. Li et al. introduced the quantitative formula into floor field model to describe the abnormal behavior caused by tension of pedestrians, and studied the influence of tension on lane formation [100].

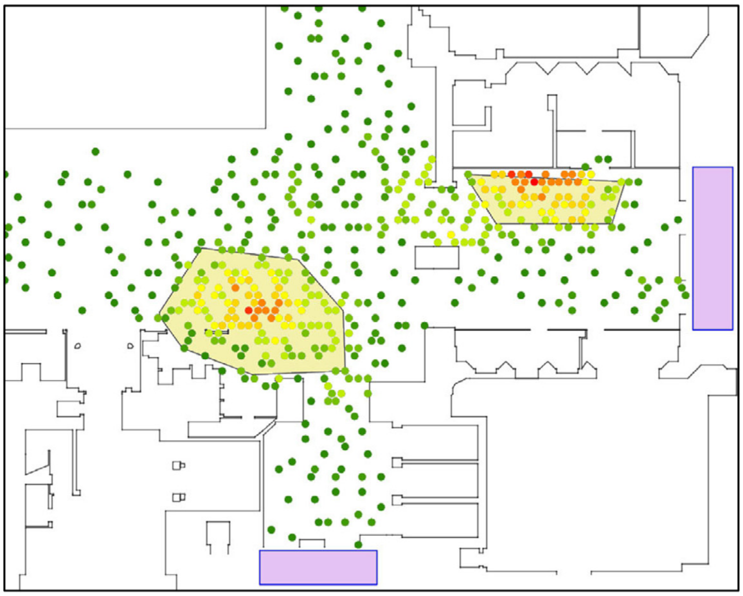
(1-3) Other simple scenarios

The other simple scenarios were also widely studied, such as crossroad, corner, T-shaped intersection, room with multi-exits, etc. Muramatsu et al. simulated the pedestrian flow at a crossroad with periodic boundary condition [57] and open boundary condition [58], and explored the relationship between critical density and the strength of drift. Jian et al. proposed a perceived cost potential field CA model with aggregated force field, which has obvious advantages in evacuation scenarios with large density [98]. They simulated the evacuation process at corner, and successfully reproduced the fundamental diagram and phase transition process of pedestrian flow. Peng et al. used the multi-floor field CA model to study the congestion of T-shaped intersection, and investigated the phase transition point in the process of evacuation [74]. Chen et al. established a force-driven CA model to study the evacuation process of pedestrians at the T-shaped intersection [108]. When the width of corridor exceeds the critical value, evacuation time is rapidly reduced due to the weakening of blocking behavior.

Room with multi-exits is also a research hotspot. In this scenario, the key point needed to consider is the issue of exit selection. Xu et al. proposed an improved floor field model by considering the degree of obstruction at exit in the directional visual field, and simulated the behavior of pedestrian evacuation in room with multi-exit [72]. On the basis of most feasible distance to exit, Huang et al. proposed an improved calculation method for static floor field, and adopted logic-based discrete selection model for exit selection in multi-exit rooms with internal obstacles [73].



(**a**) Wisla Krakow stadium. (Was [111])



(**b**) Railway station (Davidich [109])

Fig. 7. Two complex scenarios.

(2) Complex scenarios.

Complex scenarios are generally dependent on real scenes. They are used to study the dynamic and behavior features of people in real scenes, which can be a practical accepted tool for assessing the effects of evacuation policies and plans. Davidich et al. proposed a model for waiting pedestrians based on CA, and simulated several real-life scenarios for a major German railway station [109]. They used the proposed model to evaluate the impact of waiting pedestrians and predict the problematic areas in public spaces. Was et al. proposed a new method for creating realistic and effective models of crowd dynamics, which considered the agent-based approach combined with non-homogeneous and asynchronous CA model [115]. The proposed method made it possible to model pedestrians' dynamics in complex environments, like stadiums or shopping centers, and enables mimicking of the pedestrians' complex decision-making process on different levels: strategic and tactical/operational. Two typical complex scenarios are shown in Fig. 7.

In the following, simulation scenarios and research issues on CA models can be summarized in Table 5.

5. Conclusions and future problems

This paper gave a brief overview of CA models and proposed the research paradigm, modeling framework and classification of CA models for evacuation. Based on modeling framework, CA models were classified into lattice gas models,

Table 5
Conclusion of simulation scenarios and research issues.

No	Paper info.		Simulation scenarios			Research issues		
	Ref.	Meth.	Cate.	Scenario	Situ.	Cate.	Issue	Phenomenon
1	Kirchner et al. [51]	FF	S-U	R	N	RQ-B1	SO	C, A
2	Yang et al. [29]	FF	S-U	R	E	RQ-E	Influence of fire	–
3	Kirchner et al. [40]	FF	S-U	AE	E	RQ-B2	Exit competition	–
4	Kirchner et al. [30]	FF	S-U	R	N	RQ-B1	SO	C, A
5	Nishinari et al. [33]	FF	S-U	R	N	RQ-B1	SO	C, A
6	Isobe et al. [60]	LG	S-U	R	E	RQ-E1	Escape time distribution	–
7	Song et al. [65]	LG	S-U	R	N	RQ-B1	SO	C, A
8	Song et al. [70]	FF	S-U	R	N	RQ-B1	SO	C, A, FS
9	Weng et al. [68]	LG	S-U	R	N	RQ-B1	SO	C, A, FS
10	Henein et al. [91]	FF	S-U	R	N	RQ-B1	SO	FS, FH
11	Yamamoto et al. [111]	LG	S-U	R	N	RQ-E1	Exit width	–
12	Guo et al. [66]	LG	S-U	R	N	RQ-B1	SO	C, A
13	Guo et al. [47]	FF	S-U	R	E	RQ-E1	Parameter influence	–
14	Zhao et al. [93]	FF	S-U	R	E	RQ-B2	Following behavior	–
15	Yanagisawa et al. [31]	FF	S-U	R	E	RQ-B1	F	–
16	Yue et al. [42]	LG	S-U	R	N	RQ-E	Exit distribution	–
17	Zheng et al. [35]	FF	S-U	R	N	RQ-E2	Barrier wall	–
18	Tanimoto et al. [84]	FF	S-U	R	E	RQ-E1	Barrier before exit	–
19	Georgoudas et al. [54]	EPF	S-U	UO	N	RQ-E2	Evacuation guide	–
20	Zheng and Cheng [32]	FF	S-U	R	E	RQ-B2	Conflict behavior	–
21	Liu et al. [71]	FF	S-U	R	E	RQ-E2	Evacuation signs	–
22	Guo et al. [116]	LG	S-U	R	E	RQ-B1	SO	C, A
23	Xie et al. [25]	FF	S-U	R	E	RQ-E1	Exit width	–
24	Shi et al. [69]	LG	S-U	R	N	RQ-B1	SO	O
25	Wei et al. [34]	FF	S-U	R	N	RQ-E2	Exit utilization	–
26	Hu et al. [97]	FF	S-U	R	N	RQ-E2	Evacuation strategy	–
27	Guo et al. [26]	FF	S-U	R	N	RQ-B1	SO	C, A
28	Cao et al. [62]	LG	S-U	R	N	RQ-E	Evacuation efficiency	–
29	Fu et al. [82]	FF	S-U	R	N	RQ-B1	SO	C, JT
30	Nicolas et al. [43]	FF	S-U	R	N	RQ-B	Microscopic behavior	–
31	Guan et al. [44]	FF	S-U	R	E	RQ-B2	Competitive behavior	–
32	Guo et al. [99]	CPF	S-U	R	E	RQ-B1	Dynamic characteristics	–
33	Burstedde et al. [6]	FF	S-U/B	R/LC	N	RQ-B1	SO	C, A, L
34	Kirchner et al. [81]	FF	S-U/B	R/LC	N	RQ-B1	F	–
35	Zhang et al. [56]	CPF	S-U/B	R/LC	N	RQ-B1	SO	C, A, L, JT
36	Muramatsu et al. [28]	LG	S-B	LC	N	RQ-B1	SO	C, JT
37	Maniccam[23]	LG	S-B	LC	N	RQ-B1	SO	C, JT
38	Isobe et al. [41]	LG	S-B	LC	N	RQ-B1	SO	L, CA
39	Fukamachi et al. [63]	LG	S-B	LC	N	RQ-B1	SO	C, JT
40	Yue et al. [64]	LG	S-B	LC	N	RQ-B1	F	–
41	Peng et al. [74]	FF	S-B	TI	N	RQ-B1	SO	C, JT
42	Suma et al. [52]	FF	S-B	LC	N	RQ-B1	SO	L
43	Leng et al. [92]	FF	S-B	LC	N	RQ-B	Simulation	–
44	Lu et al. [94]	FF	S-B	LC	N	RQ-B	Simulation	–
45	Jian et al. [98]	PF	S-B	B	E	RQ-B1	SO/F	C, JT
46	Guo et al. [87]	FF	S-B	LC	N	RQ-B1	SO	L
47	Wang et al. [50]	FF	S-B	TI	E	RQ-E2	Guiders' configuration	–
48	Zheng et al. [39]	FF	S-B	BR	E	RQ-E	Influence of fire	–
49	Huang et al. [88]	FF	S-B	BR	E	RQ-B1	SO	C, A, SB
50	Kaji et al. [90]	FF	S-B	LC	E	RQ-B2	Hagen–Poiseuille	–
51	Li et al. [100]	CPF	S-B	LC	E	RQ-B1	SO	C, L
52	Zhang et al. [112]	FF	S-B	LC	N	RQ-E2	Signs configuration	–
53	Muramatsu et al. [57]	LG	S-M	B-C	N	RQ-B1	SO	C, JT
54	Muramatsu et al. [58]	LG	S-M	NB-C	N	RQ-B1	SO	C, JT
55	Zhao et al. [75]	FF	S-M	MR	N	RQ-B2	Exit choice behavior	–
56	Guo et al. [85]	FF	S-M	MR	E	RQ-B2	Exit choice behavior	–
57	Henein et al. [49]	FF	S-M	MR	E	RQ-B1	SO	C, JT, FH
58	Xu et al. [72]	FF	S-M	MR	N	RQ-B2	Exit choice behavior	–
59	Hrabak et al. [45]	FF	S-M	MR	E	RQ-B	Micros characteristics	–
60	Nagai et al. [61]	LG	C	C	N	RQ-E1	Exit distribution	–
61	Yang et al. [96]	FF	C	SM	E	RQ-B2	Kinship behavior	–
62	Huang et al. [73]	FF	C	MR	E	RQ-E1	Exit distribution	–
63	Liu et al. [38]	FF	C	C	E	RQ-B1	Simulation vs. experiment	–
64	Fang et al. [67]	LG	C	TB	N	RQ-B2	Exit choice behavior	–
65	Alizadeh [37]	FF	C	C	E	RQ-E1	Exit distribution	–

(*continued on next page*)

Table 5 (*continued*).

No	Paper info.		Simulation scenarios			Research issues		
	Ref.	Meth.	Cate.	Scenario	Situ.	Cate.	Issue	Phenomenon
66	Zheng et al. [79]	FF	C	MR	E	RQ-E	Influence of fire	–
67	Guo et al. [85]	PF	C	R	N	RQ-B2	Route choice	–
68	Georgoudas et al. [55]	EPF	C	C	N	RQ-E2	Evacuation management	–
69	Yuan et al. [110]	FF	C	SS	E	RQ-E	Influence of fire	–
70	Ma et al. [36]	LG	C	HB	E	RQ-E2	Evacuation strategy.	–
71	Varas et al. [27]	FF	C	C	N	RQ-E1	Exit distribution	–
72	Guo and Huang [59]	PF	C	C	E	RQ-B1	Simulation vs. experiment	–
73	Chen et al. [108]	FF	C	C	N	RQ-E1	width of corridor	–
74	Davidich et al. [109]	PF	C	RS	N	RQ-B1	Simulation vs. experiment	–
75	Was et al. [86]	FF	C	Gy	N	RQ-B	Simulation	–
76	Zhu et al. [78]	FF	C	C	E	RQ-B2	Exit choice behavior	–
77	Fu et al. [83]	FF	C	C	E	RQ-B1	SO	C, A, FS
78	Tang et al. [76]	FF	C	RS	E	RQ-B2	Check-in behavior	–
79	Pereira et al. [89]	FF	C	CR	N	RQ-B1	SO	C
80	Lu et al. [48]	FF	C	TB	E	RQ-B1	SO	C, A

Notes: Cate. (Category of scenario): S-U simple-unidirectional; S-B simple-bidirectional; S-M simple-multidirectional; C complex.
Scenarios: LC long corridor; B bottleneck; UO U-shaped obstacles; Co corner; R room; La Lane; TI T-shaped intersection; B-C crossing with boundary; NB-C crossing without boundary; R random flow in room; C classroom; TB teaching building; SM shopping mall; Gy gymnasium; HB high-rise buildings; SS subway station; Te terminal; RS rail station.
Situ. (**Situation**): N normal; E emergency.
Cate. (Category of issues): RQ-B1 evacuation behavior—dynamic characteristics; RQ-B2 evacuation behavior—study of behavior. RQ-E1 evacuation efficiency—building design; RQ-E2 evacuation efficiency—intervention measures.
Issue: SO self-organization phenomenon; F fundamental diagram.
Phenomenon: C clogging; A arching; FS faster-is-slower; SB Symmetry breaking; SG stopping-and-going; T turbulent; H herding; Z zipper effect; L lane formation; FH freezing by heating; O oscillations; JT jamming transition.

floor field models and other field-based models, such as potential field model, electrostatic-induced potential field model and cost potential field model. From the summary of related articles, three main challenges of CA models for evacuation were presented, and the improvements for each type of challenge were summarized. The typical simulation scenarios and research issues are then proposed through the analysis of relevant research results.

Similar to all evacuation models, the CA-based models also face the problem of model validation. Based on verifying the correctness and reliability of CA-based models, relevant research results of CA models can be significant. Two kinds of validation methods for CA models are widely developed. The first one is qualitative assessment, which aims to reproduce the classic collective effects and self-organization phenomena that can be observed from empirical results. In existing studies, CA models can reproduce most of the self-organization phenomena in the evacuation process, such as clogging [51,89], arching [33,48], faster-is-slower [68,70,83], symmetry breaking [88], lane formation [6,56,87], freezing by heating [49,91], oscillations [69] and jamming transition [23,82]. The other is quantitative assessment, which compares the simulation results with the real data from real-life. Klupfel et al. simulated the egress time for pupils' evacuation based on CA and compared the results predicted by the simulation with the actual time from an evacuation exercise in a primary school [117]. Moreover, one of the most commonly-used evaluation index is the fundamental diagram [118,119], which describes the empirical relationship between the velocity, density and flow of pedestrians, i.e., flow–density dependence and velocity–density dependence. Was et al. introduced a proxemic approach to CA model based on social distances model, and validated the model by exemplary fundamental diagram (flow–density relation) [120]. Tsiftsis et al. evaluated the crowd supervising system with the use of real data, by comparing the fundamental diagram of many different crowd distributions to the corresponding diagrams of real-life distributions [121]. Gavriilidis et al. a fuzzy logic inspired CA-based model and validated the model by incorporating comparison of the corresponding fundamental diagram with those from the literature for a building that has been selected for hosting the museum 'CONSTANTIN XENAKIS', in Serres, Greece [122].

In the following, the advantages and disadvantages of CA models are to be discussed. The CA models use a simple, local-rule and discrete method to convert non-linear relationships between various elements of the system into executable programs, and they can simulate complex, global and continuous crowd movement processes. The advantages of CA models are mainly embodied in simple implementation, fast computing efficiency and strong extensibility. On the one hand, the cellular automaton realizes a complex global phenomenon by setting up simple local rules. In comparison with the traditional analytical equation method, the rules are simple and the description is natural, which makes the user easier to understand and implement. Moreover, due to the use of discrete space, the model itself has the characteristics of computing parallelly, which makes the calculation speed greatly improved. With high computing efficiency, it is more suitable for real-time simulation scenarios or large-scale simulations. Because of the inherent parallelism of CA model, it can be further improved by combining with hardware implementation. Koumis et al. proposed an implementation method for CA model based on GPU, to further speed up the response of the model [123]. Giitsidis et al. implemented the CA model in a field programmable gate array (FPGA) device, whose implementation presents advantages of low-cost, unified and repeated structure and portability [124]. Progias et al. presented a CA-based wildfire spreading model and implemented on FPGA to execute in a parallel [125]. In addition, the CA models can be regarded as multi-agent models [126,127], which provide an intuitive framework for defining behavior rules of agents. Therefore, it has the strong extensibility and can be flexible to add the description of scenes, hazards and individual attributes. The latest studies prove that most important aspects of crowd simulation, such as: environment factors, accident factor, individual characteristic and interaction all can be simulated using CA models. This is very helpful to simulated different scenarios and study the heterogeneity of crowd.

In Section 3, we introduced some main challenges of CA models for evacuation, and introduced the corresponding improvements of CA models. However, due to the accuracy of model description and the applicability of scenes, the following interesting problems on CA models should be further studied.

(1) Problem 1: How to express the force in a confined space with high-density crowd. For a confined space, i.e. a scene with small space and high-density crowd, CA models are hard to depict the unnatural emergent behavior such as individuals stopping and waiting for space to clear up [18]. In the high-density situation, the contact forces in crowd is the critical factor affecting the movement of the crowd. It may generate high pressures that can asphyxiate people in the crowd and even push down a brick wall. However, CA models cannot properly take these high-pressure characteristics into account [11]. The possible solution is allowing multi individuals simultaneously occupy one cell to describe the contact forces and modifying the conflict mechanism to make individuals can choose an occupied cell. It is for the description of the eagerness that individuals try to occupy one cell immediately when another individual leave.

(2) Problem 2: How to express the wayfinding ability in an extra-large space. CA models ignore the ability of realistic individuals that may start their evacuation with only partial information about the environment and during the simulation be able to extend their memory (or mental maps) as they explore the environment and communicate with other individuals in the crowd [18]. For an extra-large space, i.e. a scene with large space and low-density crowd, there is a great possibility that individuals are not familiar with the layout of scene and may be ineffective to obtain the location of exits. In this case, the original CA models cannot describe the crowds' movement accurately. The possible solution is combining the CA models with wayfinding method which can reference foraging algorithm or odor source search algorithm to accurately describe the movement of the crowd in extra-large spaces. Optimized guided evacuation can also be combined with CA in order to minimize the total evacuation time [128].

(3) Problem 3: How to describe the non-local effect. The CA model makes decisions based on the state of neighboring cells and focuses on the local effects between individuals. In the actual scenario, the decisions are not only influenced by the state of neighboring cells, but also by non-neighbor cells. When pedestrians choosing the walking direction, they will anticipate consciously or unconsciously, such as the anticipation to avoid collision and anticipation to avoid congestion. These anticipation behaviors are affected by the non-local state, so it is necessary to adopt the description of non-local effect. One way to solve this problem is adding the state of non-neighbor cells to the calculation of transition probability and deciding the moving direction with the state of neighboring cells together.

(4) Problem 4: How to describe the heterogeneous groups. For CA models, the crowds are generally described as homogeneous. However, this is contrary to the heterogeneous individuals in actual situations. The heterogeneity will play an important factor on the global behavior. The descriptions of heterogeneous individuals mainly include two aspects, i.e. physical characteristics and mentality properties. Considering essential properties of mentality is a fundamental task for many scientific areas such as informatics, psychology, and management science. Hence, it will be important to incorporate the mentality properties into CA models [17]. The latest developments adopted many mentality properties, such as herding, panic, and anticipation. However, they are mostly from the hypothesis of authors and lack of a combination with the actual evacuation process. A better research method is to excavate the typical psychological state of evacuation from actual video and explore the spatial–temporal correlation between psychological state and evacuation situation. The evacuation process will be studied by setting heterogeneous group in accordance with the real situation.

(5) Problem 5: How to express the non-adaptive actions. The CA model only describes individual adaptive movements, while ignore the effects such as falling, injury, incapacitation, and others for the fallen agents that can appear during an emergency evacuation with agents in panic [18]. However, a series of non-adaptive actions, such as surprise run, sudden turn, and fall often appeared in the actual evacuation process. These non-adaptive actions may often be a major cause of disasters. So, the expression and study of non-adaptive actions are particularly important. The research on non-adaptive actions can be carried out in two aspects: realizing physical actions and studying the causes of non-adaptive actions.

(6) Problem 6: How to evaluate the expandability of the model. The values of parameter for CA models are generally obtained by parameter traversal. It may be accurate for the specific simulation scene and scale of crowd, but it is difficult to guarantee the accuracy when extended to larger scale of crowds and scenes. We usually take crowd with small scale and small scene as the object to study. But, in realistic evacuation, the scale of both crowd and scene will be larger. So, the expandability of CA models for both crowd and scene need to be studied and improved in the future.

(7) Problem 7: How to combine CA models with cognitive science and neural networks. With the development of cognitive science, people's research on the human brain and mental working mechanism has gradually deepened. However, most of the existing rules in the CA model are based on research results related to physics, psychology, and behavior. Visual information cognitive models can be combined to the framework of CA and it can describe crowds' movement more accurately from a visual and cognitive perspective in the future. CA model is based on expert-defined rules and its accuracy and applicability need to be verified. Therefore, how to combine real data with the mechanism model is an urgent problem to be solved. In the future, we can use the rules as a blueprint to combine the CA model and neural networks. On the one hand, we can use real data and neural networks to help the CA model to conduct rule mining. On the other hand, the neuron settings in the neural network can refer to the basic rules in CA.

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