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Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches

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Abstract

Building evacuation simulation provides designers with an efficient way of testing the safety of a building before construction. A significant number of models have been developed in a variety of disciplines (computer graphics, robotics, evacuation dynamics, etc.). This paper presents a review of crowd simulation models and selected commercial software tools for high rise building evacuation simulation. The commercial tools selected (STEPS and EXODUS) are grid-based simulations, which allow for efficient implementation but introduce artifacts in the final results. This paper focuses on describing the main challenges and limitation of these tools, in addition to explaining the importance of incorporating human psychological and physiological factors into the models. The paper concludes with an overview of fundamentals that should be applied to simulate human movement closer to real movements of people, where interaction between bodies emerges and flow rates, densities, and speeds become the result of those interactions instead of some predefined value.

Keywords: Evacuation simulation tools; Crowd simulation; High rise building design

1. Previous work

There have been many models developed in order to provide designers with ways of forecasting evacuation times for buildings. A large number of models for pedestrian simulation have been developed over the years in a variety of disciplines (computer graphics, robotics, evacuation dynamics, etc.). These models can be classified into two subsets: macroscopic and microscopic models. Macroscopic models focus on the systems as a whole while microscopic models study the behavior and decisions of individual pedestrians and their interaction with other pedestrians in the crowds. Macroscopic models include regression models, route choice model, queuing models, and gas-kinetics models.

Regression models use statistically established relations between flow variables to predict pedestrian flow operations under specific circumstances. The characteristics of this flow depend on the infrastructure (stairs, corridors, etc.) [15].

Route choice models describe pedestrian wayfinding based on the concept of utility. Pedestrians choose their destinations in order to maximize the utility of their trip (in terms of comfort, travel time, etc.) [11].

Queuing models use Markov-chain models to describe how pedestrians move from one node of the network to another. Nodes are usually rooms, and therefore links are usually portals or doors. Markov-chain models are defined by a set of states together with transition probabilities. At each extrapolation step, a successor state is selected by either sampling from the transition distribution, or identifying the most probable successor [12].

Gas-kinetics models use the analogy with fluid or gas dynamics to describe, using partial differential equations, how density and velocity change over time [10].

Microscopic models include social forces (particle systems) [9], rule based, [24] and cellular automata models [22]. Research models in computer graphics, also considered microscopic models to explore ways of creating virtual humans or animals that behave in an autonomous way. They address realistic body and leg movements with graphical display realism.

The most commonly used techniques to simulate crowd evacuation using microscopic models are social forces and

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Table 1
Microscopic models features

Behavior method	Communication or signals	Individualities or roles	Spatial structure for motion
Social forces	No	Some	Continuous
Rule based	No	No	Continuous
CA	No	No	Regular grid

cellular automata (CA) models. The main difference between them is whether they treat the space as continuous (social forces) or discrete (CA), as can be observed in Table 1.

Social forces models have been used to simulate panic situations. An agent's local motion within a room is based on Helbing's model [9] which describes human crowd behavior with a mixture of socio-psychological and physical forces. Pedestrians i, $(1 \leq i \leq N)$ of mass m_i like to move with a certain desired speed v_i^0 in a certain direction e_i^0 and they tend to adapt their instantaneous velocity v_i within a certain time interval τ_i. At the same time, the individuals try to keep a distance from other individuals j and from the walls w using interaction forces f_{ij} and f_{iw}. The change of velocity in time t is given by the acceleration equation (Helbing, 2000) [9]:

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = m_i \frac{v_i^0(t)e_i^0(t) - v_i(t)}{\tau_i} + \sum_{j(\neq i)} f_{ij} + \sum_W f_{iW}.$$

This model generates realistic phenomena such as arching in the portals and the "faster is slower" effect, and mass queuing/herding behavior as individuals tend to follow what others do.

Rule based models [24,25] have been widely used among the computer graphics community to simulate flocks of animals, or virtual humans. The most well known model to simulate life-like complex behavior is Reynolds' local rules "boids" model [24]. This model is an elaboration of a particle system with the simulated entities (boids) being the particles. The aggregate motion of the simulated flock is created by a distributed behavioral model. Each simulated agent is implemented as an independent actor that navigates according to its local perception of the dynamic environment, the laws of simulated physics that rule its motion, and a set of behaviors programmed by the animator. The aggregate motion of the simulated flock is the result of the dense interaction of the relatively simple behaviors of the individual simulated boids.

The basic model to simulate generic flocking behavior consists of three simple rules which describe how an individual boid maneuvers based on the positions and velocities of its nearby flock mates (Fig. 1):

- separation: steer to avoid crowding local flock mates
- alignment: steer towards the average heading of local flock mates
- cohesion: steer towards the average position of local flock mates

Each boid has access to the whole environment description, but flocking only requires reaction within a specific neighborhood, which is given by a distance (from the center of each boid) and an angle (from each boid's direction of flight). This neighborhood can be considered as limited perception. Each boid will avoid not only collision against other boids but also with obstacles in the environment. In addition to the basic three rules used to simulate flocking, Reynolds [25] introduced the more general concept of steering behaviors and placed flocking within that context. Steering behavior enhances the behaviors already presented in the original boids model by building parts for complex autonomous systems. Each of these new rules defines only a specific reaction on the simulated environment of the autonomous system.

Cellular automata models divide the space in a uniform grid (Fig. 2). Each agent occupies a particular grid position (cell) and moves between these positions depending on the modeling system. Cellular automata evolve in discrete time steps, with the value of the variable at one cell being affected by the values of variables at the neighboring cells. The variables at each cell are updated simultaneously based on the values of the variables in their neighborhood at the previous time step and according to a set of local rules [22].

Research models in computer graphics have several cognitive agent architectures proposed to generate human-like behavior. They generally consist of knowledge representation, algorithms that learn, and modules that plan actions based on that knowledge [7,34]. Particle systems and dynamics for modeling the motion of groups with physics were also used [4,5]. In addition, multi-agent crowd systems were also utilized where the agents are autonomous, typically heterogeneous, and concerned with coordinating intelligent behaviors among themselves. Some of these applications include crowd behavioral models used in the training of military personnel [33] and crowd motion simulations to support architectural design for both everyday use [6] and emergency evacuation conditions [2,23].

2. Psychological and physiological factors that affect human behavior

It is necessary to study the psychology literature in order to understand the psychological factors that affect human behavior and movement. Crowd evacuation from large and complex public building spaces is usually slowed down by a lack of knowledge of the detailed internal connectivity of the building's rooms. In such circumstances, individuals may not be aware of some suitable paths for evacuation. Building occupants usually decide to make use of familiar exits, which are often the way in which they enter the building, and tend to ignore emergency exits or paths not normally used for circulation [28].

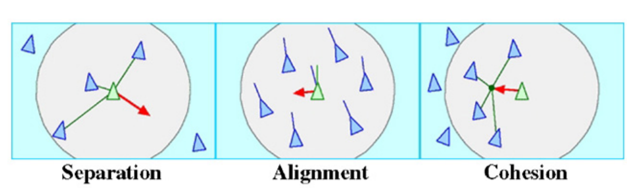

Fig. 1. Reynolds' boids.

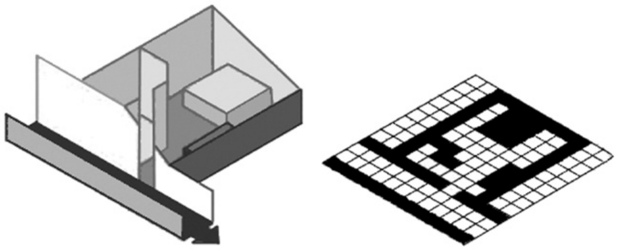

Fig. 2. 3D environment and its corresponding grid of cells. Walls and other fixed obstacles are black; the white cells are areas that can be occupied by pedestrians.

The perceived space depends on the individual ability and psychological condition of the person. Most people react to time pressure by an increase in the speed of their actions, as well as by subjectively choosing information. In general, the evacuation of a building due to imminent danger is accompanied by considerable physical and psychological stress. For example, raising stress levels reduces awareness, especially the orientation ability within a building [30].

Decision skills in emergency situations are influenced by several factors such as the uncertainty of changes that might occur to the environment and the time pressure under which decisions have to be taken. If people have not been properly trained for these situations, they are likely to feel stressed and might reach the point where they find themselves incapable of making the right decision [14]. In contrast, trained individuals such as firefighters deal with a dynamically changing environment and choose the best sequence of actions based on their perception and knowledge. Their decision-making process is subjective, and it is based on the importance they assign to each factor, such as saving lives, keeping fire from spreading, minimizing risks for themselves or the rest of the team, etc.

In an evacuation situation caused by a fire, the main sources of stress could be too much or too little information coming at one time (several people in the same room taking different decisions and shouting different information about blocked rooms), complex and dynamically changing situations that result in uncertainty, and time pressure.

There has been much computational work done in crowd simulation using different methods to perform local motion such as cellular automata (CA), social forces models, and rule based systems. All these models simulate the movement of people within a familiar environment trying to achieve their goal while avoiding collisions with walls, obstacles and other individuals in the crowd, but there is still a lack of psychological and physiological elements built into the autonomous agents to provide them with a more human-like decision making.

3. Commercial applications

The National Institute for Standards and Technology (NIST) recently conducted a survey of currently available crowd simulation software [18]. The main focus of commercial applications is to validate their systems in terms of egress (flow rates, densities, congestion areas, evacuation times, etc.). They use either macroscopic or microscopic approaches. Microscopic approaches allow for individualities, and therefore different behaviors and physiological elements. The microscopic models most commonly used in industry applications are social forces and cellular automata models. In contrast, research methods tend to focus on developing autonomous agents able to navigate large complex virtual environments while avoiding static obstacles and other agents. They are clearly microscopic models, but in addition address realistic body, legs, movements and graphical display realism.

Table 2 presents a sample of commercial software available for crowd simulation:

- *LEGION* (Legion International Ltd. 2003): Uses speed, density and space utilization maps to qualitatively and quantitatively analyze the use of space over time [23]. LEGION oversimplifies the behavioral representation of individuals by using only four parameters and one decision rule (based on least effort) to simulate individual behaviors.
- *EXODUS* [35]: Agent-based model with coarse grid geometry (CA). Uses a 2D grid to map the geometry of the building. The grid contains nodes that can be connected with eight other neighboring nodes through arcs. The simulation calculates shortest distances to the exits and stores that information in the environment. This tool is described in more detail in the following sections of the paper.
- *SIMULEX* [36]: Agent-based model with coarse grid geometry (CA). It is a partial behavior model that relies on inter-person distances to specify walking speed of individuals. The model allows also for overtaking, body rotation, sideways stepping and small degrees of back stepping. The movement algorithm is based on a combination of the results of many vide-based analyses of individual movement.
- *PEDROUTE* [23]: Optimization models, based on coarse grid geometries and including global perspective for individuals. The underlying assumptions and principles used in PEDROUTE are the same as other spatial interaction/entropy maximizing models and fail to incorporate the individual basic mechanisms underlying pedestrian movements. This program cannot represent the interaction of each pedestrian with other pedestrians and the external environment, only the overall behavior.

Table 2
Commercial software main features

	Behavior method	Communication or signals	Individualities or roles	Spatial structure for motion
Simulex	Distance maps	No	Some	Continuous
LEGION	Least effort	Some	Some	Continuous
EXODUS	CA	No	Some	2D grid
STEPS	CA	No	Some	2D grid
PEDROUTE	Spatial entropy maximizing	No	Few (groups)	Coarse grid

- *STEPS* [37]: Agent-based model with coarse grid geometry (CA). Each individual occupies one cell at any given time and moves in the desired direction if the next cell is empty. Each occupant has its own characteristics, patience factor and familiarity behavior. This tool is described in more detail in the following sections of the paper.

For the purposes of studying the current challenges in modeling high rise buildings, two of these models (EXODUS and STEPS) have been selected. Both are very good representatives of cellular automata models. For this study, both systems have been fully tested and analyzed to determine their achievements but also their limitations.

In the following sections we will explain in detail how to model geometry and human behavior for each of these systems in order to run simulations. Some previous work on validation will be presented, and finally the main limitations observed will be explained. Conclusions and alternative solutions to the problem of modeling high rise buildings are presented.

4. Modeling parameters

To simulate the evacuation, two tasks have to take place: modeling the geometry and defining people and their movements. The geometry modeling requires the space to be divided into a series of planes, each discretized using a uniform Cartesian mesh. People are modeled based on their physical dimensions and personality parameters that the software provides. The planes are broken down into smaller cells to represent the area occupied by a single individual, and the arcs between cells represent possible movements. The parameters used to populate the model are based predominantly on previous reports and studies [16,17].

4.1. Importing geometry

Most of the commercial tools for crowd simulation can import CAD files. Only the geometry of each plane is imported, and stairwells have to be added by hand, which leads to the introduction of errors that are hard to detect in both software tools tested, and which strongly affects the simulation results.

Each stairwell has to be defined and linked to floors both above and below, indicating the exact Cartesian position in the plane. Each floor is later divided into a grid. Grid size is crucial because it determines the maximum density rate per meter square, and it can also affect the flow rates in some parts of the building, as will be discussed in the section on limitation of the software.

4.2. Modeling human behavior

In grid-based models such as the ones used for this comparison paper, each individual occupies one cell at any give time step. The behavior control moves the individual from one cell to another based on the shortest distance to a destination, supervising also the waiting periods, and other behaviors such as overtaking or sidestepping.

There is a large amount of data in the fire evacuation literature to calculate the movement component of total evacuation time. There are two principal approaches for estimating the evacuation of a building. One approach applies a hydraulic analogy, simulating people as fluid particles. Another approach considers the behavioral aspects of people. Both approaches require information on movement characteristics such as:

- *Speed*: rate of travel along corridors, ramps and stairwells.
- *Flow*: number of persons passing a particular segment of the egress system per unit of time.
- *Specific Flow*: flow per unit width of the egress component (persons/second of doorway width).

Most of this information on the movement of people, including disabled individuals, has been collected through fire drills and for normal movement. A summary of the main parameters used in the simulation is given in Table 3.

5. Simulation

Simulation is the main tool to reproduce evacuation situations using computer technology to assess dangers and obtain a set of recommendations for evacuation procedures or alterations of the current environments, such as creation of shelter areas, modifications in the layout of each floor, etc. Before the construction of the actual building, simulation is a great tool for designers to study the movement of people within an environment and, based on that, to decide how to improve the layout of a building to decrease the evacuation times in case of emergency. The fundamental driving mechanism for individual movement is the desire to move at a free walking speed towards the next target point in the shortest amount of time and without collision. The decision process is adhered to by every individual in the model. For each target (exit point), a potential is calculated at each grid cell on the planes. The potential value represents the distance between individual cells and the targets considering the presence of blockages (walls, columns, etc.). At every time step, each target is scored based on the time of arrival, and a final score is derived. Based on the derived final score of the target, the individual located in a cell attempts to reach the low-scored target through a neighboring cell in the grid.

6. Validation

Both systems have been fully evaluated with data both from simulation drills and data gathered after real evacuation

Table 3
Mean speed for individuals [26]

Impairment	Level walkway (m/s)	Stairwells-down (m/s)	Stairwells-up (m/s)
Electric wheelchair	0.89		
Manual wheelchair	0.69		
Crutches	0.94	0.22	0.22
Walking stick	0.81	0.32	0.34
No disability	1.24	0.70	0.70

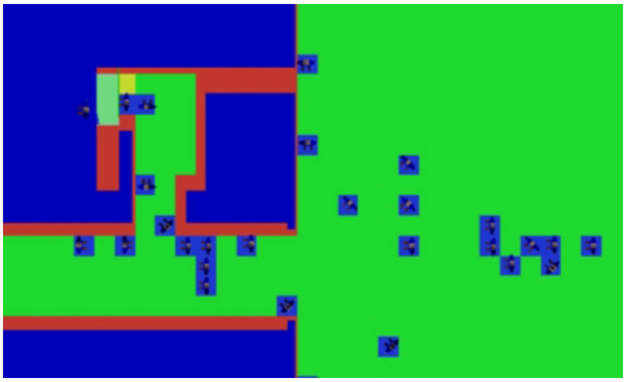

Fig. 3. Only one person at a time can fit through the opening of the stairwell, when the actual width is 1 m (the yellow cell, indicates partially blocked cell, and thus not available for human occupancy).

scenarios. The most important real evacuation scenario, where a large amount of data was obtained is the World Trade Center evacuation. EXODUS [8,3] in particular has carried out a large study on this case, although the real evacuation times are not known since the buildings collapsed before everybody could evacuate. STEPS [13,31,32] has also been validated using both measured data from evacuation drills and design standards, such as the National Fire Protection Association (NFPA 130).

7. Limitations of the software

In order to study the challenges of simulating high rise buildings, several simulations were performed with buildings of different number of floors to compare the results. This paper does not focus on egress results per se, since that information can be found in the literature on validation, but instead this work focuses on observing the results concerning the movement of the simulated agents and its consequences on the overall evacuation simulation.

Since both systems described in this paper are grid based, this section presents a discussion on artifacts that this type of model introduces regarding the way they treat the space and the implication that this has in the movement simulation. Some of the limitations that current commercial software tools have in terms of simulating human psychology and physiology are also described in detail.

- *Grid size*: Using a cellular automata model and therefore having a discrete grid for the simulation creates several limitations. Some of the main problems are getting fixed densities and unrealistic flow rates through portals. Grid size becomes a crucial parameter to calibrate in order to achieve the desired behavior. Individuals will move with their desired velocity, unless none of the cells around them is available, which causes the individual to wait for the next empty cell in the desired direction of movement.
  Having a fixed grid size forces the maximum densities to be limited. So for example if the grid size is defined as 0.25 m^2 the maximum density at any time will be 4 persons/m^2, while the literature on crowd behavior reports maximum densities of 7.4 persons/m^2 where people can still move [29].
  The second big issue arises when the grid is not accurately aligned with the geometry. This can lead to artifacts where only one person at a time can get through a door in the simulation, when in reality the door size is big enough to fit to several people crossing it simultaneously. This can be observed in Fig. 3:
- *Fatigue factor* is not included in the simulation. The speed values given in the literature are based on those collected during fire drills and normal situations. During an actual fire evacuation in a high rise building, slower speeds when walking downstairs have been reported. This can be the result of tiredness when walking downstairs for long periods of time (accounting for unfit, older or disabled people [27]). Tiredness yields to people needing to stop in order to rest, which can provoke bottlenecks.
- *Route selection*: Path finding in grid-based models consists in traversing the centers of squared cells. Distances between centers can be stored before the simulation takes place. The method is usually based on "potential maps" which identify a discrete approximation of the shortest path towards the destination and stores this information in the cells in order to achieve an efficient simulation. The main problem that potential maps have is that they favor 45° movement, and the resulting routes are not always realistic Fig. 4. The following screen shot from EXODUS shows this effect.
  Potential maps computed on grids have the following problems [1]: they yield highly unrealistic space utilization, cannot guarantee equivalence on return trips, which artificially segregates opposite flows, and finally they distort the path length and pedestrian travel time.
- *Uneven use of stairwells* occurs due to familiarity or initial distance to exits, which yields to different utilization of the stairs (Fig. 5). Because distances are computed before the simulation, and route selection is based on the potential maps, some stairwells may attract more individuals than others. This can have a big impact on the overall evacuation time. This can be a positive emergent behavior if it matches

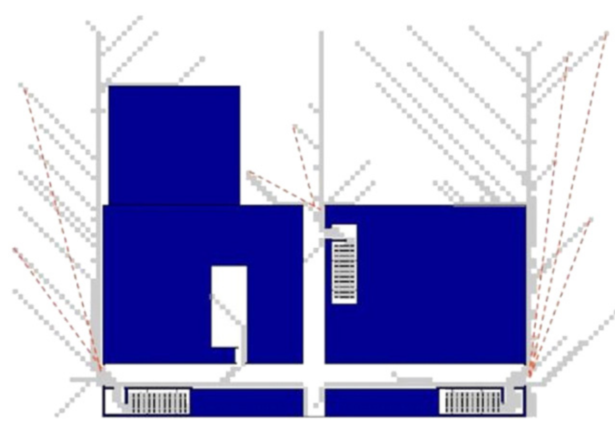

Fig. 4. Paths followed based on potential maps in a cellular automata model (grey) and expected paths for real humans (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

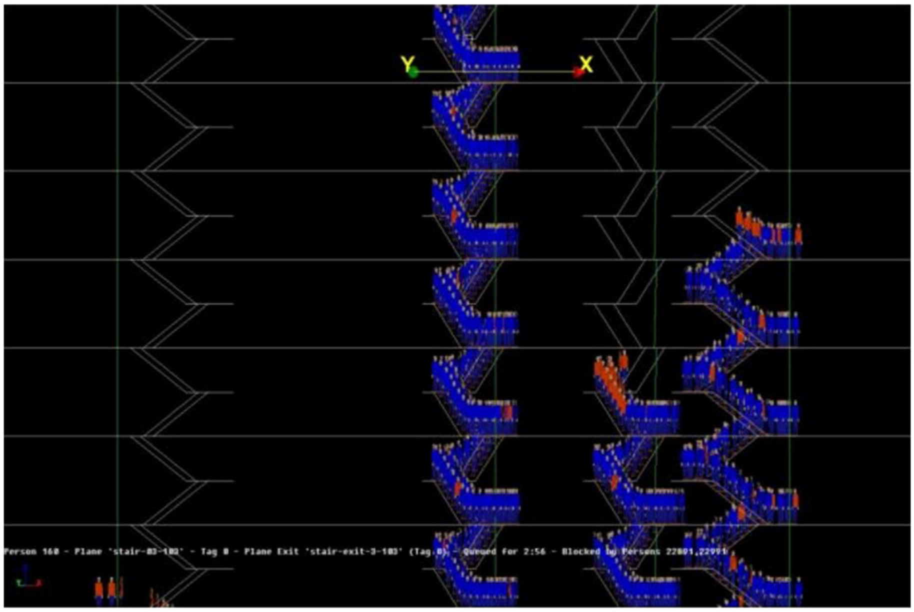

Fig. 5. Uneven utilization of stairwells during route selection. Individuals' decisions are based only on shortest distance. The final evacuation time is thus increased since a large part of the simulation one stairwell is not being used.

what would actually occur in the real building, but how to accurately validate the positive impact of this behavior is still not clear.

- *Limitation in stairwells*. The main problem regarding the utilization of staircases arises from the size of the cells within the grid. Commonly a size of 0.5×0.5 m^2 is given for each cell, assuming that a real human distance from shoulder to shoulder can be up to 0.5 m. This together with the pre-assigned speeds leads to unnatural results where the evacuation times obtained assume the best case scenario. From the data gathered after the World Trade Center Attack [16,17], it can be observed that the average speed in the staircase was 0.2 m/s, which is half the slowest egress speed observed in humans when walking downstairs. Speed values that appear in the literature have been measured during drill evacuations which lack all the unexpected elements that appear during a real emergency. In this case, the main reason for this discrepancy was the fact that the counter flow of firefighters going upstairs, carrying all the necessary gear with them, led to almost blocked staircases. It was hard to fit two people walking simultaneously in the stairs, when one of them was carrying big heavy gear, and thus the actual speeds of the rest of the crowd walking downstairs were drastically reduced. This normal situation during an emergency evacuation cannot be simulated with cellular automata approaches, given that it is not possible to fit agents larger than the cell size, and neither can the model assume the cell size to be bigger to fit the larger type of agent, since this would lead to a utilization of space lower than the real one. A secondary but also important problem when simulating high rise buildings arises from physiological and health related factors. From the real data obtained after the aforementioned attack, it could be observed how some of the bottlenecks created in the staircases where due to several human factors such as unfit or older people suffering from fatigue and needing to stop and rest, as well as some people needing to stop for other reasons (such as removing uncomfortable shoes to walk faster). These effects are psychological and physiological elements that need to be integrated within the model through an agent-based model.

The limitations described above directly affect the output of the simulation, and may lead to unrealistic results. Grid size limitations can produce the unrealistic effect of allowing only one person at a time to walk through a 1 m wide door; this will obviously increase the overall evacuation time, since the flow rate through that door will not match the real flow rate possible for a one meter width door. One tedious way of solving this problem, is to slightly modify the underlying geometry to allow for two available cells, but this process requires very careful study of the geometry during the simulation to detect and prevent artifacts in the final result.

Fatigue is also an important element to consider in high rise buildings, since the current systems assume people to maintain their maximum speed throughout the simulation, which in a real high rise building evacuation would not be the case, and thus the simulation could provide faster evacuation times than the ones during a real scenario. It is also very important to consider that fatigued people not only will reduce their maximum walking speed along the evacuation route, but also may provoke bottlenecks for the rest of the population.

Route selection based on a 2D grid yields longer paths than the straight line between two points, and thus errors are introduced in the time that it takes a person to go from one point to another in the building.

Finally, stairwell selection based on precalculated information and not allowing re-routing based on bottlenecks, can be desired in some simulation but may also increase evacuation times in some other cases where stairwell selection does not necessarily match human preferences.

In conclusion, CA models can be used to simulate evacuations and to perform studies on human behavior based on building geometry, but it is still important to keep in mind their limitations when analyzing the results of a study to make decisions about building design.

8. Discussion

In addition to the review carried out on commercial applications for evacuation simulation, we also studied other crowd simulation approaches used commonly within the computer graphics research community. The goal was to evaluate their possibilities and study how they could be combined with the current commercial tools to bridge the gap between simulation tools and real emergency evacuations [20,21].

Commercial applications' main interest is to validate their systems in terms of egress (flow rates, densities, congestion areas, evacuation times, etc.). Models based on cellular automata lack realism because they are restricted to checkerboard configurations since the agents can only occupy discrete cells in a grid. Agents move based on some potential field calculated on the grid. Agents are therefore assumed to move within a static environment where the paths towards the exits do not change over time. Agents move from the current cell to the desired destination cell based on occupancy of the space.

In contrast, research methods in computer graphics tend to focus on developing autonomous agents able to navigate large complex virtual environments while avoiding static obstacles and other agents. However, in most cases they ignore the problems that arise when dealing with very high density crowds. These systems usually apply some sets of rules based on modifying the speed or trajectory of the agents to avoid collision. Consequently, these models are sufficient for medium and low density crowds; however, when the crowd is very dense, they yield unnatural emergent behavior such as individuals stopping and waiting for space to clear up.

Neither the research models nor the commercial models consider the concept of body-to-body contact leading to pushing agents in a crowd, or individuals being dragged by the crowd. Further effects such as falling, injury, incapacitation, and others walking over the fallen agent that can appear during an emergency evacuation with agents in panic are also ignored.

In terms of global navigation, the published systems for crowd simulation assume that agents have complete information about the environment. They assume that an agent can access the entire internal structure of the environment and use graph search algorithms to perform navigation. Or else they assume that the environment can be discretized as a grid that stores potentials or as distance maps that the agents will follow locally to reach the goal.

It is essential to provide an agent with the ability to explore partly known environments and learn new features. Another crucial aspect of crowds that is ignored elsewhere is that people have the ability to communicate with others in order to exchange information [21]. It is important therefore to enhance the current crowd systems with the ability of having realistic agents 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. Agents should also exhibit different behaviors based on different roles. These ideas have currently been introduced in some systems [20,21] in order to achieve virtual agents driven by some psychological factors with the purpose of modifying the overall performance of an individual agent based on its mental state. It is necessary thus to incorporate psychological and physiological elements that can affect agents' behaviors in ways similar to behaviors observed in real people (i.e. altruism, fatigue, route selection, panic affecting decision making).

In terms of human motion, it is important to consider approaches that allow realistic contact between individuals such as Helbing's social forces model [9] or Pelechano's system [19]. Evacuation simulation systems should use models where flow rates, densities, and speeds emerge as a result of interaction between individuals instead of some predefined value, and where virtual agents can move in continuous space instead of some discrete grid, since this leads to unrealistic trajectories that can affect the overall evacuation times.

The challenges that CA models present affect the simulation result of any type of building. The main concern when it comes to simulating high rise buildings is that these challenges are magnified and it is thus necessary to be more careful when analyzing the results of the simulation to make design decisions. For example, inefficient route selection in a small building, as described in Section 7, will impact the result by slightly increasing the time to move between two points, which can be acceptable for the simulation, but when simulating a larger building, the introduced error will be magnified to the point where the result could become invalid. Fatigue is also an element that does not impact the evacuation simulation of a low rise building, but it does affect high rise buildings, as it has been reported from real scenarios. And a similar difference is apparent with the counter flow in the stairwells due to the fire brigade; in a low rise building, the stairwell would end up blocked for a short period of time, whereas in a high rise this effect could be catastrophic.

This paper does not claim that CA models are not good under any circumstances to simulate evacuation, since these models have been validated for small buildings. The motivation for this study is to point out all those details about CA models that can end up introducing an important error when working with high rise buildings, and which thus need to be taken into account when using the model and when analyzing the results of a simulation.

A large amount of data used for this study has been based on the World Trade Center, even though it is an extreme evacuation scenario. The main reason for using this information was that after September 11, a large amount of data on human behavior was gathered and made public, which revealed the differences between real human behavior and the behavior exhibited in the simulations. The data also presents a source of information to study the problems that can emerge during a real emergency situation that have not been included to date in simulations.

9. Conclusion

Even though current software based on cellular automata approaches has been widely used and validated, there is still a need to develop models that can closely simulate human behavior. It is important to consider physical interactions between individuals and the resulting impact of these interactions in the behavior of the virtual humans (trajectories, bottlenecks, flow rates, etc.). On top of this improved human movement model, it is essential to integrate agent-based approaches that endow the agents with physiological and psychological elements that can describe the virtual humans' mental state at any given time and drive their decision making, orientation skills and possible roles within the crowd. Communication between agents is another crucial element to integrate in realistic models to achieve more accurate evacuation results. From the data gathered in the literature, it can be observed how communication has an important impact on the evacuation since it actually drives when the evacuation starts.

Crowd simulation systems are bridging the gap between real evacuation performance and the tedious process of calculating the evacuation times following engineering guides for safe egress. At present, these tools provide the designer with graphical information of where the bottlenecks could appear, and also make easier the study of how some changes in the building could modify the overall evacuation. Even though these systems have been validated for some particular scenarios, further work needs to be carried out to improve the accuracy of the results.

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