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A Review and Implementation Guide for Basic Cellular Automata Models in Pedestrian Evacuation Simulation

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Abstract

Efficient and safe evacuation of individuals during emergencies is critical to building design and public safety planning. Cellular Automata (CA) models have emerged as a valuable tool for simulating and analyzing pedestrian evacuation dynamics, offering a balance of computational efficiency and the ability to capture complex emergent behavior. This paper comprehensively reviews basic CA models for pedestrian evacuation simulation, exploring their fundamental principles, strengths, limitations, and implementation considerations. We delve into commonly used models like Floor Field Cellular Automata (FFCA) and Social Force Cellular Automata (SFCA), highlighting their unique characteristics, advantages, and potential drawbacks. A practical implementation guide outlines step-by-step procedures for developing and executing CA-based simulations, from defining the virtual environment and establishing behavioral rules to analyzing the simulation output. We emphasize the importance of data-driven approaches for model calibration and validation, ensuring the accuracy and reliability of simulation results. Finally, we discuss future directions for CA-based evacuation modeling, including integrating more sophisticated behavioral rules, developing hybrid models, and exploring three-dimensional simulations to enhance realism and predictive capabilities. This comprehensive review aims to equip researchers, practitioners, and students with the knowledge and tools to effectively utilize CA models for enhancing safety and preparedness in various evacuation scenarios.

1. INTRODUCTION

The ability to safely and efficiently evacuate individuals from buildings and public spaces during emergencies is crucial for minimizing casualties and ensuring public safety [1]. This is particularly critical in spaces with high occupant densities, such as assembly buildings [2] or historical mosques where unique architectural features can pose additional challenges [2–4]. Understanding crowd movement and behavior under these circumstances is paramount for developing effective evacuation plans, optimizing building layouts, and informing emergency response strategies. Pedestrian evacuation modeling is a vital tool in this process, offering a virtual environment to explore different scenarios, pinpoint potential bottlenecks, and guide decision-making for safer crowd management [5,6].

Among the diverse approaches to pedestrian evacuation modeling, Cellular Automata (CA) models have gained prominence due to their inherent advantages. CAs provide a powerful computational framework for simulating complex systems composed of discrete components interacting under simple rules [7,8]. Their inherent simplicity allows for straightforward implementation and high computational efficiency, making them well-suited for simulating large-scale evacuations within reasonable timeframes [9,10] Furthermore, CAs capture emergent behavior, where macroscopic patterns arise from the interplay of microscopic rules, a key characteristic of crowd dynamics.

This paper aims to provide a comprehensive review and implementation guide for basic CA models used in pedestrian evacuation simulation. By exploring the foundational principles of CA modeling, reviewing key model types, and offering practical implementation guidance, we seek to equip researchers,

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practitioners, and students with the knowledge and tools needed to leverage this versatile approach for informed evacuation planning and design.

The paper is structured as follows: Section II presents the core concepts of CA modeling, highlighting its relevance to pedestrian evacuation. Section III delves into a detailed review of common basic CA models, including the Lattice Gas Model, Floor Field Model, and other field-based approaches, discussing their strengths, limitations, and specific applications. Section IV offers a practical implementation guide, outlining a step-by-step process for developing and executing CA-based simulations. Section V explores the strengths and limitations of basic CA models, considering their accuracy, applicability, and potential for improvement. Finally, Section VI concludes the paper, summarizing key findings and suggesting future research directions for advancing the field of CA-based evacuation modeling.

2.FUNDAMENTALS OF CELLULAR AUTOMATA FOR EVACUATION MODELING

Cellular Automata (CA), with their unique ability to simulate complex systems arising from local interactions, have become an invaluable tool for understanding and predicting crowd dynamics during evacuations. Their inherent simplicity, combined with their capacity to capture emergent behavior, allows researchers to model the often-unpredictable nature of pedestrian movement in a computationally efficient manner.

A regular lattice of cells at the heart of a CA model, each representing a discrete unit of space within the simulated environment. These cells, like the pixels of a digital image, are the building blocks of the model, and their states, analogous to the colors of those pixels, represent the condition of that space at a given time. In the context of pedestrian evacuation, a cell's state could denote whether it's occupied by a person, blocked by an obstacle, or vacant and available for movement. This discrete representation mirrors the real-world scenario where individuals move in steps rather than continuously gliding through space.

The evolution of a CA model unfolds over discrete time steps, like frames in a movie, guided by a set of predefined local rules. These rules, akin to the laws of physics governing the motion of objects, dictate how the state of each cell changes based on its current state and the states of its neighboring cells. Similar to a pedestrian's field of vision, the neighborhood defines the set of cells that directly influence a given cell's behavior. Commonly used neighborhoods include the von Neumann neighborhood, comprising the four orthogonally adjacent cells, and the Moore neighborhood, encompassing all eight surrounding cells, including diagonals.

The magic of CA lies in its ability to generate complex global patterns and behaviors from these simple, local interactions. As each cell's state is updated based on its neighborhood, intricate dynamics emerge from the collective behavior of individual cells. This bottom-up approach, where macroscopic phenomena arise from the interplay of microscopic rules, mirrors the self-organization often observed in real-world crowds, where individual decisions and movements give rise to collective patterns like lane formation, bottlenecks, and shockwaves.

Several key features make CA particularly well-suited for simulating pedestrian evacuation. First, their inherent discreteness naturally aligns with the step-by-step movement of pedestrians, avoiding the complexities of continuous motion. Second, the focus on local interactions reflects the reality that pedestrians primarily react to their immediate surroundings - the presence of obstacles, the density of the crowd, and the movement of those nearby. Third, CA models are inherently parallel, meaning that the state of each cell can be updated independently, allowing for efficient computation of large-scale simulations. Finally, their capacity to generate emergent behavior from simple rules makes them ideal for capturing the often-unpredictable dynamics of crowds, where seemingly random individual actions can lead to organized collective patterns.

Developing an effective CA evacuation model involves carefully considering several design choices. The cell size determines the level of detail, with smaller cells providing greater accuracy but demanding more computational power. The chosen cell states must capture relevant aspects of pedestrian behavior, such as location, direction, speed, and even panic levels. The neighborhood definition dictates the interaction range and model complexity, while the local rules, the heart of the model, need to incorporate factors like obstacle avoidance, desired speed, and herding behavior. Finally, the treatment of boundaries, whether periodic (as in a continuous loop) or open (allowing entry and exit), influences the overall flow dynamics. By carefully crafting these design choices, researchers can build CA models that effectively capture the essential dynamics of pedestrian evacuation, providing valuable insights for optimizing safety and preparedness in various real-world scenarios.

3.REVIEW OF BASIC CELLULAR AUTOMATA MODELS FOR PEDESTRIAN EVACUATION

In the quest to effectively simulate the intricate dynamics of crowd movement during evacuations, researchers have developed a diverse array of CA models. This section delves into a detailed examination of some of the most foundational models, each representing a distinct approach to capturing pedestrian behavior's essential elements and interactions within a confined environment.

3.1 Lattice Gas Model: A Simple First Step

The Lattice Gas Model (LGM), also known as the drift-random walk model, emerged as one of the earliest attempts to apply CA principles to pedestrian dynamics [11]. Imagine a bustling city square, bustling with pedestrians, each moving towards their own destination. The LGM simplifies this scene by representing the square as a grid, where each cell symbolizes the space occupied by a single individual. These individuals, like particles in a gas, move on the grid, each with a preferred direction, often guided by the allure of the nearest exit.

The LGM introduces a "drift probability" (*D*) that biases the movement of these particles toward their preferred direction. Picture it as a gentle breeze nudging pedestrians towards their goal, influencing their choices at every intersection. At each time step, a particle can step into one of its unoccupied neighboring cells, with the probability of moving in the preferred direction enhanced by this drift. The probabilities of moving in other directions are then evenly distributed among the remaining vacant cells.

This model, while conceptually straightforward and computationally efficient, exhibits limitations in its realism. The simplified movement rules often result in unnatural trajectories, failing to capture the subtle adjustments, hesitations, and avoidance maneuvers characteristic of real pedestrians. Moreover, the LGM struggles to accurately simulate movement within complex environments adorned with obstacles and multiple exits, where a simple drift probability cannot fully represent the intricate decision-making processes of individuals navigating a maze of choices.

Despite its limitations, the LGM has provided valuable insights into fundamental aspects of pedestrian dynamics, such as jamming transitions in counterflow, where two opposing streams of pedestrians impede each other's progress, and the impact of exit configuration on overall evacuation efficiency. It served as a stepping stone, paving the way for more sophisticated models.

3.2.Floor Field Model: Guiding Movement with Virtual Fields

The Floor Field Model (FFM), introduced by Burstedde et al. and further developed by Kirchner & Schadschneider, represents a significant leap forward in CA-based evacuation modeling[9,10]. This model recognizes that pedestrian movement is not solely driven by a simple desire to reach an exit but is influenced by both the static environment and the dynamic presence of other individuals.

Imagine navigating a crowded airport terminal. The FFM captures this scenario by introducing virtual fields that act like invisible forces guiding pedestrians' movements. The Static Floor Field (SFF) embodies the unchanging features of the environment – the beckoning exits, the imposing walls, and the intricate layout of corridors and obstacles. This field, like a map etched into the floor, guides pedestrians towards exits by assigning higher values to cells closer to those desired destinations.

The Dynamic Floor Field (DFF), on the other hand, represents the ever-changing influence of the crowd itself. As pedestrians move, they leave a subtle "trace" on the DFF, increasing the attractiveness of those recently traversed paths. This trace, like a faint scent lingering in the air, encourages others to follow, capturing the herding behavior often observed in crowd dynamics.

The transition probability for a pedestrian to move to a neighboring cell is then calculated by considering the combined influence of the SFF, the DFF, and additional factors like obstacle avoidance. This intricate interplay of virtual forces leads to more realistic movement patterns, capturing the subtle adjustments, pauses, and detours that characterize pedestrian behavior.

The FFM's ability to handle complex geometries, its flexibility in incorporating diverse factors like individual characteristics and panic, and its increased realism have made it a cornerstone of CA-based evacuation modeling. It has been widely used to simulate evacuations from diverse environments, from single rooms and multi-story buildings to ships and aircraft, providing valuable insights into the impact of exit design, crowd density, and various behavioral factors on evacuation efficiency.

3.3 Other Field-Based Models: Exploring New Dimensions of Influence

Beyond the LGM and FFM, researchers have explored various field-based models to capture the multifaceted influences that shape pedestrian movement. Like specialized lenses, these models provide unique perspectives on crowd dynamics, each emphasizing different aspects of the complex interplay between individuals and their environment.

The Potential Field Model, similar in spirit to the FFM, utilizes a potential field to guide pedestrians towards exits [12]. However, this potential field is not simply based on distance to exits but can incorporate additional factors, such as pedestrian congestion and route capacity, offering a more nuanced representation of path attractiveness.

The Electrostatic-Induced Potential Field Model draws inspiration from the realm of physics, using a virtual potential field analogous to electrostatic interactions to attract or repel pedestrians [13]. Imagine exits emitting a negative charge, drawing pedestrians toward them like magnets, while obstacles and walls emanate a positive charge, repelling individuals and encouraging them to seek alternative paths.
The Cost Potential Field Model takes a more economic approach, introducing the concept of "cost potential" [14]. Each cell is assigned a cost, representing the time, effort, or risk of moving to that location. Pedestrians, like rational agents seeking to minimize their expenses, then make movement decisions based on the cost potential of neighboring cells, balancing the desire to reach an exit with the need to avoid congestion, obstacles, and potential hazards.

These field-based models, each with its unique perspective and level of complexity, offer a rich toolbox for exploring the intricate tapestry of pedestrian evacuation dynamics. The choice of the most appropriate model depends on the specific scenario, the desired level of detail, and the research questions being investigated.

4. IMPLEMENTATION GUIDE FOR BASIC CELLULAR AUTOMATA MODELS

This section provides a practical, step-by-step guide to implementing basic CA models for pedestrian evacuation simulation. We'll delve into the essential considerations for each stage, from setting up the virtual environment to analyzing the simulation output, empowering you to build and execute your own CA-based simulations. While the focus is on general principles applicable across various models, remember that specific implementation details may differ depending on your chosen CA model, programming language, and simulation platform.

Step 1: Defining the Virtual Stage - Building the Evacuation Environment

The first step in creating a CA-based evacuation simulation is to meticulously construct a virtual representation of the physical space where the evacuation will unfold. This digital environment serves as the stage for your simulated crowd, dictating their movement possibilities and influencing their behavior.

- **Grid Creation:** Begin by dividing the evacuation space into a grid of cells, the fundamental building blocks of your CA model. Carefully consider the appropriate cell size, striking a balance between the desired level of detail and computational efficiency. Smaller cells offer a more precise representation of the environment but demand greater processing power. The typical choice is to let each cell represent the space occupied by a single person, approximately 40cm x 40cm [10].

- **Populating the Grid:** Transform your architectural plans into a digital reality by populating the grid with the essential elements of your chosen environment. Mark the cells representing walls, obstacles (furniture, columns, etc.), and other immovable features that will constrain pedestrian movement. Clearly define the boundaries of the space, preventing agents from venturing outside the designated area.

- **Exit Placement:** Carefully position the exits, the ultimate destinations for your simulated crowd. The number, size, and location of exits are crucial in shaping evacuation dynamics and influencing the overall evacuation time.

Step 2: Setting the Scene - Initializing the Crowd and Their Characteristics

With the virtual environment in place, it's time to populate it with your digital crowd. Each agent in your simulation represents a single individual, carrying a set of characteristics and behaviors that will shape their movement decisions.

- **Agent Placement:** Distribute agents within the grid, either randomly or based on specific initial conditions. For example, if you're simulating a lecture hall, you might position agents in rows to mimic a seated audience. For a train station, you might distribute agents more randomly to reflect the natural flow of people.

- **Assigning Initial States:** Define the starting conditions for each agent. This includes their location within the grid, desired direction of movement (often towards the nearest exit), initial speed (if your model allows for variable speeds), and any other relevant attributes. These attributes might include factors like their familiarity with the environment, propensity to panic, or tendency to follow others.

Step 3: Directing the Action - Defining the Rules of Movement

The heart of a CA model lies in its rules, the set of instructions that govern how agents move and interact within the environment. Simple yet powerful rules determine the emergent behavior of your simulated crowd, shaping the overall evacuation dynamics.

- **Movement Rules:** Define how agents select their next move. In the LGM, for example, the movement is determined by a drift probability towards the preferred direction and equal probabilities for other directions [11]. In the FFM, movement is governed by the combined influence of the static and dynamic floor fields [9].

- **Interaction Rules:** Define how agents interact with each other and the environment. These rules might include obstacle avoidance mechanisms, where agents adjust their direction to avoid collisions with walls, furniture, or other pedestrians. You might also incorporate rules for herding behavior, where agents tend to follow the movements of those around them, or rules for panic, where agents might deviate from optimal paths or increase their speed in response to perceived danger.

- **Exit Rules:** Determine how agents behave when they reach an exit. This might involve removing them from the simulation, adding them to a tally of successfully evacuated individuals, or triggering specific events, such as a decrease in overall panic levels or a change in the dynamic floor field.

Step 4: Executing the Simulation

With the environment, initial conditions, and rules in place, it's time to set your simulation in motion. This involves stepping through discrete units of time, updating the state of each agent based on the defined rules and the states of their neighboring cells.

- **Time Step Loop:** The core of your simulation is a loop that iterates through time steps. In each time step, the model evaluates the rules for each agent, determining their next actions based on their current state and their neighborhood.

- **State Updates:** The states of all agents are then updated simultaneously or sequentially. Simultaneous updates, where all agents move at the same time, can lead to conflicts if multiple agents attempt to occupy the same cell. These conflicts can be resolved by various mechanisms, such as randomly selecting a "winner" or introducing a friction parameter that represents the probability of no one moving [15]. Sequential updates, where agents are updated one by one in a predetermined or random order, can avoid conflicts but might introduce artifacts if the update order is not carefully chosen.

- **Data Collection:** Throughout the simulation, collect relevant data for analysis. This might include the number of evacuated agents at each time step, the total evacuation time, the density of agents in different areas, the flow rate through exits, and any other metrics relevant to your research questions.

Step 5: Analyzing the Performance - Interpreting the Simulation Output

The final stage of the implementation process involves analyzing the data generated by your simulation to draw conclusions and answer your research questions. This analysis often involves:

- **Visualization:** Create visual representations of the simulation results, such as animations of the evacuation process, density maps showcasing areas of congestion, or graphs plotting the number of evacuated agents over time. Visualizing the results can help you identify patterns, bottlenecks, and areas where the evacuation process could be improved.

- **Metric Calculation:** Calculate relevant metrics, such as the average evacuation time, the flow rate of agents through exits, the density of agents in different areas, and the frequency and severity of conflicts.

- **Interpretation:** Interpret the results in the context of your research questions, drawing conclusions about the effectiveness of different evacuation strategies, the impact of environmental factors, and the behavior of crowds under specific conditions.

By carefully following these steps, you can build and execute your own CA-based evacuation simulations, gaining valuable insights into the dynamics of crowd movement and contributing to the development of safer and more efficient evacuation plans.

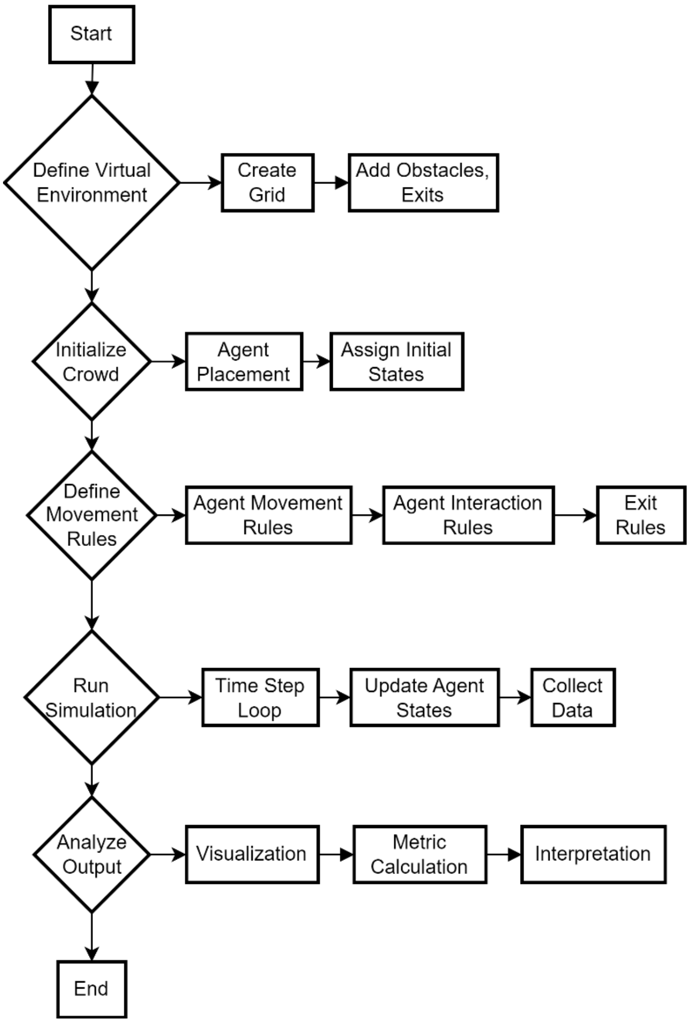

Figure 1: *Flowchart illustrating the steps involved in implementing a basic CA model for pedestrian evacuation simulation.*

5.DISCUSSION: HONING THE POWER OF CELLULAR AUTOMATA FOR EVACUATION SIMULATION

Cellular Automata (CA) models, with their elegant simplicity and remarkable ability to capture emergent behavior, have staked a significant claim in the field of pedestrian evacuation simulation. They offer a potent blend of computational efficiency and the capacity to simulate vast crowds navigating intricate environments, providing invaluable insights into the complex dance of human behavior under duress [9,10]. However, like any tool, CA models possess both strengths and limitations, shaping their applicability and guiding our pursuit of continuous improvement.

One of the most compelling advantages of CA models lies in their inherent computational efficiency. Unlike continuous models that demand computationally expensive calculations for each pair of interacting agents, CA models, with their discrete nature and local interaction rules, operate with a grace and speed that enables the simulation of large-scale evacuations with relatively modest processing power. This efficiency stems from the fact that the state of each cell can be updated independently, lending itself beautifully to parallel processing, where multiple calculations are performed concurrently, dramatically reducing simulation time.

Beyond their speed, CA models excel at capturing emergent behavior, a hallmark of complex systems where macroscopic patterns arise organically from the interactions of simple, local rules. Picture a murmuration of starlings, thousands of birds swirling in mesmerizing patterns, each reacting solely to its immediate neighbors, yet collectively creating a breathtaking aerial ballet. Or envision a school of fish moving in synchronized waves, individual actions giving rise to a mesmerizing collective flow. CA models, by mirroring this bottom-up approach, can effectively simulate the self-organization and unpredictable dynamics often observed in real-world crowds. Simple rules governing individual pedestrian movements can generate complex collective phenomena such as lane formation, bottlenecks, shockwaves, and even the counterintuitive "faster-is-slower" effect, where a crowd's eagerness to move quickly can paradoxically lead to a slower overall evacuation [16].

The flexibility and extensibility of CA models further enhance their allure. Researchers can readily tailor these models to mirror specific evacuation scenarios and address particular research questions. They can introduce new rules, modify existing ones, and seamlessly incorporate a diverse array of factors that influence pedestrian behavior. Obstacle avoidance can be implemented by adjusting movement probabilities based on the presence of walls and furniture, while varying walking speeds can be captured by allowing agents to traverse multiple cells within a single time step [17]. Herding behavior can be simulated by increasing the attractiveness of paths already trod by others, capturing the human instinct to follow the crowd [18]. Panic, with its potential to disrupt order and lead to less predictable movements, can be modeled by introducing randomness into the system or by allowing agents to deviate from otherwise optimal paths [16]. Even strategic decision-making, rooted in game-theoretic principles, can be integrated, allowing agents to evaluate different options and choose those that minimize their perceived risk or cost [19].

However, despite their undeniable strengths, it's crucial to acknowledge the inherent limitations of basic CA models. Their elegance lies in their simplicity, yet this simplicity can sometimes be a source of abstraction, potentially leading to a loss of realism in certain situations. The discrete representation of space and time, while computationally advantageous, can fail to capture the subtle nuances of pedestrian movement, such as the slight adjustments, hesitations, and intricate avoidance maneuvers that characterize real-world crowd dynamics [5].

Calibration and validation pose another significant challenge. Accurately tuning a CA model's parameters and rules to align with real-world evacuation data demands meticulous consideration and often involves making assumptions and simplifications. Obtaining reliable empirical data for validation, such as detailed recordings of pedestrian movements during actual evacuations, can be fraught with difficulties, incurring high costs and raising ethical considerations. This scarcity of robust validation data can limit the confidence we place in a model's predictions and hinder its ability to inform real-world decision-making [20].

Perhaps the most daunting limitation lies in capturing the full complexity of human behavior during evacuations. While CA models can incorporate simplified representations of herding, panic, and route choice, the intricate interplay of individual psychology, social influences, and environmental factors often eludes them. Individuals within a crowd are not homogeneous units; they possess diverse personalities, motivations, risk perceptions, and decision-making styles. Social ties, such as families or groups of friends evacuating together, can exert a powerful influence on movement patterns, as demonstrated in the work of Lu et al. [21]. Factors like stress, anxiety, and access to information can further complicate matters, leading to unpredictable behaviors that deviate from the simplified rules of basic CA models.
Fortunately, these limitations are not insurmountable barriers but rather stepping stones on the path toward continuous improvement. Several promising avenues exist for enhancing the realism, accuracy, and applicability of CA models for pedestrian evacuation.

- **Embracing the Power of Data:** Imagine CA models infused with a constant stream of real-world data from surveillance cameras, sensor networks, and even social media feeds [22,23]. This data can be used not only to calibrate model parameters and fine-tune behavioral rules but also to validate simulation outputs against actual observations, ensuring that our models reflect the complexities of real-world evacuations.

- **Building Bridges with Hybrid Models:** Combining the strengths of CA with other modeling techniques, such as agent-based modeling (ABM), can lead to more comprehensive and insightful simulations [24]. While CA excels at simulating crowd dynamics at a macroscopic level, ABM allows for the representation of individual agents with unique characteristics, behaviors, and decision-making processes. These hybrid models can capture both the emergent patterns of the crowd and the nuanced choices of individuals, providing a more holistic view of evacuation dynamics.

- **Integrating Behavioral Insights:** Drawing from the rich tapestry of psychology, cognitive science, and behavioral economics can inject a dose of human realism into CA models. Understanding how individuals perceive risk, process information under stress, make decisions in the face of uncertainty, and respond to social influences can lead to more accurate and nuanced simulations [25,26].

- **Expanding into Three Dimensions:** Moving beyond the constraints of two-dimensional representations, the development of three-dimensional CA models can unlock new possibilities for simulating evacuations from multi-level environments, such as high-rise buildings, stadiums, and underground spaces [27,28]. These models can capture the challenges of navigating stairs, ramps, and elevators, leading to more realistic representations of crowd movement and providing invaluable insights for architects, urban planners, and emergency responders.

Continually pursuing these advancements will equip us with increasingly powerful tools for understanding and mitigating the risks inherent in crowd evacuations. These models, in turn, will contribute to the design of safer buildings, the development of more effective evacuation plans, and ultimately, the creation of environments where people can face emergencies with greater confidence, preparedness, and resilience.

6.CONCLUSION: TOWARDS SAFER EVACUATIONS THROUGH THE POWER OF SIMULATION

This exploration of basic Cellular Automata (CA) models for pedestrian evacuation has revealed their remarkable ability to capture the intricate dynamics of crowds in motion, offering a valuable toolset for enhancing safety and preparedness in a wide range of scenarios. We began our journey by laying the groundwork, delving into the fundamental principles of CA and their unique suitability for simulating complex systems. From the grid-based representation of space and discrete time steps [7] to the elegant interplay between local rules and emergent behavior [8], CA models provide a compelling framework for unraveling the complexities of pedestrian evacuation.

We then turned our attention to specific models, each representing a distinct approach to capturing the essence of pedestrian movement and interactions. The Lattice Gas Model, with its simple drift probability, offered a foundational understanding of how individual agents navigate towards exits, while the Floor Field Model, with its sophisticated interplay of static and dynamic fields, significantly advanced the realism of CA-based simulations [9,10]. We explored other field-based models, such as the Potential Field Model [12], the Electrostatic-Induced Potential Field Model [13], and the Cost Potential Field Model [27], each providing a unique lens through which to understand the forces influencing pedestrian movement.

Our implementation guide equipped readers with a practical roadmap for building and executing their own CA-based simulations, outlining the essential steps involved in transforming architectural plans into a digital reality populated with simulated crowds. We emphasized the importance of thoughtful consideration when defining the virtual environment, initializing the crowd's characteristics, establishing behavioral rules, and analyzing the resulting data. The power of data-driven approaches, using real-world observations to calibrate and validate models, was highlighted as a crucial step towards ensuring the accuracy and reliability of simulation results [24].

While CA models offer significant advantages in terms of computational efficiency and their ability to capture emergent behavior, we acknowledge the ongoing challenges in representing the full nuance and complexity of human behavior during evacuations. The inherent abstraction of CA models, with their discrete representation of space and time, can sometimes lead to a loss of fidelity in capturing the subtle movements and interactions of pedestrians [5]. Accurately simulating the heterogeneity of individual responses, the influence of social dynamics (such as kinship behavior as explored in Yang et al., 2005), and the impact of psychological factors like stress and anxiety require continuous refinement and the integration of insights from diverse fields.

Looking ahead, the future of CA-based evacuation modeling is bright, propelled by the pursuit of greater realism, accuracy, and insight. The integration of data-driven approaches, fueled by increasingly sophisticated data sources and analysis techniques, promises to enhance both the calibration and validation of models. Developing hybrid models, blending the strengths of CA with other techniques like agent-based modeling, can lead to more comprehensive simulations that capture both the emergent patterns of the crowd and the nuanced decisions of individual agents [24,29]. Incorporating insights from behavioral science, psychology, and cognitive modeling can breathe life into our simulations, moving beyond simplistic representations of panic and herding towards a richer understanding of how individuals perceive risk, process information, and make decisions under pressure [25,26]. Finally, the development of three-dimensional CA models will allow us to simulate crowd movement within multi-level environments, providing a more realistic representation of evacuations from complex structures like high-rise buildings and stadiums [27,28].

The knowledge we gain from these simulations transcends academic curiosity, holding the potential to save lives and mitigate risks in the real world. By informing the design of safer buildings, optimizing the layout of public spaces, and enhancing the effectiveness of evacuation procedures, CA models empower us to anticipate potential hazards, evaluate various interventions, and ultimately, create environments where people can navigate emergencies with greater confidence and safety. As research in this field continues to advance, we can expect CA models to play an even more prominent role in shaping a safer and more resilient future.

REFERENCES

[1] A.Y. Topraklı, S. SEDIHEMAITI, G. Ağraz, Osmanlı klasik dönem tipi modern camilerin tahliye problemine ilişkin değerlendirme, Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi 34 (2019) 2261–2270. https://doi.org/10.17341/gazimmfd.490086.

[2] M.S. Satır, A.Y. Topraklı, Türkiye yangın yönetmeliğine göre toplanma amaçlı yapıların tahliye performansının simülasyon tabanlı analiz edilmesi, Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi 39 (2024) 2343–2352. https://doi.org/10.17341/gazimmfd.1281882.

[3] A.Y. Topraklı, M.S. Satır, Türkiye'deki 15. ve 16. yy. dönemi tarihi camilerinin tahliye sürelerinin analizi, Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi 39 (2024) 1953–1962. https://doi.org/10.17341/gazimmfd.1171323.

[4] M.S. SATIR, A.Y. TOPRAKLI, Ankara-Altındağ bölgesindeki 18 tarihi caminin yangın tahliye risklerinin nitel ve nicel analizi, Gazi Üniversitesi Mühendislik Mimarlık Fakültesi Dergisi 36 (2021) 1613–1630. https://doi.org/10.17341/gazimmfd.824520.

[5] N. Pelechano, A. Malkawi, Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches, Autom Constr 17 (2008) 377–385. https://doi.org/10.1016/j.autcon.2007.06.005.

[6] X. Zheng, T. Zhong, M. Liu, Modeling crowd evacuation of a building based on seven methodological approaches, Build Environ 44 (2009) 437–445. https://doi.org/10.1016/j.buildenv.2008.04.002.

[7] S. Wolfram, Statistical mechanics of cellular automata, Rev Mod Phys 55 (1983) 601–644. https://doi.org/10.1103/RevModPhys.55.601.

[8] B. Chopard, Cellular Automata Modeling of Physical Systems, in: Encyclopedia of Complexity and Systems Science, Springer New York, New York, NY, 2009: pp. 865–892. https://doi.org/10.1007/978-0-387-30440-3_57.

[9] A. Kirchner, A. Schadschneider, Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics, Physica A: Statistical Mechanics and Its Applications 312 (2002) 260–276. https://doi.org/10.1016/S0378-4371(02)00857-9.

[10] C. Burstedde, K. Klauck, A. Schadschneider, J. Zittartz, Simulation of pedestrian dynamics using a two-dimensional cellular automaton, Physica A: Statistical Mechanics and Its Applications 295 (2001) 507–525. https://doi.org/10.1016/S0378-4371(01)00141-8.

[11] M. Muramatsu, T. Irie, T. Nagatani, Jamming transition in pedestrian counter flow, Physica A: Statistical Mechanics and Its Applications 267 (1999) 487–498. https://doi.org/10.1016/S0378-4371(99)00018-7.

[12] R.-Y. Guo, H.-J. Huang, Route choice in pedestrian evacuation: formulated using a potential field, Journal of Statistical Mechanics: Theory and Experiment 2011 (2011) P04018. https://doi.org/10.1088/1742-5468/2011/04/P04018.

[13] I.G. Georgoudas, G. Koltsidas, G.Ch. Sirakoulis, I.Th. Andreadis, A Cellular Automaton Model for Crowd Evacuation and Its Auto-Defined Obstacle Avoidance Attribute, in: 2010: pp. 455–464. https://doi.org/10.1007/978-3-642-15979-4_48.

[14] P. Zhang, X.-Y. Li, H.-Y. Deng, Z.-Y. Lin, X.-N. Zhang, S.C. Wong, Potential field cellular automata model for overcrowded pedestrian flow, Transportmetrica A: Transport Science 16 (2020) 749–775. https://doi.org/10.1080/23249935.2020.1722283.

[15] A. Kirchner, K. Nishinari, A. Schadschneider, Friction effects and clogging in a cellular automaton model for pedestrian dynamics, Phys Rev E 67 (2003) 056122. https://doi.org/10.1103/PhysRevE.67.056122.

[16] D. Helbing, I. Farkas, T. Vicsek, Simulating dynamical features of escape panic, Nature 407 (2000) 487–490. https://doi.org/10.1038/35035023.

[17] W.G. Weng, L.L. Pan, S.F. Shen, H.Y. Yuan, Small-grid analysis of discrete model for evacuation from a hall, Physica A: Statistical Mechanics and Its Applications 374 (2007) 821–826. https://doi.org/10.1016/j.physa.2006.08.003.

[18] D. Helbing, F. Schweitzer, J. Keltsch, P. Molnár, Active walker model for the formation of human and animal trail systems, Phys Rev E 56 (1997) 2527–2539. https://doi.org/10.1103/PhysRevE.56.2527.

[19] X. Zheng, Y. Cheng, Conflict game in evacuation process: A study combining Cellular Automata model, Physica A: Statistical Mechanics and Its Applications 390 (2011) 1042–1050. https://doi.org/10.1016/j.physa.2010.12.007.

[20] R. Alizadeh, A dynamic cellular automaton model for evacuation process with obstacles, Saf Sci 49 (2011) 315–323. https://doi.org/10.1016/j.ssci.2010.09.006.

[21] L. Lu, C.-Y. Chan, J. Wang, W. Wang, A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model, Transp Res Part C Emerg Technol 81 (2017) 317–329. https://doi.org/10.1016/j.trc.2016.08.018.

[22] Y. Ji, W. Wang, M. Zheng, S. Chen, Real Time Building Evacuation Modeling with an Improved Cellular Automata Method and Corresponding IoT System Implementation, Buildings 12 (2022) 718. https://doi.org/10.3390/buildings12060718.

[23] P. Dang, J. Zhu, S. Pirasteh, W. Li, J. You, B. Xu, C. Liang, A chain navigation grid based on cellular automata for large-scale crowd evacuation in virtual reality, International Journal of Applied Earth Observation and Geoinformation 103 (2021) 102507. https://doi.org/10.1016/j.jag.2021.102507.

[24] Y. Li, M. Chen, Z. Dou, X. Zheng, Y. Cheng, A. Mebarki, A review of cellular automata models for crowd evacuation, Physica A: Statistical Mechanics and Its Applications 526 (2019) 120752. https://doi.org/10.1016/j.physa.2019.03.117.

[25] G.-N. Wang, T. Chen, J.-W. Chen, K. Deng, R.-D. Wang, Simulation of crowd dynamics in pedestrian evacuation concerning panic contagion: A cellular automaton approach, Chinese Physics B 31 (2022) 060402. https://doi.org/10.1088/1674-1056/ac4a66.

[26] Q. Xiao, J. Li, Evacuation Model of Emotional Contagion Crowd Based on Cellular Automata, Discrete Dyn Nat Soc 2021 (2021) 1–18. https://doi.org/10.1155/2021/5549188.

[27] L. You, C. Zhang, J. Hu, Z. Zhang, A three-dimensional cellular automata evacuation model with dynamic variation of the exit width, J Appl Phys 115 (2014). https://doi.org/10.1063/1.4883240.

[28] L. Wang, M. Liu, B. Meng, Incorporating topography in a cellular automata model to simulate residents evacuation in a mountain area in China, Physica A: Statistical Mechanics and Its Applications 392 (2013) 520–528. https://doi.org/10.1016/j.physa.2012.09.019.

[29] A. von Schantz, H. Ehtamo, Spatial game in cellular automaton evacuation model, Phys Rev E 92 (2015) 052805. https://doi.org/10.1103/PhysRevE.92.052805.

APPENDIX A: SOFTWARE TOOLS FOR CA-BASED EVACUATION MODELING

This appendix provides a curated list of software tools and libraries commonly used for developing and executing CA-based pedestrian evacuation simulations. The list includes both commercial and open-source options, along with brief descriptions of their key features and capabilities.

Commercial Software:

- **FDS+Evac:** Developed by the National Institute of Standards and Technology (NIST), FDS+Evac is a widely used tool for fire and evacuation modeling. It combines a computational fluid dynamics (CFD) model for fire simulation with a CA-based approach for pedestrian evacuation. It allows for detailed analysis of smoke spread, fire development, and pedestrian movement during fire emergencies. https://github.com/firemodels/fds
- **MassMotion:** A sophisticated 3D simulation software developed by Oasys, MassMotion is designed for analyzing pedestrian movement and crowd behavior in various built environments. It uses a combination of CA and agent-based modeling techniques to simulate complex scenarios, optimize pedestrian flow, and assess safety measures. https://www.oasys.com/software/engineering/pedestrian-modelling/
- **Pathfinder:** Developed by Thunderhead Engineering, Pathfinder is another powerful tool for simulating pedestrian movement and evacuation. It utilizes a continuous-space model that allows for more realistic pedestrian interactions and movement compared to traditional grid-based CA models. It's particularly well-suited for analyzing complex geometries and high-density crowds. https://www.thunderheadeng.com/pathfinder/

Open-Source Software and Libraries:

- **NetLogo:** A popular agent-based modeling environment, NetLogo also provides support for CA modeling. Its user-friendly interface and extensive library of pre-built models make it a great option for both beginners and experienced modelers. https://ccl.northwestern.edu/netlogo/
- **Repast Simphony:** A Java-based ABM toolkit, Repast Simphony also offers support for CA modeling. Its flexible architecture and extensive documentation make it a powerful tool for researchers and developers working on complex simulations. https://repast.github.io/
- **Python Libraries:** Python, a versatile programming language widely used in scientific computing, offers several libraries for CA modeling:
  - **NumPy:** A fundamental library for numerical computing in Python, NumPy provides efficient array operations that can be used to implement CA models.
  - **SciPy:** Building upon NumPy, SciPy offers a collection of algorithms and functions for scientific computing, including image processing tools that can be useful for visualizing CA simulations.
  - **Mesa:** A Python framework specifically designed for agent-based modeling, Mesa also supports CA modeling and provides a structured approach to building and running simulations.

This list provides a starting point for exploring the diverse landscape of software tools available for CA-based evacuation modeling. The choice of the most appropriate tool depends on several factors, including the specific requirements of the simulation, the user's experience level with different programming languages and modeling environments, and budget constraints.