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ORIGINAL RESEARCH PAPERS

Pedestrian Simulation in Transit Stations Using Agent-Based Analysis

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Abstract The research discusses experiential outcome in the application of crowd simulation technology to analyze the pedestrian circulation in public spaces to facilitate design and planning decisions. The paper describes how to connect spatial design with agent-based simulation (ABS) for various design and planning scenarios. It describes the process of visualizing and representing pedestrian movement, as well as pathfinding and crowd behavior study. An ABS consists of a large number of agents, which are controlled by simple localized rules to interact with each other within a virtual environment, thereby formulating a bottom-up system. The concept of the ABS has been widely used in computer science, biology, and social science to simulate swarm intelligence, dynamic social behavior, and fire evacuation. The simulation consists of interacting agents which can create various complexities. This paper describes research on using local interactions to generate passenger flow analysis. An ABS is used to optimize the pedestrian flow and construct the micro-level complexity within a simulated environment. We focus on how agent-driven emergent patterns can evolve during the simulation in response to various design iterations. The research extends to the agents' interactions driven by a set of rules and external environment. Our research method includes data collection, quantitative analysis, and crowd simulation on two train stations and surrounding areas in Sihui train station in Beijing, and Xuzhou, China. By proposing a mix-use program with the local public transportation system, the new development is integrated with the existing urban infrastructure and public space. Through the multi-agent simulation, we evaluate the crowd flow, total travel time, density, and public accessibility. Based on the result of ABS, we discussed whether various space design methods can improve pedestrian flow efficiency and passenger experience, as well as shortening transfer time, and reducing congestion.

Keywords Agent-based simulation · Pedestrian flow analysis · Self-organizing

1 Introduction

There were many computational methods applied to simulate agents involving movement, including "the simple statistical regression, spatial interaction theory, accessibility approach, space syntax approach and fluid flow analysis" [1]. Michael Batty described the property of "Autonomy" and "the embedding of the agent into the environment" as two key properties of agents in an agent-based system (ABS). An ABS consists of numerous agents, which follow localized rules to interact with a simulated environment, thereby formulating a bottom-up system. Since Craig Reynolds' artificial "bodies" and flock simulation, the concept of ABS has been widely used to study decentralized systems that include human social interaction. In urban modeling, agents can be defined as autonomous "physical or social" entities or objects that act independently of one another [1]. ABS focuses on agents' properties and processes, responsible for responding to

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external changes, specifically how agents can “sense” and “act” to form a complex system. The movements are usually based on simple rules such as separation, alignment, and cohesion. Computer scripts can be used to control agent’s velocity, maximum force, range of vision, and other properties.

In the early research phase, we compared the bottom-up ABS with cellular automation (CA) methods, as well as space syntax, to examine agents’ generation, spatial properties, and interaction with the environment.

1.1 Comparing ABS with Cellular Automation

Cellular automation (CA) calculates cells’ changing state through time, based on the state of neighboring cells and context. As two famous bottom-up systems, both CA and ABS compute the status of a changing object over time. However, it is important to understand the distinction between cells and agents. Batty describes agent as “mobile cells, which—objects or events that located with respect to cells but can move between cells” [1]. However, the behaviors of CA are often unpredictable and lack purposive planning goals. It is difficult to use CA to add rules and other “purposive goals” to the system beyond context awareness. Similar to Betty’s global attraction surface in his study on the agent’s movement, we need a system to introduce external force rules to influence the agents’ behavior.

1.2 Comparing ABS with Space Syntax

Space syntax is another method to study movement pattern and accessibility of a network based on lines, nodes, and connections. With its own “agent analysis” tool, space syntax does not actually measure the interactions among agents, but provides fast feedback between geometric elements and their accessibility value within a grid of cells.

We studied space syntax as a reference tool for ABS. Through importing the College of Design Architecture Art and Planning (DAAP) building floor plan into space syntax analysis tool, we produced heat map to represent accessibility and spatial integration. Warmer colors represent higher spatial integration values. We computed the integration value of each cell by using the analysis tools in space syntax and visualized the values with colors. The qualitative values extracted from the space syntax analysis are imported into Grasshopper for further computing. In order to convert the space syntax results into a heat map representation, we created a data processing method to expand the color values automatically from paths to zones. It became obvious that even though space syntax provided a fast way to visualize interactions between agents and environment, however it cannot simulate the interactions among agents such as complex social behavior.

We also researched several other commercial agent-based tools in the entertainment industry. Mass animation tool has been widely used to simulate the behavior of crowds, where the agents’ movements are computed based on the interaction among themselves, as well as the interaction with the environment. We explored A* pathfinding an algorithm used to create the cognitive agents, which can populate a spatial model and navigate through a “cell”-based map. Different from the “reactive” agent in Reynolds’ flock simulation, these cognitive agents have their artificial intelligence (AI). The agents have the ability to respond to the changing environment and other agents’ movement in real time and adjust their behavioral parameters. The AI agents can make decisions while evaluating the results generated in a real-time environment.

These tools and methods allowed us to understand the autonomous, bottom-up ABS approach and compare the effectiveness of various agent-related computations (Fig. 1).

2 ABS for Crowd Simulation

ABS allows a complex movement pattern to emerge from the simple interaction among agents. Each agent can sense its neighbors and react to them by modifying its location, velocity, shape, or other attributes. ABS for crowd behavior simulation is established in the same relational model and computational strategy from the early physiological field. Some of the emerging methods in the crowd simulation involve utilizing ABS to generate realistic crowd dynamics that respond to crowd’s visibility in the environment, and even to social factors. All of these simulation methods modeled the interaction of agents, despite model the path directly. In another word, we can understand the dynamics of crowd movement better by not modeling them at the global level but instead through simulating the local interactions among these components and automatically constructing the movement patterns at the relational level (Fig. 2).

2.1 Path Visualization

Our visualization process began with a CSV text-based spreadsheet, which was constructed based on the simulated movement of agents over a period of time. Through Grasshopper script and Autodesk Maya software, points were created to present the spatial location of agents, and form a continuous path in real time. This approach visualized the bottom-up interaction of individual agents to respond to other agents within the system. First, the *X*, *Y*,

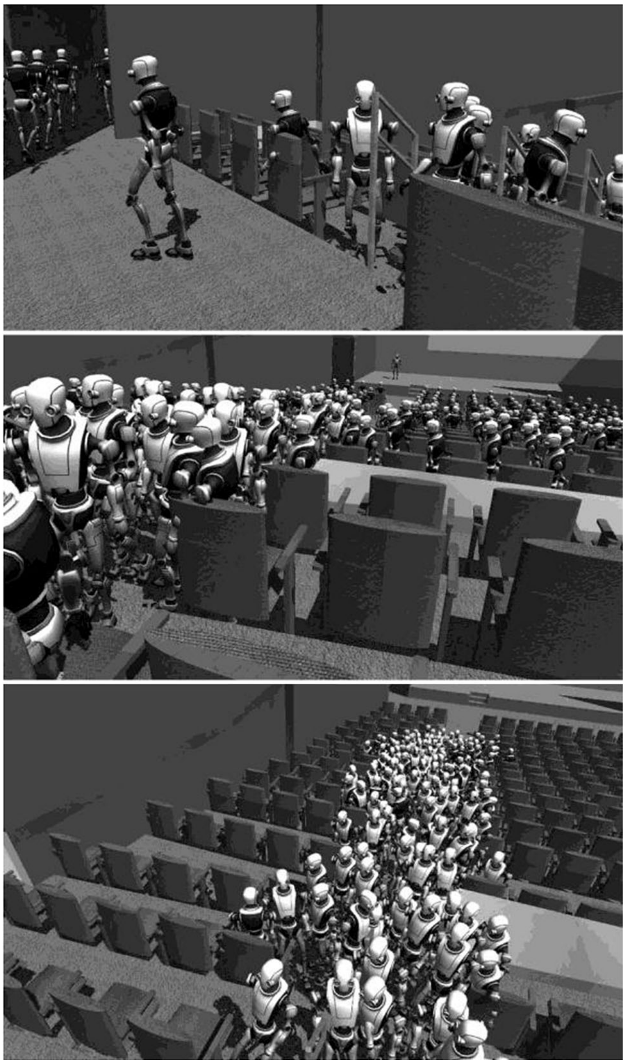


Fig. 1 Evacuation simulation and crowd behavior study. AI-controlled avatars evacuate from lecture hall in DAAP building. University of Cincinnati (UC). By Laura Kennedy, University of Cincinnati

Fig. 2 A large number of agents are boarding in simulated Beijing subway station. Agents interact with each other and the arriving train. By Ming Tang

Z values of each point were woven into a time line. Once the respective movement was reconstructed, the paths connecting those points formed overplayed curves. The color map representing the agent density was used to study possible evacuation routes, safety issues, and pathfinding. We generated various charts to visualize the interaction between neighboring agents, based on their proximity, attraction, and collision. The virtual environment is formed by a series of static collision objects, including interior walls and nondestructive furniture. As a reactive agent, every agent along a path is analyzed in its relationship to other agents within the system. We optimized the movement paths through a computer simulation based on the proximity and interaction of agents (Fig. 3).

With ABS, the autonomous "action" of each agent lies within modifying its movement based on the repulsion or attraction to neighboring agents, as well as the environment itself. Over a period, a crowd behavior is automatically formed as agents stop and remain equilibrium.

3 Urban Design Projects with Agent-based Simulation

3.1 Pengcheng Square, Xuzhou, China

Pengcheng Square is a proposed urban design project in Xuzhou, China. Designed by Beijing Jiaotong University, the goal is to create a mixed-use urban cluster, which includes residential, commercial, cultural, and public spaces. The existing subway system is integrated with the

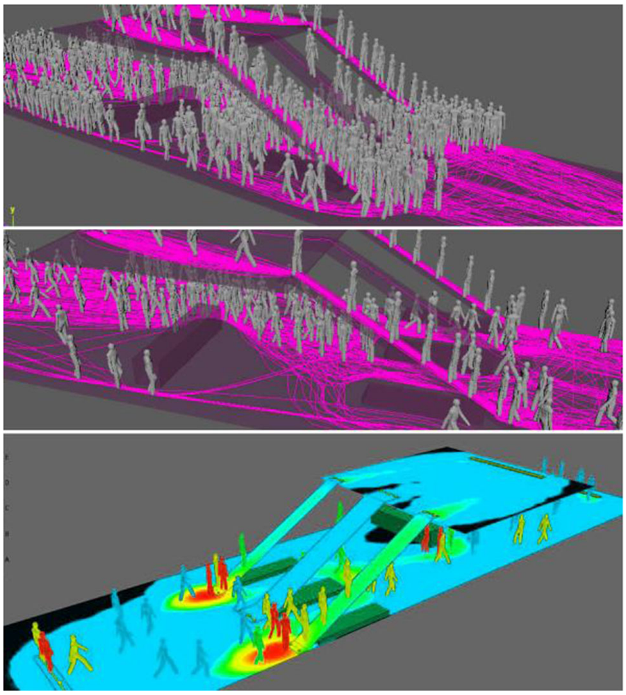


Fig. 3 Path visualization with curve and heat map. By Ming Tang

new proposed program to form a new urban center. Researchers from the University of Cincinnati and Beijing Jiaotong University collected the existing and projected pedestrian flow, in order to generate various scenarios for crowd simulation. A complex crowd movement pattern emerged based on the microscale interactions among agents. Multiple paths and crowd movement automatically adopted a set of rules based on both bottom-up movements, as well as the top-down planning methods.

In Xuzhou project, we defined the estimated agent number based on the peak hours and grouped agents based on the different activates such as entering the train station, leaving the train station, and transferring between gates. We also added a pedestrian group for shopping. Once these groups are assigned with start points and destinations, the ABS generates crowd interactions over time. The self-organizing pattern of the movement emerged based on the connection between circulation space and its proximity to the existing subway entrances. The spatial organization of public space, as well as the proposed pathways for pedestrian flow, was simulated and evaluated by ABS (Fig. 4). The agent speed and regional density data are exported as spreadsheets and presented as various graphs to allow planners to compare the different scenarios quantitatively. The agents are also color-coded to represent various pedestrian groups with the different entrances and departure routes. The simulation is exported as animations to allow designers and planes to compare the design iterations qualitatively.

3.2 Sihui Train Station, Beijing, China

The research on the Sihui train station is focused on its connection to the public space and potential spaces for parking and retail. In Beijing Sihui Station project, there are several site issues have been studied. For instance, the ground parking is too close to the station entrance. Some temporary buildings are blocking the direct views of the entrance. We initiated agent number by directly counting the crowd during peak hours and use it as the base to construct the ABS. We collected daily passenger transport data through ticketing system and in comparison with the onsite observations. We also estimated the future passenger growth after the new urban development in Beijing–Tianjin–Hebei Metropolitan Region. Through the multi-agent simulation, we evaluated the crowd flow, total travel time, density, and public accessibility in different scenarios such as peak hours, in order to predict the future flow in the next few years. Based on the results of ABS, we analyzed whether various parking strategies can improve the pedestrian flow efficiency and passenger experience, as well as shortening transfer time, and reducing congestion. We used the results of ABS to suggest the possible areas for retail development without affecting the pedestrian movement (Fig. 5).

When designing a public space outside a subway station, designers usually give priority to the issues of passengers' flow during peak hours. However, besides this basic function, designers should also consider public space to facilitate other urban functions. For example, users' all three levels of physiological, psychological, and emotional needs should be considered in the planning stage. In many Chinese cities, the scale of public space outside the subway station is large and often appears to be empty. As a consequence, the walking distances are long, and the environment quality is poor. Other problems include lacking service facilities, lacking public gathering places, and eventually lacking spatial identity.

Conventionally, the public space should be organized based on its purpose. It should serve for pedestrian flow, vehicular traffic, as well as spontaneous and social activities. However, in the planning process, it is often possible that planners cannot clearly define the needs of different functions. Sometimes environment usage deviates from the designer's original plan [2]. This is known as the concept of "adapted use." For example, in the Sihui station, there are unplanned car parking lots on both sides of the public space, which should be defined as the adapted use. We

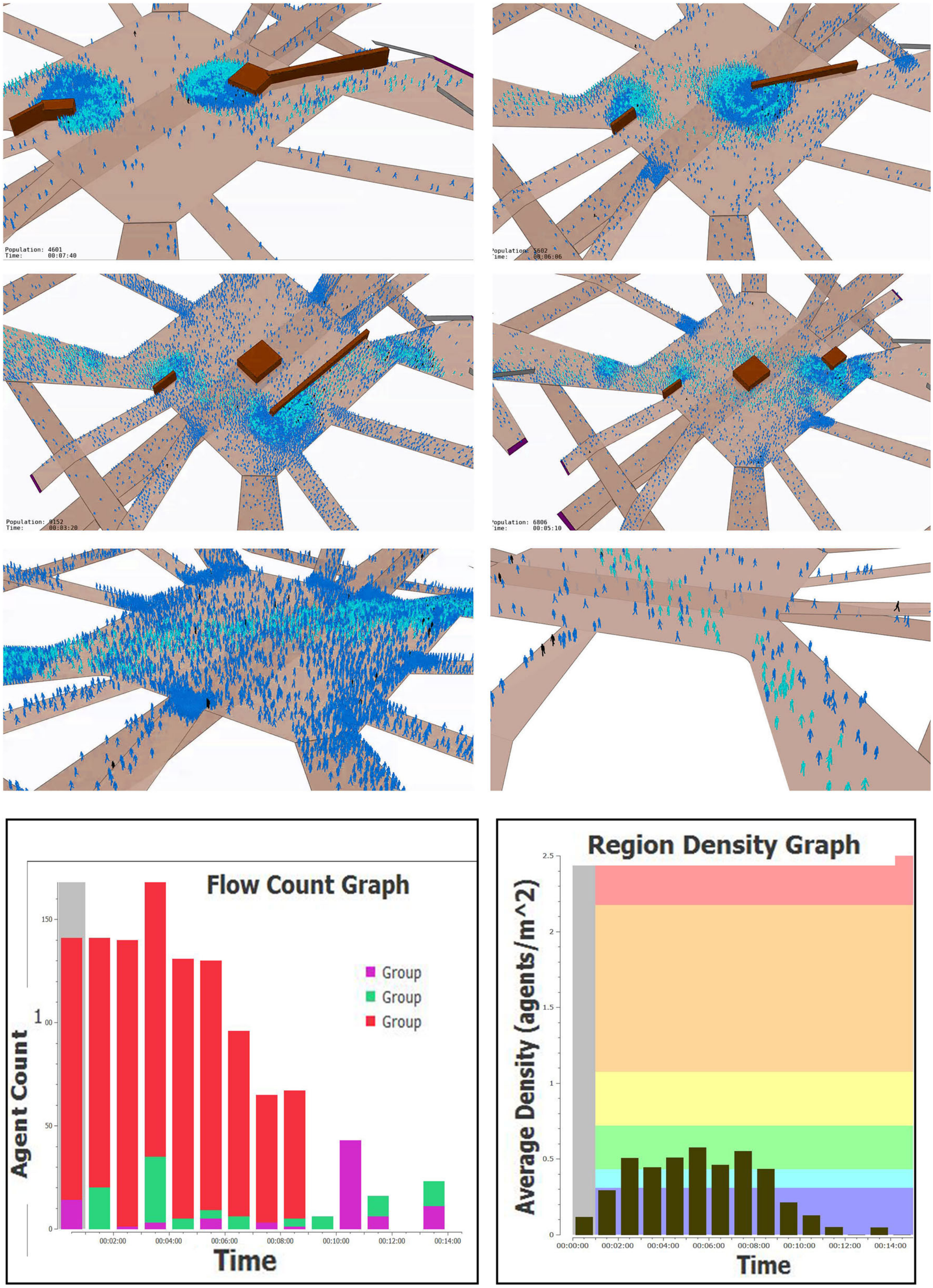
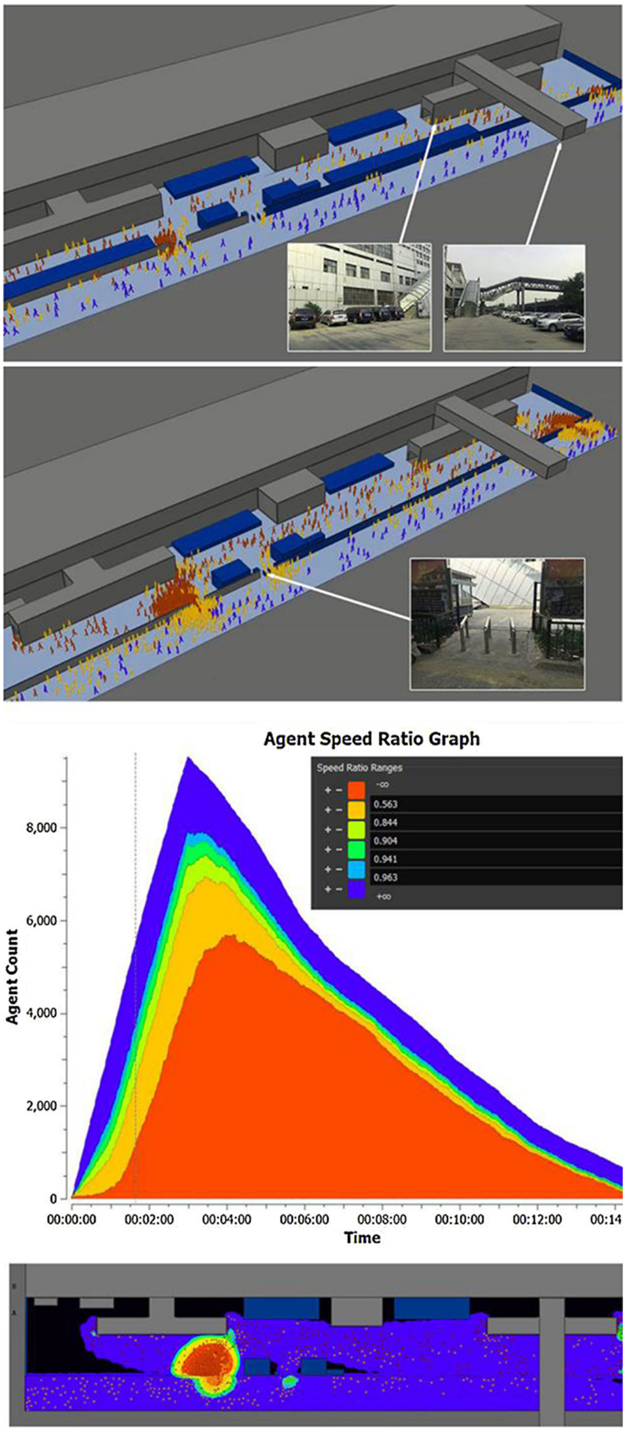


Fig. 4 Adaptive urban model, Xuzhou, China. Multiple design iterations were simulated with projected pedestrian flow. *Top* The agent with *dark blue* and *light blue* represents two route groups of pedestrian flow and their interaction in the proposed central square. The designers simulated four spatial layouts with different partition walls. The crowd aggregation patterns are studied against a time line. *Bottom* The central square is defined as the focus region to measure the agent density change over time. The "flow count graph" and the "region density graph" were created



◀**Fig. 5** *Top* Data collection from ticketing system. *Middle* Peak hours crowd simulation. 100 people/min. *Middle* The number of the agent with low moving speed is represented as a *red color graph*. The value increases due to the congestion in the certain area. The value eventually drops down once the congestion is dissolved. By studying the curve graph over the time line, designers and planners can understand the length and scale of a congestion and its impact on the crowd movement. *Bottom* Peak hours crowd simulation. 300 people/min. ABS shows that congestion areas of A/B exit square are mainly in three places located on the exit of the fence. Simulation results show that most *blue* and *black* area can be used for parking, business, leisure, and other functions. These areas can be used to accommodate more diverse urban functions. The agent speed analysis is used to compare the performance of various exits

borrowed the concept of “adapted use” and “bucketed space” to discuss the human behavior based on time and space. By ABS, we analyzed different pedestrian behaviors under various conditions. First, we revealed the circulation needs in different periods of time based on humane design. Second, we analyzed how to meet different pedestrian behaviors in time and space distribution. Third, we explored several ways to improve the efficiency and comprehensive use of the public space outside the train station.

4 Conclusion

The research compared several crowd simulation systems such as agent-based simulation, Cellular Automation, Space Syntax and investigated how to integrate ABS into design phase in two urban design projects. Different from the traditional top-down planning method, this crowd simulation method relies on the emergent properties and local interactions among agents. Within the process of ABS, design can be improved by observing the interaction between simulated crowd and the surrounding environment. Designers can observe agents’ changing behavior by proposing different spatial features. The crowd simulation could produce measurable improvement in the design. The ABS can predict certain “bottleneck” areas with potential congestion issues near train station entrances. Together with traditional humanistic evaluation and ABS, a new relationship of designer and design agent has been forged.

In the two urban design projects in China, we applied ABS for crowd analysis. The benefit is evident for analyzing alternative design scenarios. The result of simulation was used to suggest the pedestrian paths, as well as comparing different spatial organization of building programs. ABS can provide an invaluable analysis through simulating clearly defined rationales, such as choose the shortest route between spatial points, choose the less congested route by evaluating “cost” of each route, and select between elevator, escalator, and stairs by comparing the waiting time. However, these rationales will be easily overridden by the unpredicted crowd behaviors during the emergency evacuation such as panic, preferring the previous entrance as the emergency exit, and following a crowd. These uncertainty and complex variables make the ABS became subjective and lost the quantitate strength. In another word, an agent's behavior would not be "realistic" enough for the emergency exits and fire evacuation analysis due to the lacking of complex social behaviors. Because the ABS is generated as a highly abstract in the micro-level, designers should consider to combine ABS with other empirical methods, and building codes to construct a realistic crowd movement model for the panic and extreme conditions. To study these extreme scenarios with complex behaviors, the research team is investigating virtual reality method using real human subjects to replace the ABS method.

5 Future Research

We are currently investigating crowd behavior using immersive virtual reality and augmented reality technology. The goal is to create an immersive virtual environment which allows a real person to react to different environmental conditions and behaviors of artificial agents, and test various design theories in both micro- and macro-levels. We are adapting various processes learned from previous ABS methods. Oculus Rift and HoloLens devices will be applied to the study of crowd behavior, to ultimately facilitate and enhance design decisions such as spatial organization. We are modeling various human–computer inferences to test the influence of smoke, fire, signage, lighting, and architectural features for egress. In an ideal situation, these immersive experiences should be integrated with ABS and serve as a feedback loop for crowd simulation.

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