Social Distancing and Behavior Modeling with Agent-Based Simulation

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Abstract. The research discusses applying agent-based simulation (ABS) technology to analyze the social distancing in public space during the COVID-19 pandemic to facilitate design and planning decisions. The ABS is used to simulate pedestrian flow and construct the micro-level complexity within a simulated environment. This paper describes the various computational methods related to the ABS and design space under the new social distancing guidelines. We focus on the linear phases of agent activities, including (1) environmental query, (2) waiting in a zone, (3) waiting in a queue, and (4) tasks (E-Z-Q-T) in response to design iterations related to crowd control and safety distance. The design project is extended to the agents' interactions driven by a set of tasks in a simulated grocery store, restaurant, and public restroom. We applied a quantitative analysis method and proximity analysis to evaluate architectural layouts and crowd control strategies. We discussed social distancing, pedestrian flow efficiency, public accessibility, and ways of reducing congestion through the intervention of the E-Z-Q-T phases.

Keywords: Agent-based simulation · Social distancing · Crowd control

1 Introduction ABS for Crowd Behavior Simulation

An Agent-based simulation (ABS) consists of multiple agents controlled by rules to interact with each other within a virtual environment, thereby formulating a bottom-up system. The ABS concept 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 who can create various complexity. Agents can be defined as autonomous "physical or social" entities or objects that act independently of one another. An ABS consists of numerous agents, which follow localized rules to interact with a simulated environment, thereby formulating a dynamic system. Since Craig Reynolds' artificial "bodies" and flock simulation, the ABS concept has been widely used to study de-centralized systems, including human social interaction.

Many computational methods were applied to simulate agents involving movement, including "*the simple statistical regression, spatial interaction theory, accessibility approach, space syntax approach and fluid-flow analysis*" (Batty [1]). Michael Batty described the property of "*autonomy*" and "*the embedding of the agent into the*

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environment" as the two fundamental properties of agents in an ABS. ABS focuses on the agent's properties and processes to respond to external changes, specifically how the 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 an agent's velocity, maximum force, range of vision, and other properties. Many research projects have been done to examine how agents "sense" the landscape and "walk" through it, such as studying train station crowd control (Tang [2]), building-occupant relations with discrete-event trigger (Schaumann [3]), dynamic coupling for flood evacuation simulation (Shirvani et al. [4]), and Clayton and Yan's panic evacuation simulation (Clayton, Yan [5]). Several scholars have discussed the research related to context awareness of the multi-agent system to assist space planning. (Gerber [6], Buš [7], Hua [8], Aschwanden[9] and Keifer [10].)

The ABS for pedestrian simulation can be traced back to the "level of services" by John Fruin in the 1960s and later the "social forces model" in the 1990s by Dirk Helbing and Peter Molnar. (Oasys [11]) The ABS approach has a significant advantage in crowd behavior simulation compared with other computation methods such as cellular automation and space syntax[1]. (Tang [2]) An agent can make decisions while evaluating the result generated in a real-time environment in an autonomous, bottom-up ABS approach. 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 and computational strategies from the early physiological field. Some of the emerging methods in the crowd simulation involve utilizing AI to generate realistic crowd dynamics that respond to the crowd's perception of the surroundings, pre-programmed tasks, and goals. Unlike the "reactive" agent in Reynolds' flock simulation [12], these "cognitive agents" sometimes act as the non-player controlled characters (NPC) found in video games, which have their own decision trees. As a result, the agents can respond to the various "social distancing rules" and other agents' movement in real-time and adjust their behavioral parameters.

2 Methodology to Simulate Social Distancing in ABS

We applied the ABS in research titled "Return to the Third Places: Architectural intervention at the Price Hill, Cincinnati during the COVID-19," which focuses on the strategies responding to the design challenges of the social distancing of public space. "Third place" is a term coined by sociologist Ray Oldenburg and refers to places where people spend time between home ('first' place) and work ('second' place). They are locations where people exchange ideas, have a good time, and build relationships. These places can be described as "a community's living room", and provide social association, community identity, and civic engagement[2]. Social distancing with a minimum of six feet

[1] "The simulated behaviors of cellular automation are often unpredictable and lack purposive planning goals….and the interactions among agents, complex social behavior cannot be simulated through space syntax." (Tang, 2018).

[2] These semipublic, semiprivate places such as restaurants, bars, gyms, houses of worship, barbershops, coffee shops, post offices, main streets, beer gardens, bookstores, parks, community centers, and gift shops—inexpensive places where people come together, and life happens.

(two meters) during the COVID-19 pandemic implies many challenges of everyday life in work and home, particularly to the "third places." The research examined several existing "third places" at Price Hill, Cincinnati, and evaluated architectural solutions to create resilient places allowing social distancing during the COVID-19 pandemic. Specifically, the research investigated the (1) Proposal for design and renovation of a grocery store, restaurant, and restroom to maintain social distancing and crowd control during COVID-19, with the addition of (2) creating an ABS allowing the proposed design to be evaluated under various occupancy and program scenarios.

We started this project by researching existing design strategies responding to the COVID-19 pandemic. We found that many people are looking for environmental stimulus to help them maintain their social distancing. Some apparent solutions currently being used are markers installed on the ground, plastic shield installed in the checkout line, and outdoor waiting areas. Some generative design strategies were available for automatically creating furniture layout with social distancing. While these all help architects propose a spatial layout, they do not completely guarantee effective use of space while maintaining safety. With that in mind, we start to model our ABS to simulate people's movement through space with particular goals, including checking in a restaurant, checking out a grocery store, and using a restroom. These procedurals are simulated into four phases: start with environment query, walk into a waiting area, walk into a waiting queue, and finally fulfill specific tasks such as taking an order, eating, checkout, or using a toilet. ABS became an essential tool to evaluate whether the proposed design would impact safety and social distancing during these activities (Fig. 1).

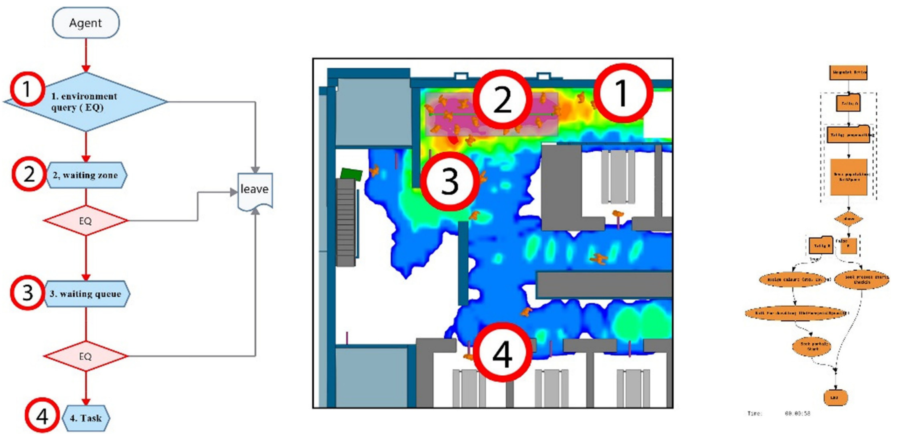

Fig. 1. Left and middle. The four phases in a sequence. 1. Environment query. 2. Waiting zone, colored based on agent proximity. 3. Waiting queue. 4. Task. Right: decision tree of an agent. The dynamics of crowd movement are not modeled at the global level but instead simulate the local interactions among the decision trees, events, and tasks.

2.1 Environmental Query

Based on the commercial ABS software called Oasys Massmotion[3], our research team applied behavior trees and the environmental query system (EQ) concept, a standard method for building NPCs in game design (Epic Game [13]). A behavior tree asset can be used to execute branches containing logic and serves as the "brain" for an agent. An AI Perception System provides a way for an NPC to receive data from the environment. The data includes where noises are coming from or if the NPC sees something. This is accomplished with the agent's Perception Component acting as a stimuli listener and gathering registered stimuli sources. Then, the behavior trees can be used to make decisions on which logic to execute.

In this process, the EQ is used to retrieve information about the environment. EQ is primarily made up of locations or Agents and the surrounding environment. EQ can instruct NPC characters to find the best possible place to provide a line of sight to a player to attack, the nearest health or ammo pickup, or the closest cover point in a computer game. In the context of crowd behavior related to environmental awareness, we collect data from EQ on the subsequent three phases (Z-Q-T), such as the current population density in the waiting area, the number of agents in the checkout line, or the dining table or toilet occupancy. The EQ gathers data as universal knowledge rather than an individual agent's sensory experience. For instance, once the agent enters the restroom, its perception system will automatically be given the number of people waiting in line from EQ. This intelligence is not based on an individual agent's vision or hearing, but universal knowledge gathered from a global EQ.

2.2 Waiting Zone and Waiting Queue

The environment in ABS is composed of various objects, including the static floor, stairs, ramp, and wall, which can be computed as a navigation mesh. The virtual environment is formed by importing a BIM model, including interior walls, stairs, and furniture. It also includes "smart geometries" such as gates, elevators, vehicles, portals, and servers, which can form impact circulations and the agent's behavior. The smart geometries are used to trigger certain events or set capacities and goals for the agents.

Among those environment objects, waiting zone and waiting queue are two essential elements dictating an agent's movement based on the predefined rules. Because of the social distancing rule, 2 m is defined as the minimum personal space, which dictates the number of people allowed waiting in a line and how many agents can be allowed to enter the waiting area. In the context of a goal-oriented movement, the agent will use an EQ to evaluate how many agents already in the waiting zone against a specific threshold value. If the zone is too crowded, the agent will choose not to enter the zone and leave the building. The same rule will apply when the agent moves from the waiting zone to the waiting queue. The following diagram highlighted the four phases (E-Z-Q-T) in the

[3] Oasys MassMotion is an advanced crowd simulation software that uses crowd modelling technology to provide leading technology to designers, operators and owners with clear information about crowding, usage patterns and occupant safety in a facility. https://www.oasys-software.com/products/pedestrian-simulation/massmotion/.

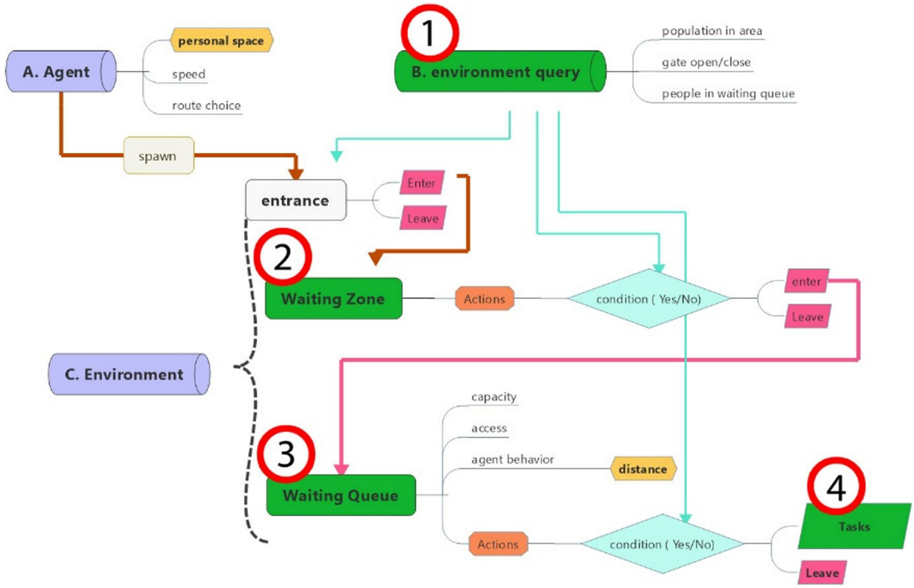

Fig. 2. Agent, environment, and environmental query system overlay with four phases. E-Z-Q-T as 1-2-3-4.

ABS. The system includes Agent profile (A), Environment (B), and the Environment query (C). (Fig. 2).

The real-time status of the waiting zone and waiting queue can be captured and broadcasted to the agent at a certain distance so it will be aware of the situation when it gets close. When the simulation is cached, a baked proximity map is also generated to indicate the number of agents close together in an area within a specific time.

The color map representing the agent proximity is used to study the social distancing and its impact on crowd behavior. We used various EQ metrics to update the agent's decision tree based on their proximity, density, and clocked time to complete specific tasks. As an independent entity, every agent in the environment constantly analyzed its proximity to other agents within the waiting zone and queue and made its own decisions. (Fig. 3 and 4).

2.3 Tasks

Besides enlarging waiting areas to help with the capacity limitations due to social distancing, we also evaluated strategies to reduce the time an agent took to complete the specific task. For instance, some stores use a Scan & Go Mobile service that allows customers to scan and pay for groceries on their smartphones to reduce the checkout time. Some stores such as Kroger provided customers self-scan shopping carts to eliminate the human cashier service. After simulating these two scenarios (regular checkout vs. smart scan without checkout), we concluded that Scan & Go Mobile service would reduce space needed near the checkout area and minimize the queue line in the store. We compared the current and projected customer flow and generated several scenarios

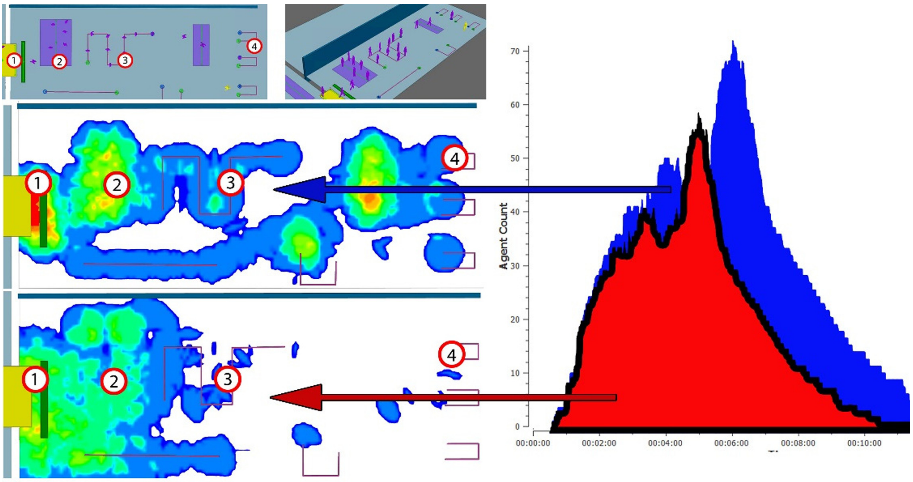

Fig. 3. Agent density and space proximity map. E-Z-Q-T as 1-2-3-4. ABS without social distancing vs. with social distancing rules. Each agent's autonomous "action" lies in modifying its movement based on its rules and environment. Top. Floor plan and interior perspective of a check-in area of a restaurant. Middle: proximity map without social distancing. Bottom: proximity map with 2-m social distancing with the same number of agents in the same given time. Notice the hot waiting areas' issues are replaced with a larger waiting area, while some agents choose not to walk in the restaurant after EQ. Right. Compare the number of occupancies. Red: agents with social distancing. Blue: agents without social distancing. (Color figure online)

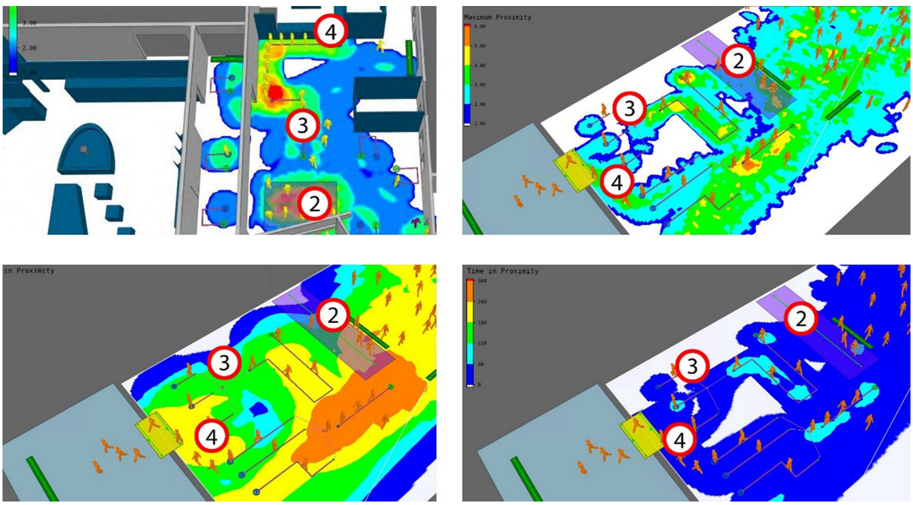

Fig. 4. The shape of queue lines, such as straight lines, L-shape lines, or U-shape lines, impacts the agent's proximity. Bottom left: the amount of time within five meters proximity. Bottom Right: the amount of time within two meters proximity. Notice all agent has less than 60 s within social distance. (blue color). E-Z-Q-T as 1-2-3-4. (Color figure online)

for crowd simulation. (Fig. 5) A fluent crowd movement pattern emerged based on the faster checkout time and fewer micro-scale interactions among agents. The impact of a speedier task on the spatial layout can be evaluated and presented through heatmaps and quantitative datasets.

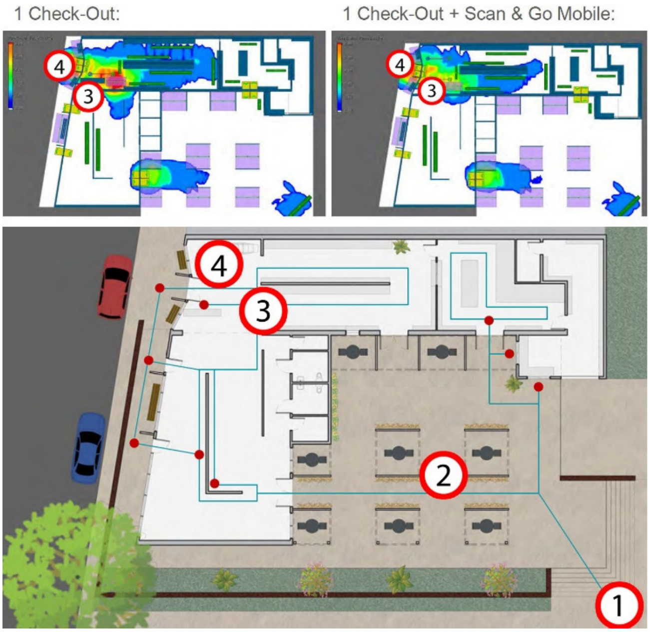

Fig. 5. Grocery store renovation. To address capacity limitations during COVID-19, we created an outdoor waiting space for the customers to sit. The waiting area includes separated personal space, each with a pergola and seating. Customers may choose to wait outdoors with social distancing before going into the grocery store or food bank. Top left: Conventional checkout methods. ABS shows that congestion areas are mainly located in the checkout area. Top right: Simulation results show that Scan & Go mobile will result in less congestion and a safe social distancing, while the conventional checkout will result in a sizeable waiting zone. These areas can be used to accommodate more customers and larger shopping areas. E-Z-Q-T as 1-2-3-4.

3 ABS for Public Restroom Design

The research on social distancing simulation in a restroom focused on the waiting area and queue outside the toilet area. We estimated the occupancy increase during the public event at the price landing park, where the proposed restroom is located. We evaluate the crowd flow through the total travel time, density, and public accessibility in different scenarios. Based on the result of ABS, we analyzed whether various waiting areas, utilities, and spatial layout can improve pedestrian flow efficiency and shorten waiting time and reduce congestion. (Fig. 6) After several iterations of the public restroom design, the E-Z-Q-T sequence was applied to analyze how agents would move through space as they go through the necessary programmatic areas.

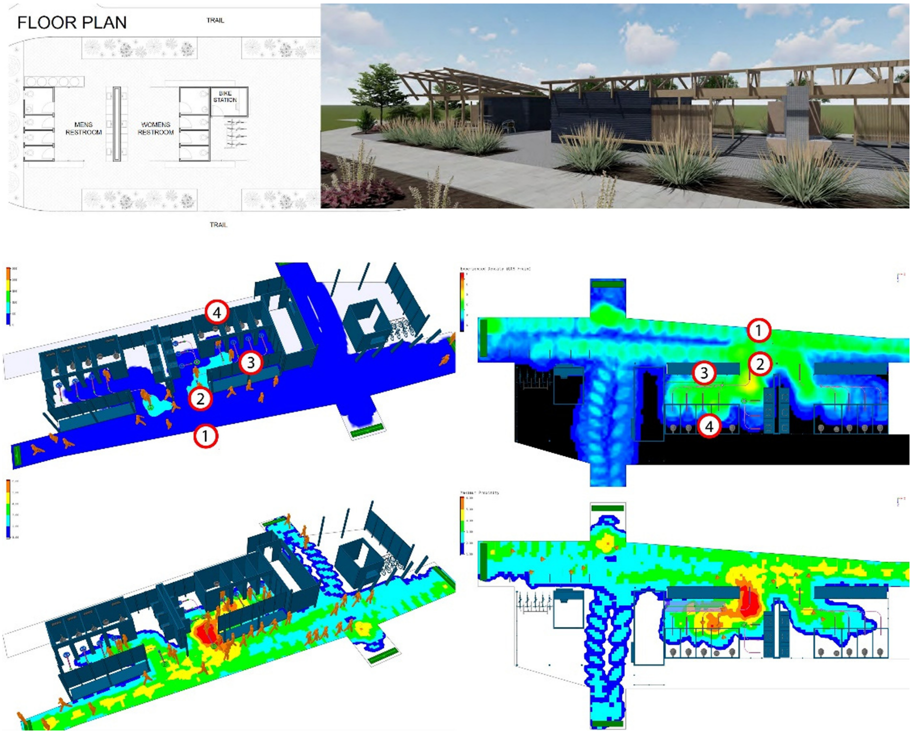

Fig. 6. E-Z-Q-T as 1-2-3-4. Design iterations were simulated with projected pedestrian flow. According to this simulation analysis, all areas are either blue or green, proving that the proposed design can handle many people while still maintaining social distancing. The red color area illustrates the high proximity waiting zone, which has direct natural ventilation. Top-left: occupancy time. Top-right: population density. Bottom-left and bottom-right: Proximity map. (Color figure online)

4 Conclusion

The crowd simulation method relies on the emergent properties and local interactions among agents. The project applied behavior simulation systems and investigated how to integrate E-Z-Q-T in space design. We observed that social distancing affected spatial organization and circulations in various ways. The social distancing requires a larger waiting area and results in a more extended connection between programmed spaces. With EQ and behavior trees, we simulated how agents enter/exit a given room, what happens when they meet agents coming the other way around a corner, the way they walk crossflows and counter-flows, and how they react to the dynamically changing crowd density in the waiting zone or queue, respecting the social distancing. Data visualization such as the proximity map became a valuable tool for us to study the capacity of a given space while maintaining a set physical distance. For instance, the blue and green areas show that the design ensures the social distancing requirements. The warmer tones mark areas that need to be improved (Fig. 7).

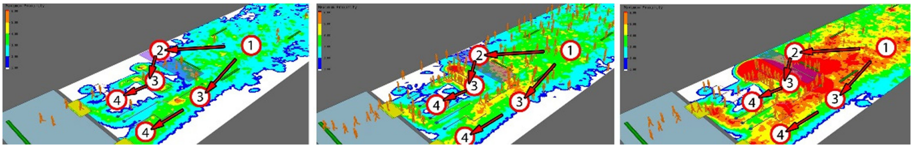

Fig. 7. Proximity map of 150, 250, and 500 people in a store. With the “travel cost” function, more agents start to choose the alternative checkout queue when the waiting zone is crowded. E-Z-Q-T as 1-2-3-4. (Color figure online)

A proposed spatial layout can be evaluated within ABS by analyzing the interaction between the simulated crowd and the surrounding environment. Designers can observe agents’ changing behaviors by testing different spatial layouts and various behavior rules. We believe the crowd simulation can produce measurable improvement in the design by predicting specific “high-risk” areas with potential congestion issues. The simulation results were used to suggest alternative pedestrian paths and compare the different crowd control strategies.

We are currently investigating the process to reinforce EQ with digital billboard placement. The design proposal is to create a visible billboard allowing the real-time occupancy data to be broadcasted to people. The new ABS will count each agent’s vision and perception system and trigger their decision tree. We have computed the most visible vertical surfaces through the environment (Fig. 8). The digital billboard will inform agents of the waiting zone and waiting queue status and create a more precise EQ for crowd simulation.

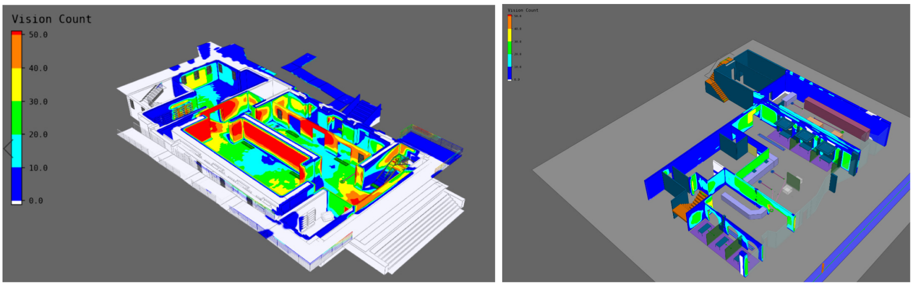

Fig. 8. Visibility analysis on the vertical surfaces.

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