ANALYZING HUMAN–BUILDING INTERACTIONS IN VIRTUAL ENVIRONMENTS USING CROWD SIMULATIONS

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Abstract

This research explores the relationship between human-occupancy and environment designs by means of human behavior simulations. Predicting and analyzing user-related factors during environment designing is of vital importance. Traditional Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools mostly represent geometric and semantic aspects of environment components (e.g., walls, pillars, doors, ramps, and floors). They often ignore the impact that an environment layout produces on its occupants and their movements. In recent efforts to analyze human social and spatial behaviors in buildings, researchers have started using crowd simulation techniques for dynamic analysis of urban and indoor environments. These analyses assist the designers in analyzing crowd-related factors in their designs and generating human-aware environments. This dissertation focuses on developing interactive solutions to perform spatial analytics that can quantify the dynamics of human-building interactions using crowd simulations in the virtual and built-environments. Partially, this dissertation aims to make these dynamic crowd analytics solutions available to designers either directly within mainstream environment design pipelines or as cross-platform simulation services, enabling users to seamlessly simulate, analyze, and incorporate human-centric dynamics into their design workflows.

Dedication

This dissertation is dedicated to the memory of my late father. He passed away even before I started my graduate studies. He always used to motivate me to pursue doctorate studies once I am done with my undergrad. This is for you, Dad. I wish you could be here today to see me graduate.

Acknowledgements

In the name of Allah, the Most Gracious and the Most Merciful.

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To my mother, mom, thank you for your neverending love and prayers! You have always been a reason for smiling in all these years even during times when I was not at my best. And to my beautiful wife, wifey, thank you for being so supportive. Your love and care have been the driving forces to get me going on my journey. Love you Guriya!

In the end, I wish to recognize various sources of funding which made my doctoral studies possible: the department of Electrical Engineering and Computer Science at York University; the NSERC Create (including CreateDAV group) and Discovery Grant Programs; the Intelligent Systems for Sustainable Urban Mobility (ISSUM) group; and the

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Chapter 1

Introduction

In environment (e.g., building) modeling, designers often need to consider and compare multiple design solutions and balance a wide range of constraints (Kalay, 2004) and performance criteria, or some other spatial and social context (Simon, 1969). It is an iterative process whereby design solutions are developed and then progressively refined to maximize the overall design performance (Rittel, 1971). Due to the ill-structured nature of design problems, several competing design solutions may be generated, which affect an environment's performance in often unpredictable ways.

Estimating how an environment layout impacts the movement and activities of its prospective inhabitants is a critical aspect of the environment design process. It is often imperative to account for human occupancy and behavior in the design and management of the environment spaces. While many established building performance evaluation methods in Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools, such as structure (Weizmann, Amir, & Grobman, 2017), energy (Clarke, 2007), construction efficiency (Ben-Alon & Sacks, 2017) and lighting (Rockcastle & Andersen, 2014), mostly rely on static environment representations. How an environment design will perform for the dynamic movement of people, its spatiotemporal impact on user experience, operational efficiency, and space utilization is mostly left to the designer's knowledge, experience, and imagination (Zeisel, 1984).

However, predicting and accounting for *Human-Building Interaction* (HBI) can be very challenging, to do unassisted, in environment layouts. By ignoring this, design artifacts often do not perform as expected, leading to potentially significant consequences in terms of the users' experience, productivity, and even safety (Lawson, 2004). Due to the complexity of environment layouts in terms of size, organization, multi-functionality, as well as the diverse nature of occupants, predicting human behavior aspects can be challenging even for the most skilled designers. Computational approaches can help to explore the implications of design decisions on human occupancy. These approaches would allow the designers to make more informed decisions throughout the design phase of an environment, and not just after its construction and occupancy.

The methodologies in Space-Syntax (Hillier & Hanson, 1984) have been used to analyze human social and spatial behaviors in an environment (Bafna, 2003). It is a well-known configurational approach which uses graph-based spatial representations (e.g., visibility graph (Desyllas & Duxbury, 2001), isovists (A. Turner & Penn, 1999), or axial map (Desyllas & Duxbury, 2001; A. Turner, Penn, & Hillier, 2005)) to infer users' behavior by measuring spatial relations and connectivity on the graph. This approach has been proven useful to test how alternative design options affect the movement of people as a function of visibility and spatial connectivity (Sailer, Budgen, Lonsdale, Turner, & Penn, 2009). However, Space-Syntax ignores the dynamic aspects of human movements in the environment space. It solely relies on the spatial configuration of the environment, which is static and does not change, whereas human movements are dynamic and change over time. A representation of such a kind cannot be simply inferred by spatial visibility and connectivity. Rather, it depends on occupants' attributes (e.g., destinations, walking velocity, walking direction, and social distancing), their location in the environment at a given time, their distance from a given target, as well as the movement of other occupants in the area.

To this end, a dynamic approach is advocated using crowd simulation techniques for simulating human-building interactions in semantically meaningful environments. Crowd simulations (also known as human behavior simulations) provide a time-based representation of the environment in-use by their prospective occupants (Kapadia, Pelechano, Allbeck, & Badler, 2015; Pelechano, Allbeck, Kapadia, & Badler, 2016). Beyond the environment layout, these methods explicitly model individual occupants and the activities they engage in (e.g., behavioral objectives, gathering at a certain point, exploring an art gallery, and evacuating the environment). The simulation of human dynamics, from person-to-person interactions to global-scale transportation networks, affords a plethora of predictive and analytical approaches across several fields. Analyses of such a kind provide an intuitive way to identify problem areas, improve environment layouts, and compare design alternatives concerning occupant related factors by looking at spatial quantitative and qualitative feedback and visualizations.

Multiple innovative solutions are developed to integrate human behavior simulations into established environment design pipelines (e.g., into CAD and BIM modeling systems). In addition, a democratized workflow to analyze human–building interactions is also presented. Such solutions allow the designers to design environment layouts that better support human-related factors by simulating movements of potential occupants in space. They provide several crowd-based analytics for human-building interactions that designers can incorporate in their designs. These analytics include path and trajectory analysis, bottleneck analysis, time and distance-based crowd traces in the areas of interests within the environment spaces, and density and speed heat maps of crowd movements, to assist designers in making crowd-informed design decisions.

1.1 Contributions

The contributions from this dissertation fall under three bins of research production, namely: (1) *Environment Design Analysis*, *Environment Design Exploration*, and *Environment Design Communication*.

1.1.1 Environment Design Analysis

In the environment design analysis, interactive computational workflows are presented to perform spatial analytics for human–building interactions by incorporating crowd-aware dynamics in the environment design using human behavior simulations. The workflows presented in Chapters 3, 4, and 5, fall under this bin of research production.

1.1.2 Environment Design Exploration

In the early stages of the environment design process, designers use parametric exploration tools to develop an initial environment model by rapidly exploring several design parameters. These explorations often involved high dimensional spaces. The dynamic evaluation of these parameter configurations can help designers make crowd-aware design decisions from the very beginning of the environment design process, and not just at the end after the environment model is already matured. However, in order for the crowd-aware analytics to be useful in early environment modeling stages, human–building simulation processes must be well coupled with parametric modeling tools. To this end, parametric modeling workflows are presented to model (a) an environment and the bounds of its permissible alterations, (b) a crowd that populates the environment, and (c) the activities that the crowd engages in. The workflows presented in Chapters 6 and 7 fall under this bin of research production.

1.1.3 Environment Design Communication

In the research bins for environment design analysis and exploration, several workflows are presented to adopt crowd-aware analytics in the environment design process both in the early parametric design stage and after a complete draft of an environment model is designed. In the environment design communication, I investigate how the complex, large-scale environment spaces can be communicated to the users, as well as how well the users perceive and understand the spatial configurations of these spaces. The perceptual study presented in Chapter 8 falls under this bin of research production. It is to identify the visual modes of environment exploration that better convey the spatial characteristics of design space to the users.

Note that the presented studies under design communication are the preliminary exploration of the visual modes for communicating spatial environment information to the end-users. There can be different ways of communicating spatial information related to environment designs, and the presented study only touches upon one of the aspects (e.g., visual exploration of the design spaces). An in-depth research is needed to conclusively approve or disapprove the hypothesis of the presented study, which needs to be investigated in the future.

1.2 Publications

Following is a list of publications that I have co-authored during my Ph.D. thesis work.

1.2.1 Related to Thesis

1. **Usman, M.**, Haworth, B., Kapadia, M., & Faloutsos, P. (2020). Democratizing the Simulation of Human-Building Interactions. In Wiley Computer Animation and Virtual Worlds. (*Accepted*)

2. **Usman, M.**, Schaumann, D., Haworth, B., Kapadia, M., & Faloutsos, P. (2020). Simulation-as- a-Service: A Cross-Platform Framework for Analyzing Human-Building Interactions. In ACM CHI workshop for Inhabiting Buildings, Data & Technology. (*Accepted – Position Paper*)
3. **Usman, M.**, Mao, Y., Schaumann, D., Faloutsos, P., and Kapadia, M. (2020). From semantic-based rule checking to simulation-powered emergency egress analytic. In Proceedings of the Simulation for Architecture and Urban Design (pp. 43–50).
4. **Usman, M.**, Schaumann, D., Haworth, B., Kapadia, M., & Faloutsos, P. (2019). Joint Exploration and Analysis of High-Dimensional Design–Occupancy Templates. In ACM Motion, Interaction and Games (pp. 1-5).
5. **Usman, M.**, Schaumann, D., Haworth, B., Kapadia, M., & Faloutsos, P. (2019). Joint parametric modeling of buildings and crowds for human-centric simulation and analysis. In Springer CCIS book series and proceedings of Computer-Aided Architectural Design Futures (pp. 279-294).
6. **Usman, M.**, Schaumann, D., Haworth, B., Berseth, G., Kapadia, M., & Faloutsos, P. (2018). Interactive spatial analytics for human-aware building design. In ACM Motion, Interaction, and Games (pp. 1-12).
7. **Usman, M.**, Haworth, B., Berseth, G., Kapadia, M., & Faloutsos, P. (2017). Perceptual evaluation of space in virtual environments. In ACM Motion in Games

(pp. 1-10).

8. **Usman, M.**, Haworth, B., Berseth, G., Kapadia, M., & Faloutsos, P. (2017). Understanding spatial perception and visual modes in the review of architectural designs. In ACM SIGGRAPH/Eurographics Symposium on Computer Animation (pp. 1-2).

1.2.2 Others

1. **Usman, M.**, Lee, T., Schwartz, M., Moghe, R., Zhang, X., Faloutsos, P., & Kapadia, M. (2020). A Social Distancing Index: Evaluating Navigational Policies on Human Proximity using Crowd Simulations. In Proceedings of the Computer Animation and Social Agents. (*Accepted*)

2. Azizi, V., **Usman, M.**, Zhou, H., Patel, S., Schaumann, D., Faloutsos, P., and Kapadia, M. (2020). Floor Plan Embedding with Latent Semantics and Human Behavior Annotations. In Proceedings of the Simulation for Architecture and Urban Design (pp. 337-344).

3. Schaumann, D., Moon, S., **Usman, M.**, Goldstein, R., Breslav, S., Khan, A., ... & Kapadia, M. (2019). JOIN: an integrated platform for joint simulation of occupant-building interactions. In Architectural Science Review, 1-12.

4. Haworth, M. B., **Usman, M.**, Schaumann, D., Chakraborty, N., Berseth, G., Faloutsos, P., & Kapadia, M. (2020). Gamification of Crowd-Driven Environment

Design. In IEEE Computer Graphics and Applications.

5. Berseth, G., Haworth, B., **Usman, M.**, Schaumann, D., Khayatkhoei, M., Kapadia, M. T., & Faloutsos, P. (2019). Interactive architectural design with diverse solution exploration. In IEEE transactions on visualization and computer graphics.

6. Schaumann, D., Moon, S., **Usman, M.**, Goldstein, R., Breslav, S., Khan, A., ... & Kapadia, M. (2019). Toward a Multi-Level and Multi-Paradigm Platform for Building Occupant Simulation. In Symposium on Simulation for Architecture and Urban Design (pp. 169-76).

7. Schaumann, D., Sohn, S. S., **Usman, M.**, Haworth, B., Faloutsos, P., & Kapadia, M. (2019). Spatiotemporal Influence and Affordance Maps for Occupant Behavior Simulation. In ACM Motion, Interaction and Games.

8. Cassol, V. J., Testa, E. S., Jung, C. R., **Usman, M.**, Faloutsos, P., Berseth, G., ... & Musse, S. R. (2017). Evaluating and optimizing evacuation plans for crowd egress. In IEEE computer graphics and applications (37(4), pp. 60-71).

9. Chakraborty, N., Haworth, B., **Usman, M.**, Berseth, G., Faloutsos, P., & Kapadia, M. (2017). Crowd sourced co-design of floor plans using simulation guided games. In ACM Motion in Games (pp. 1-5).

1.3 Dissertation Structure

This dissertation seeks to contribute dynamic workflows to analyze human–building interactions and provide interactive solutions to incorporate crowd-aware analytics in environment designs.

Chapter 2 presents the literature review and theoretical background pertaining to human behavior simulations, dynamic and static approaches to analyze environment spaces for human occupancy, and the use of human simulations as a service. This review helps to support the need, methodology, and delivery of the works presented in different bins of research production in the dissertation.

Chapter 3 covers the common methodology to run human–building simulations used in this dissertation and also discuss the individual components involved in the process, namely environment configuration, crowd configuration, and the simulator.

Chapter 4 presents an interactive tool to perform spatial analytics for human–building interactions for designing environments that better support human-related factors. It enables users to utilize both the static and dynamic approaches to analyze the environment spaces.

Chapter 5 presents a computational workflow to perform an automated semantic-based rule checking for the International Building Code rules for *Means of Egress* and the analysis of egress scenarios using human behavior simulations.

Chapter 6 presents a democratized workflow to simulate and analyze human–building interactions. It supports the development of a cross-browser cloud-based platform to run human–building simulations as a service (e.g., on-demand from a client-side web-browser), and perform crowd-aware analytics to analyze environment designs for human-occupancy and activity.

Chapter 7 presents a platform that enables the parametric representation of (a) an environment design and the bounds of its permissible alterations, (b) a crowd that populates the environment, and (c) the activities that the crowd engages in.

Chapter 8 presents a series of experiments to investigate automated joint and sequential parameter exploration workflows for human–building analysis.

Chapter 9 investigates how well the novice and expert users perceive the spatial characteristics of environment spaces and whether their perception depends on the way they explore these spaces.

Lastly, Chapter 10 summarizes all of the presented research in this dissertation. It highlights the key findings, makes recommendations, and outlines future work directions.

Chapter 2

Background & Literature Review

This chapter covers the background and literature and positions the problem space of the dissertation. It focuses on the research topics which fall under this dissertation, including human behavior simulations and their usage and applicability in virtual and built-environments. First, a review of human behavior simulations is presented (i.e., agent-based modeling via multi-agent systems). Next, an in-depth review of human-building interactions using crowd simulation is presented for both virtual and built-environments. Then the static approaches are discussed to analyze environment layouts for human occupancies using geometric and topological configurations of the environment. Lastly, a review of the democratization of human simulations and human-building interactions is presented.

The presented review of literature is by no means a comprehensive literature review of all the crowd simulation approaches. The amount of work in this area of research is enormous, as crowd simulation techniques have proven to be very useful in modeling complex large-scale systems that are beyond the scope of this review.

2.1 Human Behavior Simulation

Human behavior simulation (also known as crowd simulation) is a well-studied topic which uses autonomous virtual agents to provide temporal dynamics of human-like behaviors in the environment (Pelechano et al., 2016; Thalmann & Musse, 2013; Kapadia et al., 2015). Several techniques have been developed to simulate virtual agents (e.g., crowds), each with a different set of characteristics. The earliest models of interacting entities were largely cellular-automata for complex and evolving systems analysis. Later, 3D graphics and animation pushed the need for interacting agents in complex scenes. The first work in this area is the famous Boids (Reynolds, 1987). This method used a handful of simple rules to produce a net force that would plausibly recreate flocking and herding animals. This approach could easily be adapted for the crowding movement of many types, including particles, birds, animals, and virtual agents.

In addition to graphics and animation, robotics has been a driving factor for several crowd models in use today: from advanced human-machine interactions to video games. This area of work largely focuses on geometric optimization in the form of velocity obstacles (VO), as they may be provably collision-free–an important aspect of robotic movement–and field-based methods (Fiorini & Shiller, 1998). A velocity obstacle is, in a sense, a space-time representation of a moving agent and can be used to compute collision directions of movement for particle-based agents efficiently. This has been generalized to the reciprocal movement (reciprocity between modeled agents in their collision avoidance) (Van den Berg, Lin, & Manocha, 2008) and to the optimal reciprocal movement among an arbitrary number of agents (Van Den Berg, Guy, Lin, & Manocha, 2011). More recently, this approach has been generalized to robots of arbitrary systems of equations, affording the co-simulation of many different types of interacting robots (Bareiss & van den Berg, 2015). Similarly to velocity space optimization and generalization, new methods may optimize directly in control space using the gradient along control space to make decisions (Davis, Karamouzas, & Guy, 2019). This is similar to decision making in probabilistic fields rather than a particular space, affording improved collision avoidance in complex spaces of interacting agents (Wolinski & Lin, 2018; Wolinski, Lin, & Pettré, 2016). These methods are often very fast (particularly VO-based methods), under many conditions collision-free, and relatively easy to implement. For these reasons, they are often used not only in robotics but in games to represent large groups of interacting Non-Player Characters (NPCs). However, they often produce robot-like interactions, which stray from naturalistic and human- behaviors.

One way to implement human-like behaviors is to represent those things that humans are concerned with during navigation as repelling and attracting physical forces. For example, pushing the agents toward their goal and pulling them away from collisions. This approach was first proposed in the form of the Social Forces Model (Helbing & Molnar, 1995). This has been extended to simulate humans under distress, by layering a panic model into the steering decision (Helbing, Farkas, & Vicsek, 2000). Later models added anticipatory behaviors that improve the naturalness of the simulation. They do so by modeling the anticipation of a collision and allowing agents to move ahead of time (Karamouzas, Heil, Van Beek, & Overmars, 2009). An egocentric approach is presented to calculate space-time planning for individual agent navigation using affordance-based fields (Kapadia, Singh, Hewlett, & Faloutsos, 2009). Ease of implementation has led to rapid growth in force-based methods in AI, games, and simulation. These methods produce plausible results, but care must be taken to avoid oscillations due to undamped or underdamped forces in high-density scenarios.

Data-driven approaches have the advantage of being empirically sound in recreating real-world scenarios related to the data source. Context-aware approaches use time-dependent scenario features to search for the closest matching action in the dataset and resolve collisions based on the data at the individual or group scale (Lerner, Chrysanthou, & Lischinski, 2007; K. Lee, Choi, Hong, & Lee, 2007). Similarly, albeit more intensive, experiment-based modeling has been used to recreate single inter-agent interactions and large multi-agent interactions, which are then tuned for the data(Pettré, Ondrej, Olivier, Cretual, & Donikian, 2009). These clustering and selection of these contexts can be automated with machine learning (Boatright, Kapadia, Shapira, & Badler, 2013). Morphing, or interpolation, can be used to extend agent trajectories in time to form crowd simulations. This is accomplished by iteratively advancing a trajectory model built from data (Ju et al., 2010). A rule-based hybrid framework is presented to avoid future collisions in the crowd (Singh, Kapadia, Hewlett, Reinman, & Faloutsos, 2011). Some recent works have adopted machine learning techniques like deep learning and reinforcement learning to develop crowd simulation models that capture more realistic crowd behaviors (Peng, Berseth, Yin, & Van De Panne, 2017; Heess et al., 2017; J. Lee, Won, & Lee, 2018; Xie et al., 2019; Xu, Huang, Li, & Li, 2020).

2.2 Dynamic Approaches to Environment Design Analysis

Human behavior is dynamic and contextual by nature, and therefore, it is essential to anticipate the impact design of an environment would have on its potential occupants. It is an important yet complicated task to accomplish. Ignoring its significance can lead to an environment layout that might be less productive, unsatisfactory, having disparities between actual and expected functional performance of the environment space, and much more. However, by modeling potential human-building interactions and predicting complex human behaviors within semantically rich environments in advance, architects and designers can make informed design decisions to enhance occupants' comfort, productivity, safety, and other functional performances of the environment.

The rich body of research in modeling virtual human-like movements enables us to study human-building interactions in semantically meaningful environments. This allows us to investigate how an environment design would impact the behavior and movement of its inhabitants. An environment is designed with several purposes in mind, mostly involving human occupancies and their interactions with the design space. Human spatial cognition and architectural elements in an environment are the important attributes that control human behavior in an environment (Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff, 2005). Therefore, considering human interactions with the design space is as vital as other functional requirements in satisfying an environment's structure purposes. Several efforts have been made to analyze environment designs using crowd simulation techniques to understand and improve the design spaces for human factors.

Human movements are simulated through virtual hallways (e.g., one-way, two-way, and four-way hallways) to approximate the movement flow of crowds as a function of environment layout (Feng, Yu, Yeung, Yin, & Zhou, 2016; Berseth, Usman, Haworth, Kapadia, & Faloutsos, 2015). This work is further extended in (Haworth et al., 2016; Haworth, Usman, Berseth, Kapadia, & Faloutsos, 2015) to analyze the placements of architectural elements (e.g., pillar, obstacles) in the hallways for different crowd densities calculated using Fruin's Level of Service (Fruin, 1971a). The findings from these studies show that the placement of pillars, doors, and other obstacles have a direct and significant impact on the movement flow of pedestrians.

One common application of using crowd simulation for human-building interaction is the prediction of human movements in emergent scenarios (e.g., egress or evacuation). A computational technique is presented to calculate optimal egress routes as predictive egress planning using crowd simulations (Cassol et al., 2017). A framework is presented to simulate collaborative human behaviors and movements for emergency egress situations (Chu & Law, 2019). Several characteristics of crowd dynamics are studied for high-stress evacuations in virtual environments using crowd simulations to help improve agent movements (Moussaïd et al., 2016). The optimal placements of pillars are studied for evacuation scenarios using a specific crowd steering method (Rodriguez, Zhang, Gans, & Amato, 2013; Jiang, Li, Shen, Yang, & Han, 2014). Some approaches have focused on using crowd simulations to approximate day-to-day human behaviors in offices (Goldstein, Tessier, & Khan, 2010a), hospitals (Schaumann, Breslav, Goldstein, Khan, & Kalay, 2017), and university environments (Shen, Shen, & Sun, 2012).

Interactive methods (e.g., user-in-the-loop) are developed to rapidly design and optimize small-scale virtual environments with respect to user-defined design constraints (Haworth, Usman, Berseth, Khayatkhoei, et al., 2017). A multi-paradigm framework is presented for event-based simulations of dynamic crowds in built-environments to mutually account for human behaviors and environmental conditions such as temperature and acoustics (Schaumann, Moon, et al., 2019a, 2019b). A pre-occupancy environment evaluation framework is presented to compute alternative design options for complex environment layouts using a multi-agent narrative-based approach (Schaumann, Pilosof, Sopher, Yahav, & Kalay, 2019). An interactive system is presented to instantly predict the movement flow of potential inhabitants in large-scale realistic environment layouts (Sohn et al., 2019).

In the area of context-dependent behavioral authoring, workflows are presented to author collaborative human behaviors of heterogeneous crowds in semantically rich virtual environments. These workflows are particularly useful to evaluate not-yet-built environment layouts, author engaging story arcs in video games, and provide realistic human-building interactions. An interactive natural language style authoring interface is developed to define context-dependent crowd behaviors in a virtual environment (Zhang, Schaumann, Faloutsos, & Kapadia, 2019). This system allows to get insights on the mutual interaction between the crowds and the design space of the environment. A multi-agent behavior narrative workflow is presented to define and evaluate time-varying environment occupancy specifications and crowd behavior distributions using a resource allocation system to make informed human-aware environment design decisions (Zhang, Schaumann, Haworth, Faloutsos, & Kapadia, 2019).

The dynamic approaches (e.g., using crowd simulations) to analyze human–building interactions, however, are often integrated into specific environment design workflows and require certain hardware/software infrastructures and expertise in order to be used by the general audience.

The presented work in this dissertation is different from existing studies cited in Section 2.2 that also use crowd simulations (e.g., for egress analysis) in the following ways: (a) This work presents interactive user-in-the-loop solutions that enable the users to author a diverse range of crowd scenarios (e.g., semantically rich day-to-day activities as well as egress analysis), and not just specifically run simulations only for the egress analysis; (b) It allows users to set up crowd behaviors and their movement characteristics, including walking speed, individual and group walking behaviors, waiting at user-defined points of interest before continuing their trajectories to the next target, and much more; and (c) This work integrates these dynamic analyses workflows into mainstream environment

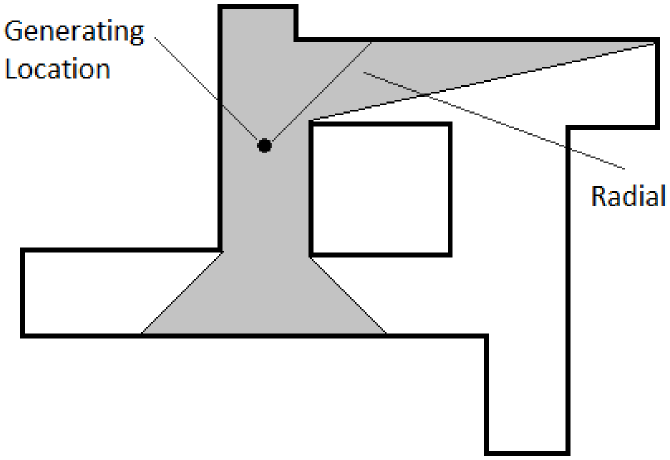


Figure 2.1. An isovist polygon, incorporating the visible area (GRAY) from a generating location (BLACK).

modeling pipelines so that users can directly use them from within the environment modeling platforms without worrying about the hassle of setting and configuring third-party or stand-alone crowd simulation processes.

2.3 Static Approaches to Environment Design Analysis

The static approaches make use of geometrical and topological properties of an environment space to analyze its design structure. They represent human-focused environment features without any explicit time-based modeling of human movements. Among the range of such approaches (Dawes & Ostwald, 1926; Penn, Hillier, Banister, & Xu, 1998), one of the widely used methods is Space-Syntax (Hillier & Hanson, 1984; Bafna, 2003). Researchers at Georgia Institute of Technology and University College London made an effort to understand large societies of human-focused spaces and established Space-Syntax theories and processes (Hillier & Hanson, 1984). It is considered as a methodology to understand the connection between human societies and spatial forms of environment spaces. The fundamental theory of Space-Syntax is that an environment's design space can be analyzed by examining its spatial configuration. According to Space-Syntax, human populations make use of environment spaces as a means to organize their societies. In between this phase, space of inhabitation is usually formed. This turns the continuous environment space into a connected and combined set of discrete units. It is useful to transform the space into a discrete configuration. In this way, different labels can easily be applied to unique individual parts within the environment space. These parts can further be assigned to different sub-groups. Now this configured environment space relates to divergent rules of human behaviors.

The main idea behind Space-Syntax is to decompose the environment space into a graph of components (e.g., network of possible choices in the space). And then analyze this graph using a given behavior (e.g., method of decision making), which will assign some values to each node (representing a physical or architectural component) in the graph. The resulting evaluated graph can then describe several characteristics of the environment space, such as spatial relations, connectivity, or integration of the different environment components. Several techniques have been developed to decompose (or represent) the environment space for static analysis. These include isovists, visibility graphs, and axial maps.

The term 'isovist' possesses a long history in architecture and areas of mathematics.

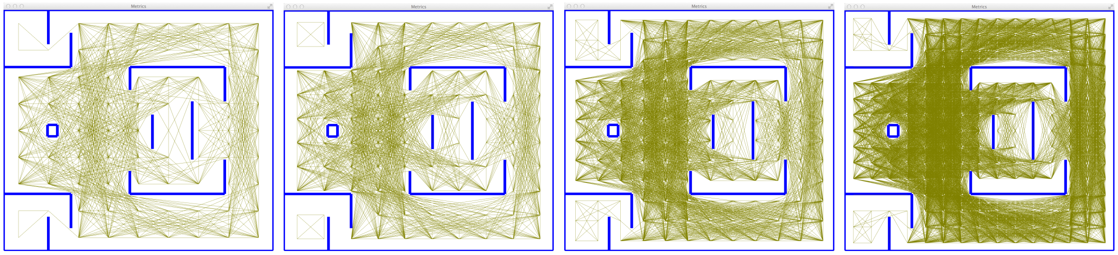
It was originated back in 1967 by a scientist named Tandy (Tandy, 1967). Isovists are also known as visibility polygons. They provide an egocentric description of the environment from the point-of-view of individuals. In terms of the graph, an isovist is a set of all visible points or nodes from a given point in space with respect to the environment. Several computational measures have been proposed to analyze the spatial features of an environment space using isovists (Benedikt, 1979; Wiener et al., 2007). Figure 2.1 shows an isovist polygon, incorporating the visible area (GRAY) from a generating location. The 'visibility graph' analysis was first proposed in 2001, driven from Space-Syntax theory analysis (A. Turner, 2001). It is a technique to represent the environment space as a graph to analyze the inter-visibility relations within environment design spaces (or even within urban networks). Various computational measures have been proposed to analyze the spatial features of an environment space using visibility graphs (Hölscher & Brösamle, 2007; A. Turner, 2001; Freeman, 1978). Figure 2.2 shows an example of a visibility graph, showing the pattern of connections (edges) for a simple environment configuration. An 'axial map' (A. Turner et al., 2005) represents a set of intersecting lines through the entire environment or urban space such that all the space is covered into closed rings. According to some researchers, the axial map is a concept of 'fewest lines' (Hillier & Hanson, 1984). It reduces the complex environment or urban space into component parts. These component parts are then used to perform spatial analysis to identify and observe environment features.

Measures from Space-Syntax have been used to analyze human movements and behaviors in built-environments (Stamps III, 2002; Gil, Tobari, Lemlij, Rose, & Penn, 2009; Hölscher et al., 2005). An interactive user-in-the-loop environment optimization system is presented to analyze environments for spatial measures from Space-Syntax and use them to compute diverse alterative design layouts (Berseth et al., 2019). Static configurations of human activities are provided for environment spaces by coupling the environment space with user and activity models (Maher, Simoff, & Mitchell, 1997; Ekholm, 2001). Human navigation and way-finding tasks are studied in a single and multi-level environment using Space-Syntax (Hölscher, Büchner, Meilinger, & Strube, 2009). A design space model is presented to integrate indoor/outdoor information to facilitate emergency respondence (Tashakkori, Rajabifard, & Kalantari, 2015).

Static approaches, however, use spatial configurations of the environment space to provide human behavior analyses without any explicit modeling of time, environment occupants, and their activities. Thus, they do not reflect the dynamic nature of human movements and behaviors.

2.4 Simulation-as-a-Service

Software-as-a-Service (SaaS) is an approach that is increasingly gaining more attention both in academic and industry practices because it separates the configuration and deployment of the software products from the clients (e.g., end-users). It allows clients to make use of the software product as an on-demand service via the internet using some client-side interface (e.g., Web Interface and Application Program Interface) (Laplante,



9x9 10x10 12x12 15x15

Figure 2.2. A series of visibility graphs at different grid resolutions, showing the connections (edges between nodes) for a simple environment configuration. BLUE lines show walls, pillars and other architectural elements in the environment.

Zhang, & Voas, 2008).

An in-depth survey is presented to discuss the risk factors, limitations, and the advantages associated with using cloud-based simulation services, highlighting the difference between software and service-based approaches while noting the elasticity and ease of technical administration of the approach (Cayirci, 2013). A discussion on cloud-computing and virtualization platforms is presented to model and simulate military and civilian applications (Cayirci & Rong, 2011). A model-driven engineering technique is presented for distributed architectures to extract geometric information of environment models from BIM and CAD tools as a remote service to run simulations. The 3D visualizations are provided via third-party software application (e.g., 3ds Max) (Wang & Wainer, 2015). The modeling and simulation of urban system simulations are presented on high-performance cloud clusters (Zehe, Cai, Knoll, & Aydt, 2015). A cloud approach is presented to remotely run simulations to examine and analyze the deployment of sensors in large-scale environments (Pax, Gomez-Sanz, Olivenza, & Bonett, 2018).

2.5 Summary

The simulation of human-building interaction is often decoupled from digital environment modeling tools used by designers and architects (e.g., CAD or BIM tools). Often, they require specific hardware/software infrastructure dependencies and expertise, limiting designers' ability to seamlessly simulate, analyze, and incorporate human-aware dynamics in practice. There is a broad need to develop dynamic workflows to perform crowd-aware analytics for human–building interactions. This chapter laid down the basis for research and an in-depth discussion on analyzing human-building interactions using agent-based crowd simulation techniques and making these analytics accessible for designers in the mainstream environment modeling pipelines.

Chapter 3

Spatial Analytics for Human–Building Interactions

In this chapter, I will present computational workflows and a tool to perform spatial analytics for human–building interactions for designing environments that better support human-related factors. I will discuss both static and dynamic approaches to understand human movements in an environment's design space. The first approach (static) relates to the environment geometry and organization, whereas the second (dynamic) additionally considers the crowd movements in the environment space. The tool presents analytics to the users as statistical numbers, movement trajectories of the crowds, and color-coded spatial environment space features as heat maps. A user study is presented whereby novice designers tested these analytics workflows to iteratively improve the environment's accessibility in real-time. Additionally, the usability and effectiveness of the system are also evaluated. For demonstration purposes, the presented analytics workflows are integrated into a mainstream environment modeling tool (e.g., Autodesk Revit).

This chapter serves as the first contribution under the research bin "Environment Design Analysis".

3.1 Overview

Environment design involves exploring a broad set of solutions to identify the one(s) that better satisfy a wide set of performance criteria while abiding specific constraints (Kalay, 2004). This is an iterative process whereby design solutions are developed and then progressively refined to maximize the overall design performance (Rittel, 1971). In the last 60 years, computational tools have been developed to assist designers in such a process. They have been helping them measure the performance of a proposed environment design mainly in terms of energy, light, structure, and cost. However, one of the critical aspects of an environment design is that how it supports the occupants' behaviors, and this is often left to designer's knowledge, experience, and imagination, which can be partial or biased (Zeisel, 1984). As a result, design artifacts often do not perform as expected, leading to severe consequences in terms of the occupants' experience, productivity, and even safety (Lawson, 2004).

The traditional Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools mostly represent geometric and semantic aspects of the environment components (e.g., walls, pillars, and doors). To analyze human social and spatial behaviors in environment spaces, (Hillier & Hanson, 1984) developed Space-Syntax, a well-known configurational approach that uses graph-based spatial representations to infer occupants' behavior by measuring spatial relations and connectivity. This approach has been proven useful to test how alternative design options affect the movement of people as a function of visibility and spatial connectivity (Sailer et al., 2009). Space-Syntax, however, ignores the dynamic aspects of human movements in space. A representation of such a kind cannot be simply inferred by spatial visibility and connectivity. It also depends on crowd attributes, including walking speed, location in space at a given time, the distance from a target, as well as the movement of other people in the space. Dynamic crowd simulation analyses are thus required to account for occupants' movement in space in the day-to-day and life-threatening emergency situations (Chu, Parigi, Law, & Latombe, 2014; Yan & Kalay, 2004).

In the following sections, both the static and dynamic workflows are presented to analyze environments for human–building interactions. In addition, an interactive tool is also presented that uses these workflows to quantify human-related factors in real-time. Analyses of such a kind provide an intuitive way to identify problem areas, improve the environment design, and compare design alternatives for occupant-related factors by looking at real-time spatial and numerical visualizations.

3.2 Behavior Analysis in Environment Design

Many approaches have been proposed to represent specific aspects of human behaviors in environment spaces using a combination of static and dynamic analyses. Such approaches include pedestrian movement (Yan & Kalay, 2004), emergency egress (Pan, Han, Dauber, & Law, 2007; Chu et al., 2014), occupants' presence and actions to support energy analyses (Goldstein, Tessier, & Khan, 2010b), movement of crowd in university buildings (Shen, Zhang, Qiping Shen, & Fernando, 2013), and collaborative medical procedures in hospitals (Schaumann et al., 2017). Nonetheless, how static and dynamic human-related analytics workflows are actually used in environment modeling to support designers' decision-making is still a relatively under-studied topic.

Preliminary studies by (Hong, Schaumann, & Kalay, 2016) and (Hong & Lee, 2018) indicated that human behavior analyses could support the iterative refinement of environment designs in terms of day-to-day and emergency behaviors. Such studies, however, measured only a few iterations over the course of an academic semester. In order to favor the use of static and dynamic analytics workflows, more advanced methods should be developed that compute design analyses in a fast-paced fashion, provide meaningful visual and numerical results that can be easily interpreted, are intuitive to use, and are connected with existing CAD or BIM tools.

3.3 Static Workflow

In static workflow, Space-Syntax processes (Hillier & Hanson, 1984; Bafna, 2003) are used to analyze human behaviors in environment spaces. A Visibility Graph (A. Turner, 2001) is used to decompose the environment space into a graph-like representation to analyze the inter-visibility relations within environment design spaces. A visibility graph is constructed by sampling the design space using a homogeneous grid. All the nodes (cells) in the graph (grid) are the vertices (V_V) of the visibility graph. After that, the line of sight is computed between the grid cells. If two grid cells are visible to each other (i.e., they have an unobstructed sight of view between them), there exists an edge (E_V) between corresponding vertices in the graph. Figure 2.2 shows sample visibility graphs constructed at different grid-scale resolutions. Once the visibility graph is constructed, a selected number of spatial metrics defined in Space-Syntax can be computed that measure salient space characteristics. These metrics are *Accessibility*, *Visibility* and *Organization of Space*.

3.3.1 Accessibility

It relates to the minimum average distance from a point to any other point in the environment space. In other words, accessibility measures the struggle and difficulty of navigating the space from a given standpoint to other areas in space. In terms of graph, a vertex with high accessibility is connected to other vertices of the visibility graph through a smaller sequence of vertices.

Accessibility is measured as negative *Tree Depth.* Let all the graph trees whose root is v_i in VG forming a forest F_i, then rank of a tree T_i with minimum depth in the forest F_i is the *Tree Depth* (Dep_i).

$$Dep_i = \text{rank}\ \ (T_i) \tag{3.1}$$

3.3.2 Visibility

It is the unobstructed line of sight between vertices. High visible areas are more connected with the surrounding spaces and provide a better field of view. Hence, they are better candidates to install a security camera, door placements, and safety signs. Visibility can also relate to *Openness of Space* from a specific standpoint.

Visibility of a vertex v_i refers to the *Degree of Visibility* of that vertex. In terms of graph, it is defined as the number of neighbours (N_i) incident to that vertex, $v_i \in V_V$, connected by the edges, $E_i \subset E_V$.

$$Deg_i = |N_i| \tag{3.2}$$

3.3.3 Organization

It relates to the navigational choices a person faces at a particular standpoint within a space. For example, how easily a person can plan and navigates through the environment or building space. Organization is measured in terms of Entropy. Navigating through areas with less entropy (i.e., less organized spaces) implies a higher chance for a person to get lost or confused.

Organization of a vertex v_i relates to the *Entropy* (Ent_i) at that vertex. It is predicted on a probability distribution $p_i\left(lvl\right)$ of a tree T_i with n_i^{lvl} vertices at each level, lvl.

$$Ent_i = -\sum_{lvl=0}^{height(T_i)} p_i\left(lvl\right) \log_2 p_i\left(lvl\right) \tag{3.3}$$

3.4 Dynamic Workflow

In the dynamic workflow, crowd simulation is used to analyze the time-based dynamics of human–building interactions. Three different crowd steering methods, namely Social Forces (Helbing & Molnar, 1995), Reciprocal Velocity Obstacle (Van Den Berg et al., 2011), and a Rule-based Hybrid framework (Singh et al., 2011) are integrated into this workflow. Further details on the human–building simulation framework can be found in Appendix A.

Two salient human-focused measures are considered, namely *Crowd Flow* and *Travelled Distance*. These measures have been widely used, especially in egress scenarios, to analyze crowd dynamics in environment designs (Berseth et al., 2015; Haworth, Usman, Berseth, Kapadia, & Faloutsos, 2017; Haworth, Usman, Berseth, Khayatkhoei, et al., 2017; Cassol et al., 2017).

3.4.1 Crowd Flow

Similar to vehicular traffic, pedestrian dynamics have also been studied in the context of environment traffic (Fruin, 1971b). The crowd flow is defined as a rate at which all the agents complete their final target activities (Berseth et al., 2015; Haworth, Usman, Berseth, Kapadia, & Faloutsos, 2017).

Simulating a crowd (C), where $A_c \subseteq A$ are the agents who completed the simulation and reach their final goals or targets (G), within some conventional time threshold (t_{sim}: the maximum simulation time set be the user). Let the average completion time of all the agents in reaching their final goals is t_a^f. The overall crowd flow of a simulation becomes f_C:

$$Flow_c = \frac{|A_c|}{t_a^f} \tag{3.4}$$

where $|A_c|$ indicates the cardinality of set A_c. Crowd flow is measured in *agents/second*.

3.4.2 Traveled Distance

The traveled distance relates to the path or trajectory followed by a virtual agent ($a \subseteq A$) to reach its target (G) in a given period of time (t_{sim}). Travelled distance can be defined as:

$$Distance_i = r_a \; t_{sim} \tag{3.5}$$

where r_a indicates the travel rate of agents and t_{sim} is the given simulation time. This work considers an average distance traveled by all the agents during the course of a simulation. Distance is measured in meters (m).

3.5 User Interaction

Both static and dynamic workflows to analyze human–building interactions are implemented into an interactive tool integrated within a mainstream environment modeling platform (e.g., Autodesk Revit). For static workflow, the tool allows users to select areas in the environment by drawing rectangular regions via drag and drop, to analyze spatial measures from Space-Syntax analysis (e.g., accessibility, visibility, and organization of the space). For the dynamic workflow, it allows users to interactively set crowd configurations within Autodesk Revit in the environment modeling editor. These configurations include setting the spawn areas for the agents, their activities (e.g., target locations), selection of crowd steering method, number of frames to simulate during the simulation, and color representation for the agents. Once crowd configurations are defined, users can then run simulations either in command-line (no visualization) or with 3D visualization of the simulation.

3.6 Spatial Feedback and Visualization

The static spatial measures from Space-Syntax analysis are computed for the user-selected areas in space, and these are quantitative data (i.e., numbers). We calculate them at each vertex in the visibility graph. To visualize them, we color-code their values as a heat map and overlay it on top of the actual floor plan of the environment. Designers can then visualize these heat maps to analyze and identify different kinds of interesting areas within selected environment spaces. For example, a designer can analyze the environment space to identify areas with high visibility so that emergency exit signs can be installed.

After the simulations are completed, the crowd-related measures (i.e., path trajectories, crowd flow, and traveled distances) are shown to the users as quantitative and qualitative feedback. Crowd flow and traveled distances are shown as numeric values since these numbers are easily understandable, and people can infer to them from their daily life experiences. Crowd trajectories are shown as qualitative data. It is a path that an agent in motion follows through space as a function of time. Designers can visualize agents' trajectories to analyze and examine the interaction between the environment space and occupants.

3.7 User Study

The goal of this study is to evaluate the usability and effectiveness of the presented workflows and the tool with respect to real-world use in the environment design. The hypothesis is that the presented tool with static and dynamic workflows provides better assistance compared to existing modeling software in generating more accessible environment design solutions increasingly for human-occupancy.

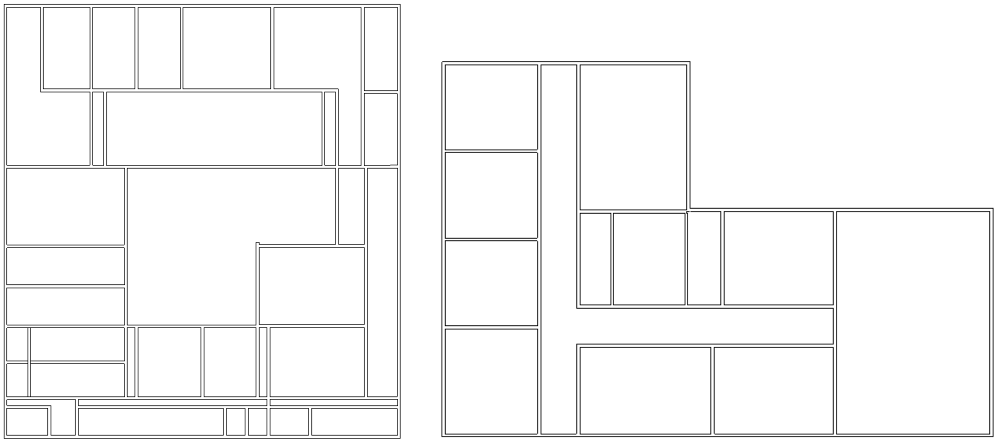
3.7.1 Material and Methods

Environments. A variety of real-world environments, including an *Art Gallery*, an *Office*, and a *Museum Space* are used to illustrate the effectiveness of presented analytics workflows. Figure 3.1 shows the layouts of these real-world environments. For this study, any openings and doorways are removed from the default environment layouts, which were added by an actual architecture firm. The users were asked to modify environments by adding openings and doorways, and modifying other architectural elements, in order to make the space (e.g., rooms) connected (i.e., traversable from other spaces in the environment). It is because any one of these spaces could be an office, meeting room, study or common area, cafeteria, or even a restroom, that someone needs to access.

To run dynamic human–building simulations, 75 virtual agents are uniformly distributed in different groups. These groups have diametric goals within the environment to achieve maximum space coverage and to ensure sufficiently rich interactions between agents, in a fashion that mimic everyday use of the space. Figure 3.2 shows an initial crowd configuration, spawn regions for agent groups, and their diametric targets, in a disconnected environment for the office space layout.

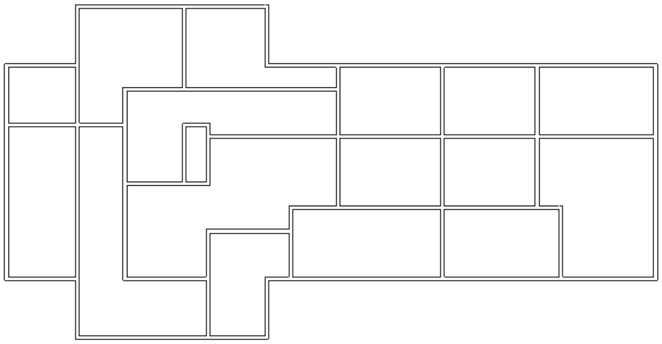
Apparatus. Three different design methods are used, one for each part of the study. $Design\ Method - A$: users are allowed to use the default environment modeling interface (i.e., standard Autodesk Revit). $Design\ Method - B$: users are allowed to use an augmented design modeling interface which exposes static workflow to perform spatial environment design analytics (as described in Section 3.3) in addition to the standard Autodesk Revit interface. $Design\ Method - C$: users are allowed to use an augmented design modeling interface that exposes dynamic workflow to perform human-building analytics (as described in Section 3.4) in addition to the standard Autodesk Revit interface. Later in this chapter, these design methods are also referred as $A\ or\ Method - A$, $B\ or\ Method - B$ and $C\ or\ Method - C$ respectively.

All participants completed the user study on a Lenovo laptop with the following specifications: Intel(R) Core i7-6700HQ CPU @ 2.60GHz (8 CPUs), 12 GB of RAM (DDR4), Nvidia GeForce GTX 1060 (Graphics Card) and Microsoft Windows 10 Home (OS). The development of the tool is done in .NET programming language, and is integrated into



Museum Space

Office Space



Art Gallery

Figure 3.1. The three real-world environments used in the study. All the openings and doorways are removed from the environment layouts. It is to let users modify environments by adding openings and doorways, and modifying other architectural elements, in order to make the environment spaces (e.g., rooms) connected (i.e., traversable from other spaces in these environments), using the presented interfaces.

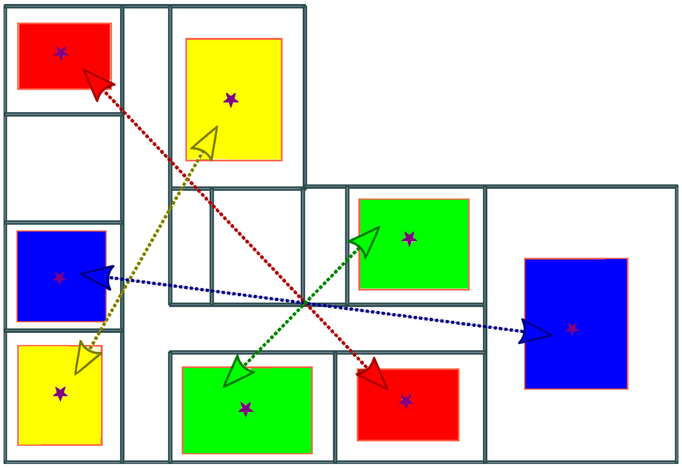


Figure 3.2. A sample crowd configuration used in the design task showing spawn regions for agent groups, and their diametric targets, in a disconnected environment for an *Office Space*. Different from traditional egress scenarios, the crowd is uniformly distributed in groups across the environment with diametric goals.

Autodesk Revit ® 2020. The framework to run human–building simulations is described in detail in Appendix A.

Participants. 15 people (8 female, 7 male and 1 non-binary/third-gender between 25 and 34 years of age) voluntarily participated in the user study. They were offered a $10 honorarium. The participants were mostly senior-level university students studying architecture and urban planning, and a few even had technical and professional certifications in architecture designing.

For the study, only those participants are recruited who have above-average knowledge and experience in interpreting architectural floor plans, understanding of pedestrians' flow and Space-Syntax concepts, and had some hands-on experience of using environment design tools (e.g., Autodesk Revit). Table 3.1 shows the demographic information collected from the recruited participants. Table B.1 (from Appendix B) shows the domain-knowledge information collected from the participants at the time of recruitment. Average scores for domain-knowledge on a scale of 1 – 5 for the ability to interpret and prior experience with architecture designs, prior experience in urban planning, and prior understanding of the considered static and dynamic spatial measures are 4.0, 4.0, 3.5, 3.9 and 3.5 respectively (self-reported).

Demographic Information

Gender	**Sex**	**Age**	**Country of Residence**
Female: 8 (53.3%)	Female: 8 (53.3%)	25 - 34 years old: 15 (100%)	Canada: 15 (100%)
Male: 6 (40%)	Male: 6 (40%)		
Non-binary/Third-gender: 1 (6.7%)	Intersex: 1 (6.7%)		

Table 3.1: Demographic information of user-study participants (self-provided).

Procedure and task. Before beginning the study session, each participant signed a consent form, was briefly instructed about the study design and spatial measures, completed two questionnaires to collect demographic information and domain knowledge, and was given a demo (practice session) on how to use the default (standard) and augmented

Autodesk Revit interfaces. Afterward, the actual study session started. Participants were allowed 15 minutes to complete individual parts of the study. Participants were given another 10 minutes to complete both a domain-specific feedback questionnaire (Table B.2 from Appendix B), and a Usefulness, Satisfaction and Ease of use, USE (Lund, 2001), questionnaire to evaluate the usability and effectiveness of spatial analytics and visualizations, after completing the design task for *Method – B* & *C*.

The study session is delivered in three parts. In all three parts, participants are asked to complete an environment design task. Each participant completed all three parts and used *Design Method – A* for the first part, *Design Method – B* for the second part and *Design Method – C* for the third part of the study. To prevent any learning effects between participants, the experimental conditions are delivered with a balanced Latin-square design for the selection of environments to complete the design tasks. For the augmented Autodesk Revit interfaces (e.g., *Method – B* & *C*), participants are instructed to press the feedback button in order to update (refresh) spatial visualizations to reflect the new design modifications. The updating or refreshing of a spatial visualization or feedback is counted as one design iteration. Participants are allowed to commit as many design iterations as necessary within the duration time (e.g., 15 minutes).

For the design task, participants are asked to add openings and pathways to a disconnected environment so people can traverse the environment in the most accessible way by modifying (but not entirely remove) different architectural and geometrical elements like walls, pillars, or other obstacles. Participants are not allowed to add more than two openings or doorways per room. The maximum time allowed to complete the design task is 15 minutes. Participants are notified 1 minute before the maximum allowed time to complete the task.

3.7.2 Analysis

Independent variables. The three real-world environments as well as the apparatus (*Design Method – A* , *B* & *C*) are the independent variables in the study.

Dependent variables. Static spatial measures from the Space-Syntax analysis (1) *Accessibility*, (2) *Visibility*, and (3) *Organization* of the space, and dynamic crowd-based measures (4) *Crowd Flow* and (5) *Traveled Distance*, for user-modified environments are the primary dependent variables. The total number of design iterations and completion time in each part of the study session are also computed as dependent variables.

3.7.3 Quantitative Results

Task completion time and elements' modifications. On average, participants spend 5 minutes and committed 250 design modifications of environment elements (e.g. walls, pillars, or other obstacles) in *Method – A*, 9 minutes and committed 130 modifications in *Method – B* and 8 minutes and committed 133 modifications in *Method – C*, respectively.

To compare users' design performances from augmented Revit interfaces (e.g., *Method – B* & *C*) with default Revit interface (e.g., *Method – A*), a similar set of spatial measures is computed in a post-study fashion for user modified designs from *Method – A*. This enables to compare the design performances between *Method – A* & *B* for static spatial measures (from static workflow) and between *Method – A* & *C* for dynamic crowd-based measures (from dynamic workflow).

Comparison of static spatial measures. *Accessibility*: a significant effect of *Design Methods* is found on participants' design performances at a significance level of $p < 0.05$ for the three conditions $[\mathrm{F}(1, 28) = 4.45 = 0.0439]$. A post-hoc comparison is then performed using the Tukey HSD test (Tukey, 1977) to compare across conditions. Tukey's test compares the means of the groups and identifies the ones which are significantly different from others. In the current analysis, the test indicates that *Method – B* has higher effects (i.e., Method – B has significantly higher mean) than *Method – A*. *Visibility*: a significant effect of *Design Methods* is found on participants' design performances at a significance level of $p < 0.05$ for the three conditions $[\mathrm{F}(1, 28) = 7.25 = 0.0118]$. A post-hoc comparison is then performed using the Tukey HSD test to compare across conditions. The test indicates that *Method – C* has higher effects than *Method – A*. *Organization*: no significant effect of *Design Methods* is found on participants' design performances at a significance level of $p < 0.05$ for the three conditions $[\mathrm{F}(1, 28) = 0.04 = 0.8385]$. However, participants' performed better in *Method – B* in general. Mean and Standard Deviation values are reported below.

Box and Whisker plots for static comparison. Figures 3.3, 3.4 & 3.5 show box and whisker plots for accessibility, visibility, organization of space, respectively, for the user designs from *Design Method – A* & *B*. Since no spatial analytics and visualization feedback was available in *Method – A*, therefore, participants failed to perform well and their modified designs from standard Revit tool produced comparatively low values for accessibility, visibility and organization of space. From *Method – B*, accessibility, visibility and organization values are reported for participants' best and final designs across all design task iterations. *Art Gallery*: Mean accessibility, visibility and organization values with standard deviation recorded from *Method – A* are 0.70 ± 0.19, 0.10 ± 0.06 and 0.19 ± 0.17 respectively, whereas the values for final designs from *Method – B* are 0.90 ± 0.06, 0.15 ± 0.09 and 0.23 ± 0.09 respectively. *Office*: Mean accessibility, visibility and organization values with standard deviation recorded from *Method – A* are 0.81 ± 0.18, 0.65 ± 0.31 and 0.38 ± 0.10 respectively, whereas the values for final designs from *Method – B* are 0.82 ± 0.13, 0.93 ± 0.06 and 0.25 ± 0.18 respectively. *Museum*: Mean accessibility, visibility and organization values with standard deviation recorded from *Method – A* are 0.30 ± 0.25, 0.32 ± 0.19 and 0.63 ± 0.20 respectively, whereas the values for final designs from *Method – B* are 0.40 ± 0.25, 0.69 ± 0.13 and 0.66 ± 0.24 respectively.

Design iterations and static spatial measures. Table 3.2 shows the number of design iterations completed by the participants during the task in *Design Method – B* and the corresponding *Accessibility*, *Visibility* and *Organization* values per iteration. Since all three environments were disconnected in the start, therefore, initial iterations have low accessibility, visibility, and organization values. However, as the users completed more design iterations and made the environments accessible and connected, the accessibility, visibility, and organization values increased. These values are color-coded from RED –

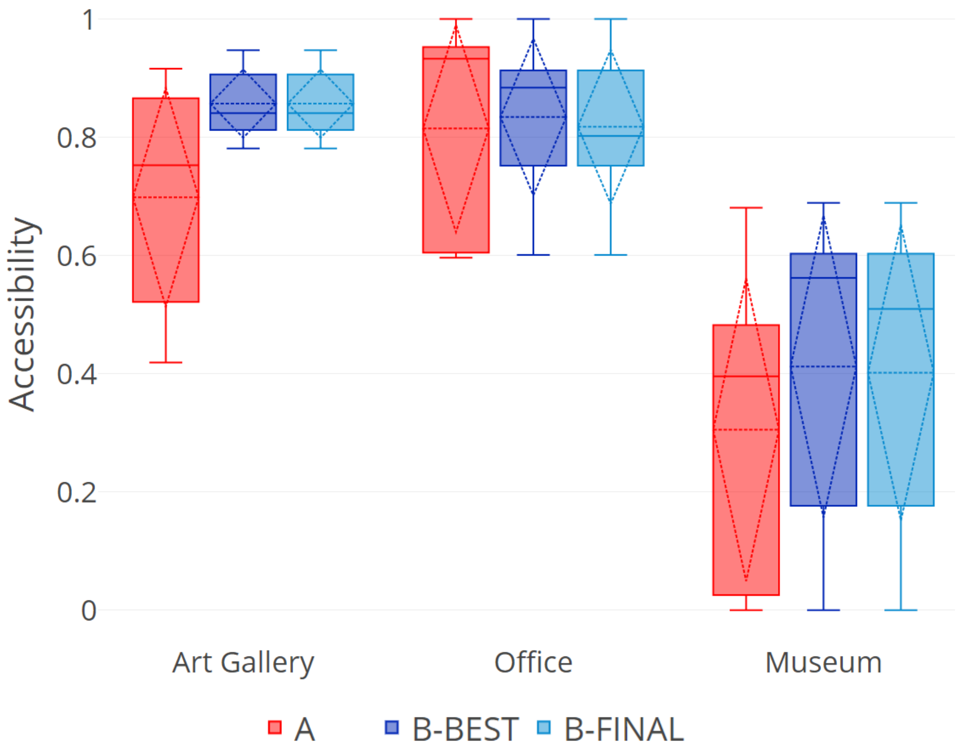


Figure 3.3. Box and Whisker plots for *Accessibility* for the user-modified environments from *Method – A* & *B*. For *Method – B*, results from best and final design iterations are shown. Since no spatial visualization feedback was available in *Design Method – A*, therefore, participants failed to perform well and their modified designs produced comparatively low values for *Accessibility*, *Visibility* and *Organization*.

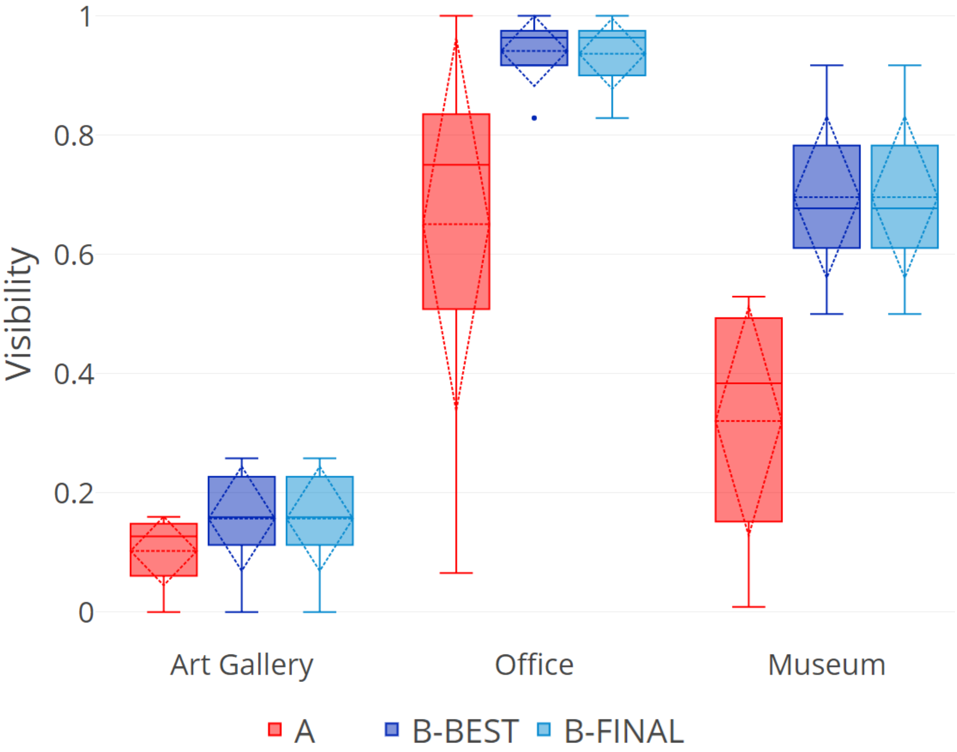


Figure 3.4. Box and Whisker plots for *Visibility* for the user-modified environments from *Method – A* & *B*. For *Method – B*, results from best and final design iterations are shown. Since no spatial visualization feedback was available in *Design Method – A*, therefore, participants failed to perform well and their modified designs produced comparatively low values for *Accessibility*, *Visibility* and *Organization*.

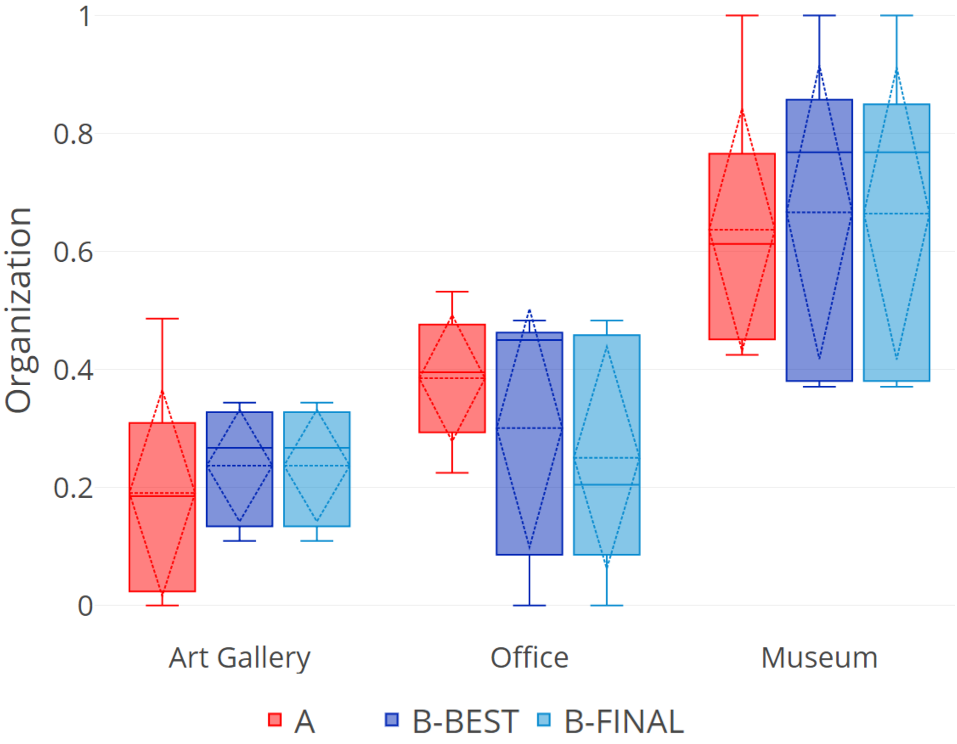
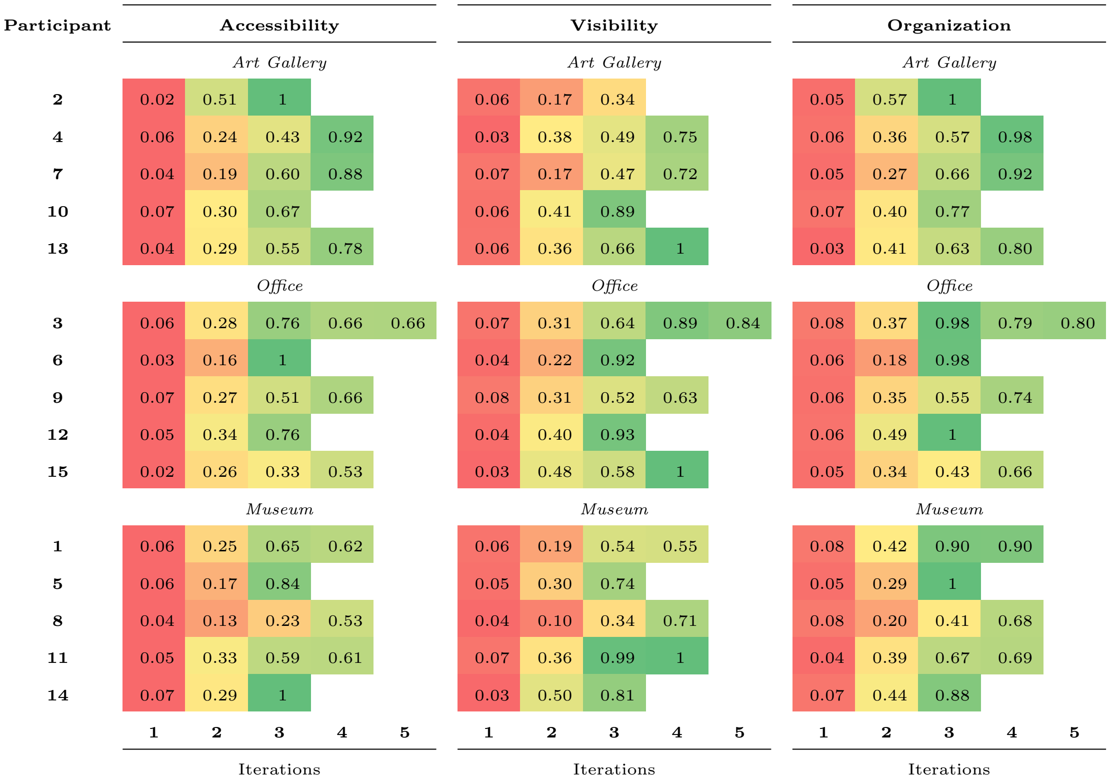


Figure 3.5. Box and Whisker plots for *Organization of Space* for the user-modified environments from *Method – A* & *B*. For *Method – B*, results from best and final design iterations are shown. Since no spatial visualization feedback was available in *Design Method – A*, therefore, participants failed to perform well and their modified designs produced comparatively low values for *Accessibility*, *Visibility* and *Organization*.

GREEN, where RED highlights low values for these spatial measures and GREEN, high.



Participant	Accessibility					Visibility					Organization				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	Art Gallery					*Art Gallery*					*Art Gallery*				
2	0.02	0.51	1			0.06	0.17	0.34			0.05	0.57	1		
4	0.06	0.24	0.43	0.92		0.03	0.38	0.49	0.75		0.06	0.36	0.57	0.98	
7	0.04	0.19	0.60	0.88		0.07	0.17	0.47	0.72		0.05	0.27	0.66	0.92	
10	0.07	0.30	0.67			0.06	0.41	0.89			0.07	0.40	0.77		
13	0.04	0.29	0.55	0.78		0.06	0.36	0.66	1		0.03	0.41	0.63	0.80	
	Office					*Office*					*Office*				
3	0.06	0.28	0.76	0.66	0.66	0.07	0.31	0.64	0.89	0.84	0.08	0.37	0.98	0.79	0.80
6	0.03	0.16	1			0.04	0.22	0.92			0.06	0.18	0.98		
9	0.07	0.27	0.51	0.66		0.08	0.31	0.52	0.63		0.06	0.35	0.55	0.74	
12	0.05	0.34	0.76			0.04	0.40	0.93			0.06	0.49	1		
15	0.02	0.26	0.33	0.53		0.03	0.48	0.58	1		0.05	0.34	0.43	0.66	
	Museum					*Museum*					*Museum*				
1	0.06	0.25	0.65	0.62		0.06	0.19	0.54	0.55		0.08	0.42	0.90	0.90	
5	0.06	0.17	0.84			0.05	0.30	0.74			0.05	0.29	1		
8	0.04	0.13	0.23	0.53		0.04	0.10	0.34	0.71		0.08	0.20	0.41	0.68	
11	0.05	0.33	0.59	0.61		0.07	0.36	0.99	1		0.04	0.39	0.67	0.69	
14	0.07	0.29	1			0.03	0.50	0.81			0.07	0.44	0.88		
	Iterations					Iterations					Iterations				

Table 3.2: Static spatial measures *Accessibility* (LEFT), *Visibility* (MIDDLE) and *Organization* (RIGHT), from Space-Syntax, for the design iterations completed by the users in *Design Method – B*. Overall, users' design performance increased as they complete more iterations and have comparatively best results in their last iterations.

Comparison of dynamic crowd-based measures. A significant effect of *Design Methods* is found on participants' design performances at a significance level of $p < 0.05$ for the three conditions $[F(1, 28) = 33.95 = 2.9175e{-}06]$. A post-hoc comparison is then performed using the Tukey HSD test to compare across conditions. The test indicates that *Method – C* (i.e., default Revit interface augmented with crows-based analytics) has higher effects than *Method – A*.

Box and Whisker plots for dynamic comparison. Figures 3.6 & 3.7 show box and whisker plots for crowd flow and traveled distance for the user designs from *Design Method – A* & *C*. From *Design Method – C*, crowd flow and travelled distances are reported for participants' best and final designs across all design task iterations. *Art Gallery*: Mean and standard deviation values for crowd flow and travelled distance recorded from *Method – A* are 0.53 ± 0.15 and 41.42 ± 2.52 respectively, whereas the values recorded from *Method – C* for the final designs are 1.01 ± 0.24 and 37.83 ± 5.16 respectively. *Office*: Mean and standard deviation values for crowd flow and travelled distance recorded from *Method – A* are 0.94 ± 0.07 and 38.96 ± 2.46 respectively, whereas the values recorded from *Method – C* for the final designs are 1.54 ± 0.16 and 38.08 ± 4.74 respectively. *Museum*: Mean and standard deviation values for crowd flow and travelled distance recorded from *Method – A* are 0.50 ± 0.35 and 40.25 ± 3.89 respectively, whereas the values recorded from *Method – C* for the final designs are 1.31 ± 0.10 and 34.45 ± 6.69 respectively. Crowd flow is measured in $agents/second$ and travelled distance in *meter*

Design iterations and dynamic crowd-based measures. Table 3.3 shows the number of design iterations completed by the participants during the task in *Design Method – C* and the corresponding *Crowd Flow* values per iteration. Since all three environments were disconnected in the start, therefore, initial iterations have low crowd flows. However, crowd flow increased as the participants committed more design iterations and made the environment accessible and connected. Flow values are color-coded from RED – GREEN,

Figure 3.6. Box and Whisker plots for *Crowd Flow* for the user modified environments from $Method - A$ & C. For $Method - C$, results from best and final design iterations are shown. Overall, user designs from the augmented Revit interface ($Method - C$) performed well, and produced high crowd flows. Since no spatial visualization feedback was available in $Design\ Method - A$, therefore, participants failed to perform well and their modified designs produced low crowd flows.

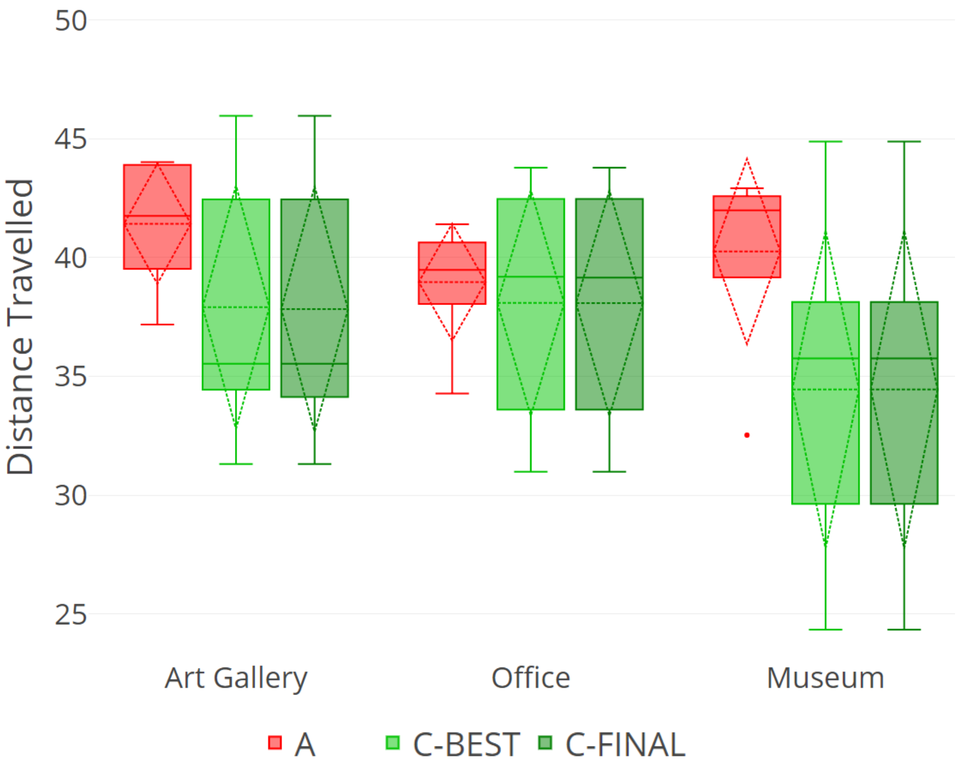


Figure 3.7. Box and Whisker plots for *Traveled Distance* for the user modified environments from *Method – A* & *C*. For *Method – C*, results from best and final design iterations are shown. Overall, user designs from the augmented Revit interface (*Method – C*) performed well (e.g., agents traveled less distances). Since no spatial visualization feedback was available in *Design Method – A*, therefore, participants failed to perform well and their modified designs made the agents to travel more distances.

where RED highlights low crowd flow and GREEN, high.

A one-way between-subjects analysis of variance is conducted. Statistical results indicate a significant effect of *Design Methods* on participants' design performances. Furthermore, posthoc tests using the Tukey HSD indicate that $Method - B$ & C have higher effects on design performances. Comparatively, user designs from $Method - B$ & C achieved higher mean values for the static and dynamic spatial measures with low standard deviations, which shows consistency among users with these design methods. Overall, as users completed more design iterations with augmented Revit ® tools, they made accessible and more human-aware environments.

3.7.4 Qualitative Results

Figures 3.8 & 3.9 show a selection of qualitative results for art gallery and museum space for the users' modified designs from standard ($Method - A$) and augmented ($Method - B$ & C) Revit interfaces. Spatial visualizations indicate that with augmented tools, users made more informed decisions and successfully achieved multi-route spaces, making the environments more accessible. Figure 3.10 shows sample designs from the user study. Two set of environment designs are shown which were designed using augmented Revit tools ($Method - B$ & C). Four design iterations are committed. Spatial feedback helped participants to design more efficient environments in the succeeding iterations. Both *Accessibility* and *Crowd Flow* values are found highest in the last iterations respectively.

Participant	**1**	**2**	**3**	**4**	**5**
	Art Gallery				
3	0	0	1.50	1.24	
6	0	0	0.80	1.04	1.15
9	0	0	0.58	1.20	
12	0	0.40	1.20		
15	0	0.20	0.40	0.92	
	Office				
1	0	1	1.38		
5	0	0.28	0.66	1.58	
8	0	0.38	1	1.66	
11	0	0.38	0.98	1.34	
14	0	0.18	0.18	1.75	
	Museum				
2	0	0.28	0.68	1.38	
4	0	0	0.34	0.86	1.12
7	0	0	0.28	1.36	
10	0	0	1.42		
13	0	0.56	0.70	1.32	

Iterations

Table 3.3: The *Crowd Flow* values for design iterations completed by users in *Method – C*. Higher flows are considered good. Overall, the flow values increased as users completed more iterations and achieved the highest flow in last iteration.

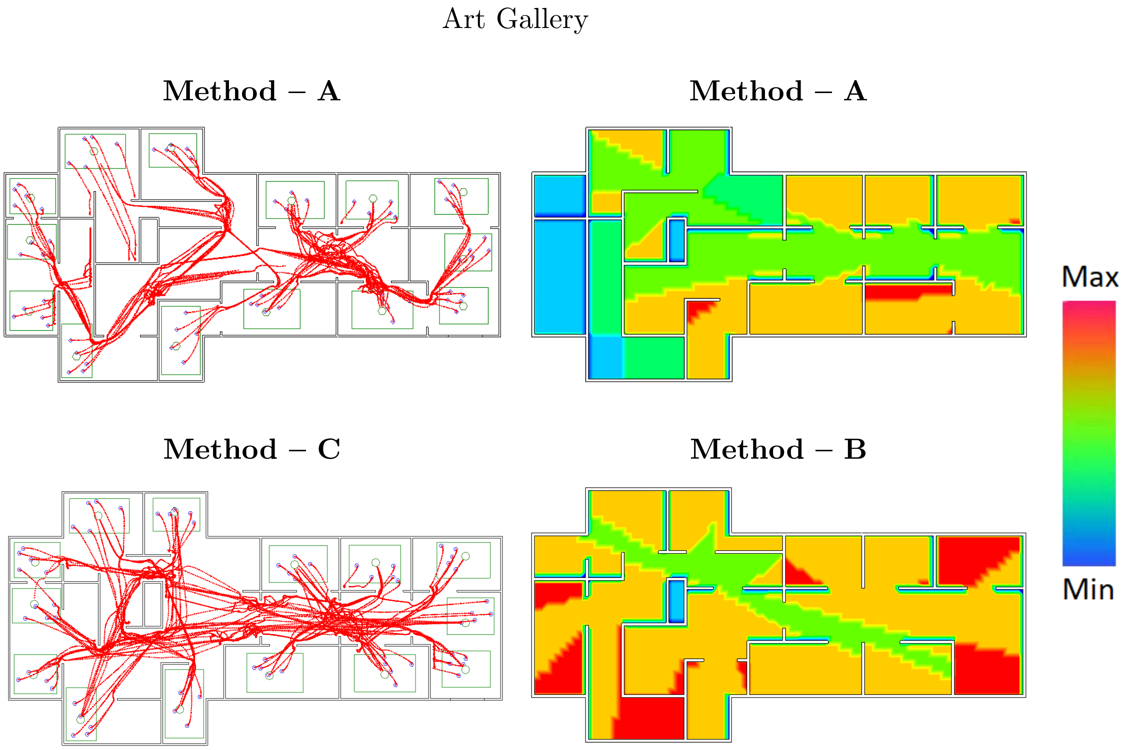


Figure 3.8. Comparing qualitative results for *Art Gallery* for the user-modified designs between: *Methods* – *A* & *B* and *A* & *C*. For augmented tools (*B* & *C*), designs from the final users' iterations are used. Users with augmented Revit interface were able to design multi-route environments (e.g., more accessible environments).

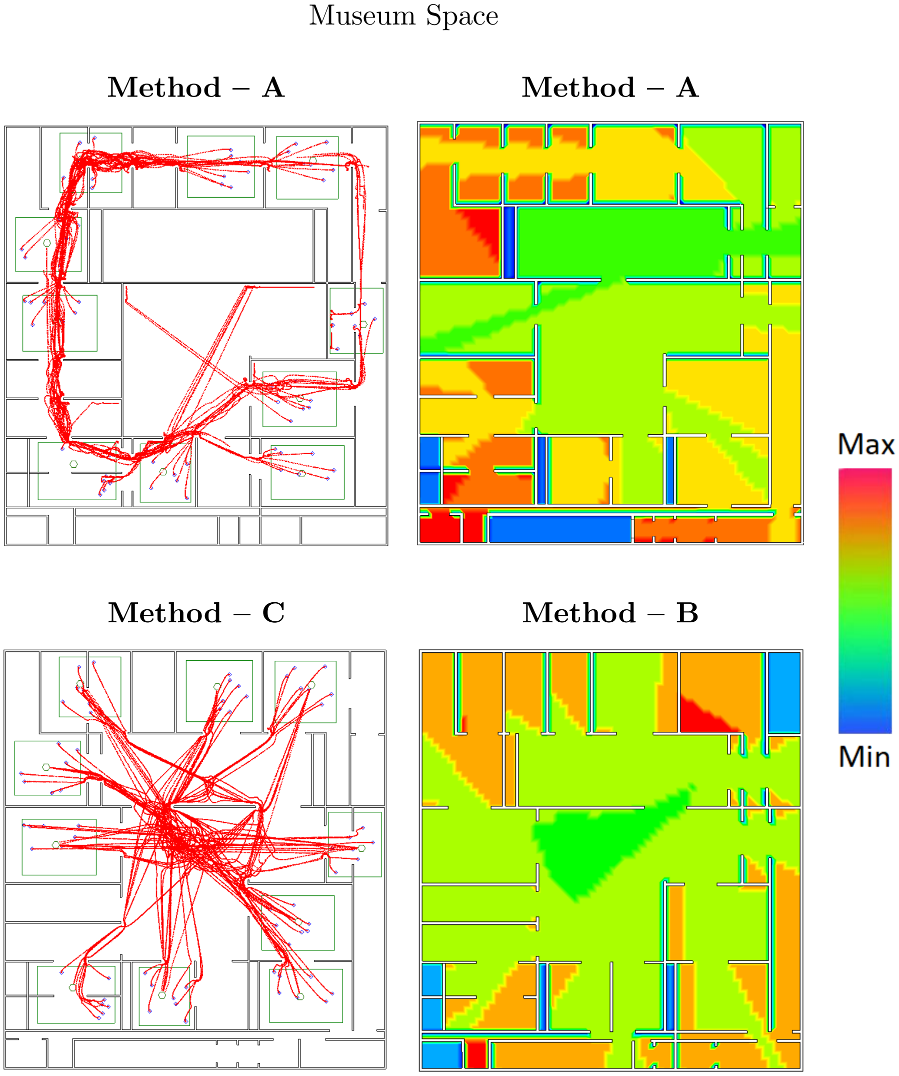


Figure 3.9. Comparing qualitative results for *Museum* for the user-modified designs between: *Methods – A* & *B* and *A* & *C*. For augmented tools (*B* & *C*), designs from the final users' iterations are used. Users with augmented Revit interface were able to design multi-route environments (e.g., more accessible environments).

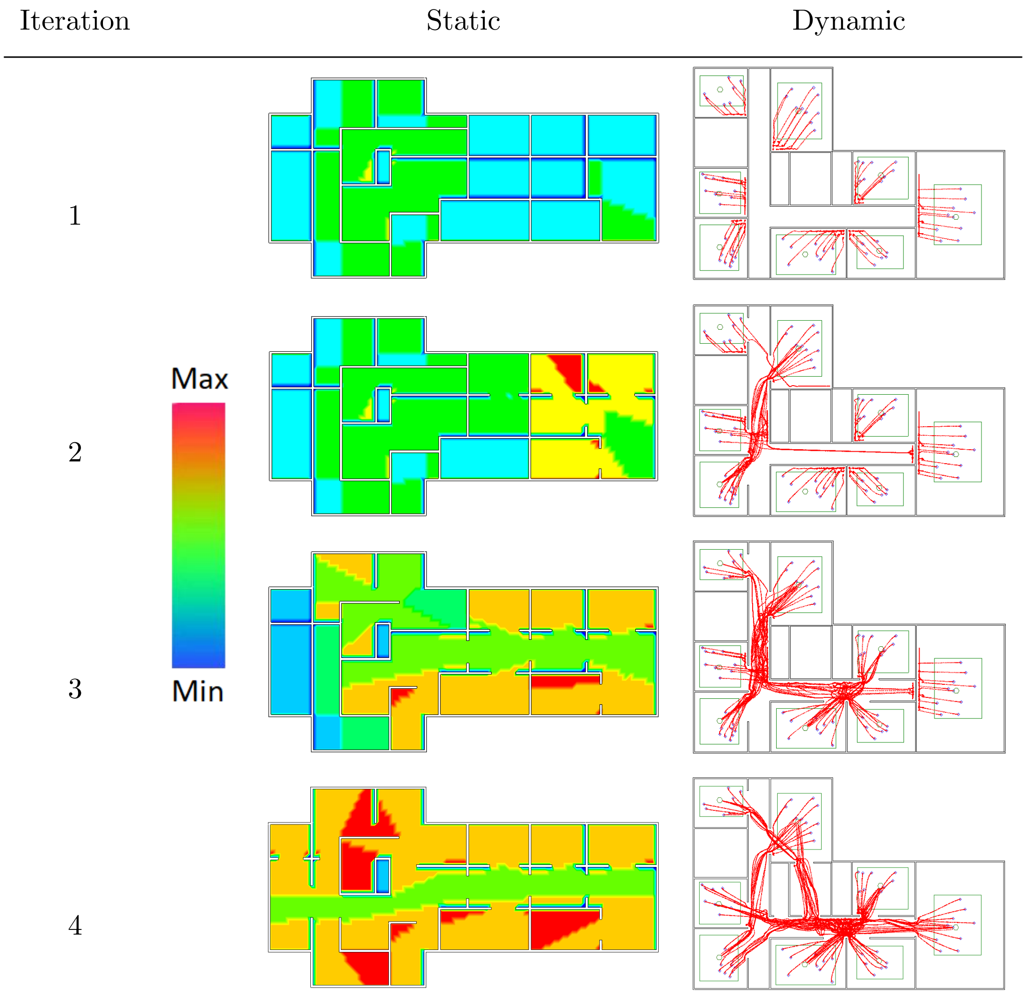


Figure 3.10. User-modified environments using augmented Autodesk Revit interfaces: *B* – Revit-default with Static Analytics (Left) and *C* – Revit-default with Dynamic Analytics (Right). Spatial feedback allowed users to design more efficient environments in the succeeding iterations (informed decision-making). Accessibility and crowd flow values for iteration 1 are reported as (0,.04), for iteration 2 as (.38,.19), for iteration 3 as (1.0,.60), and for iteration 3 as (1.66,.88) respectively. The metric values are highest in the last iteration. For static workflow, in the last iteration, heat map showing fully connected environment with less accessible areas in the surroundings (ORANGE – RED) and high accessible areas at the center (GREEN).

3.7.5 Usability and Effectiveness

To evaluate the usability and effectiveness of the presented workflows and the tool (e.g., augmented Revit interfaces), participants completed a survey – Usefulness, Satisfaction and Ease of use (USE) questionnaire, after completing the design tasks in *Method – B* & *C*. Both of the methods *B* & *C* are highly evaluated. The mean scores for *Usefulness*, *Ease of use*, *Ease of learning* and *Satisfaction* are given in Table 3.4. Overall average scores for all the USE dimensions are 80.90 and 80.92 for *Method – B* & *C* respectively. Historically, a USE scale score of 80% and above is widely considered as a good evaluation.

After completing design tasks in *Method – B* & *C*, participants also recorded their opinion on the effectiveness of spatial analytics and visualizations in real-life architecture and building designing. Table B.2 (from Appendix B) shows the exact questions which were asked from the participants and their responses. The recorded user responses are all above average (i.e., 3.7 and above out of 5). In the opinion of participants, such analytic tools can be a valuable addition to traditional architecture designing. They can help architects and designers in making informed decisions at every phase during the design process. They also believe that to some extent, the static and dynamic spatial measures are a valid representative of how human move in space and also that such tools can be adopted into professional environment design pipelines.

Usability Dimension	***Score* (Method B)**	***Score* (Method C)**
Usefulness	75.83%	76.50%
Ease of use	80.00%	78.54%
Ease of learning	85.33%	86.00%
Satisfaction	82.47%	82.66%

Table 3.4: The usability levels for each dimension in the USE Questionnaire (Usefulness, Satisfaction, and Ease of use). Overall average scores for all the USE dimensions are 80.90 and 80.92 for *Method – B* & *C* respectively.

3.8 Summary

This chapter presented static and dynamic workflows to analyze environment spaces for human-building interactions. Different from other simulation and analytics tools representing similar design metrics, the presented workflows are readily integrated into a professional environment design pipeline (e.g., Autodesk Revit) for demonstration and evaluation purposes. Beyond static spatial analyses of the environment space, the tool enables dynamic crowd simulations to investigate the impact of an environment on the building occupants, all interactively and in real-time. The user study demonstrates that using such tools, designers can progressively refine their environments to improve developed designs in terms of accessibility, visibility, organization, crowd flow, and walking distances. The presented tool itself, however, is not bounded to any specific metric, and more static and dynamic measures can be adopted. A users' questionnaire demonstrates the usability and effectiveness of the tool in supporting designers' decision-making.

Chapter 4

Semantics, Building Codes & Simulation-based Egress Analysis

In the previous chapter, I presented interactive workflows to analyze human–building interactions, integrated into a mainstream environment modeling platform (e.g., Autodesk Revit). This contribution paves the road to evaluate environment designs for *International Building Code* (IBC) involving decision-making concerning human-factors (e.g., Means of Egress).

Complying with the IBC is essential in environment design modeling. Computer-Aided Design (CAD) tools have been developed to perform BIM-based (Building Information Modeling) rule checking for fire egress scenarios. Such tools help identify design flaws for potential egress evacuations. However, these rule checking tools consider static space features without considering the space semantics (i.e., what space is designed for), and more importantly, time-based dynamics to understand how the design would impact the behavior of human inhabitants. As a result, the environment layout may pose threats to human safety.

To this end, this chapter presents the development of two computational workflows to perform an automated semantic-based rule checking for the IBC rules for *Means of Egress*. In the first workflow, a standard static egress analysis is used to compute egress routes by incorporating space semantics. Next, a dynamic approach is used to compute egress routes and the analysis of egress scenarios using human behavior simulations. This chapter serves as the second contribution under the research bin "Environment Design Analysis".

4.1 Overview

Understanding the extent to which an environment supports safe living and working conditions for the inhabitants is a critical aspect of the environment design. Building Information Modeling (BIM) and Computer-Aided Design (CAD) tools enable the generation of computational building and environment models that are amenable to the evaluation of different functional specifications, including the International Building Code (IBC) for built-designs (Eastman, Teicholz, Sacks, & Liston, 2011).

An automated rule-checking process generally validates the IBC by applying specific rules and constraints on the environment specifications without changing the design itself and reports the outcome as "pass" if they comply with the codes or "fail" otherwise. Some computational tools to perform IBC rule checking exist as standalone softwares (Solibri, 2009; Khemlani, 2005), while others are integrated into commercial environment design platforms (Nguyen & Kim, 2011). A significant research focus has been on rules for planning egress (Balaban, Kilimci, & Cagdas, 2012). However, current workflows for egress planning rely mostly on static environment specifications (e.g., geometry information), do not take into account space semantics (e.g., potential space usage), and only consider a static "distance" measure while planning the egress routes with no understanding of time-based dynamics of potential occupants.

The hypothesis is that IBC rule checking with human–building simulations and space usage information (e.g., semantics) can extend current static rule checking approaches, and thus help environment designers to design more human-focused environments. To this end, a computational tool is presented in this chapter to perform an automated semantic-based simulation-guided rule checking of IBC rules for fire egress of an environment. Unlike standard egress planning workflows, the presented approach uses crowd simulations, which yield a time-based representation of dynamic behaviors of occupants in the environment (e.g., evacuation times for egress routes). A case study is presented to showcase the limitation of standard egress rule checking workflows in favor of a semantic-based simulation-guided rule checking approach.

4.2 System Architecture

An interactive computational tool is presented that enables designers to evaluate the International Building Code (IBC) for *Means of Egress*. It allows users to assign semantics

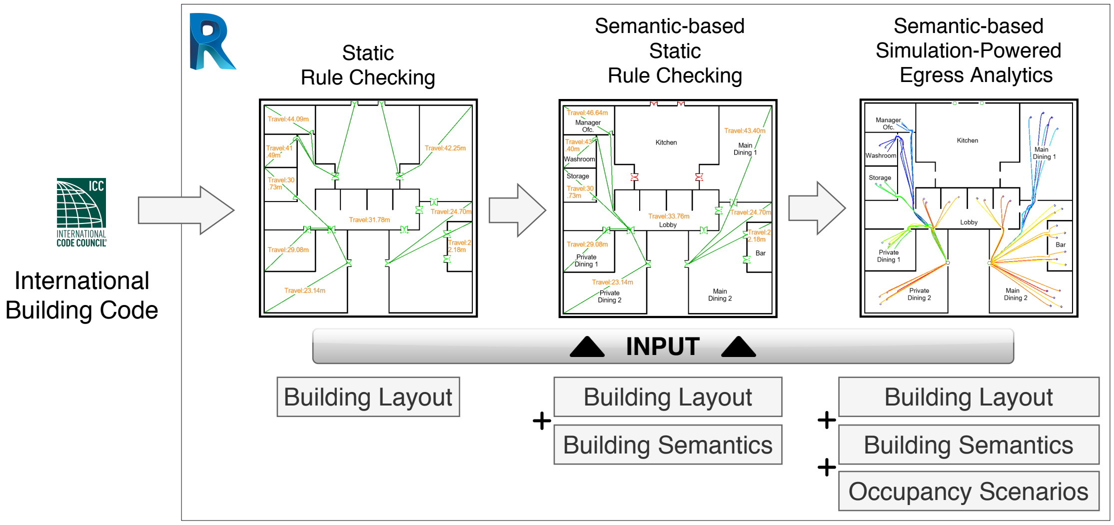


Figure 4.1. An overview of the system architecture for the semantic-based simulation-powered IBC rule checking for *Means of Egress*.

to environment spaces (e.g., labeling the rooms), compute and visualize egress plans for evacuations, analyze travel distances and evacuation times for egress routes, and analyze dynamics of potential human–building interactions for different levels of crowd occupancies. Figure 4.1 demonstrates an overview of the presented approach.

4.2.1 International Building Code

Validation of several environment design rules (e.g., geometric rules) are implemented as per the International Building Code (IBC) 2018 developed by *International Code Council* (International Code Council, 2018a). In principle, these rules must be adopted as baseline building standards while designing an environment layout. One of the ideas behind adopting IBC is the safety concern of potential occupants of the built-environment.

Since a significant amount of IBC rules deal with fire emergencies, therefore, primarily this chapter focuses on the IBC rules for *Means of Egress* (International Code Council, 2018b) . These include rules for “ceilings” (e.g., vertical rise, headroom of protruding objects from ceilings), “doors” (e.g., width and height of a door leaf, minimum/maximum door opening angles), “ramps” (e.g., slope, vertical rise, the width of a ramp), “egress paths” in the emergent evacuation of a building (e.g., travel distances, permissible and prohibited room types for egress), and “corridors” (e.g., fire-resistance, width, capacity). These rules are summarized in Table 4.1.

4.2.2 Space Semantics

The word semantic is widely known as the study of “meaning”. In the domain of environment and building design, semantics are the means to understand the built-space, allowing designers to consider for potential design space usage and accordingly account for the foreseen behavioral properties of the built-environment. An example of environment semantics for a house would be: “bedroom area” – space where people can sleep, “kitchen” – a space to prepare food, “laundry room” – a space to do the laundry, and a “washroom”.

The presented workflow requires designers to input semantic information directly into the environment (e.g., BIM model) interactively. It then automatically extracts this information to compute an egress plan and validate the selected IBC rules for *Means of Egress*. If the semantic information is missing in the environment, the tool notifies the

Category/Section	**Description**
Ceilings/1003	*"the means of egress shall have a ceiling height of not less than 7 feet 6 inches above the finished floor"* & *"protruding objects are permitted to extend below the minimum ceiling height...where a minimum headroom of 80 inches is provided over any circulation paths"*
Doors/1010	*"a door should provide a minimum clear opening width of* 32 *inches"*, *"maximum width of a swinging door leaf shall be 48 inches nominal"* & *"minimum clear opening height of doors shall be not less than 80 inches"*
Ramps/1012	*"ramps used as part of a means of egress shall have a running slope not steeper than one unit vertical in 12 units horizontal"*
Egress Paths /1016 – 1017	*"egress shall not pass through kitchens, storage rooms, closets or spaces used for similar purposes"* & *"exit access travel distance shall be measured from the most remote point of each room, area or space"*
Travel Distance /1017	*for most building types "exit access travel distance shall not exceed the value of* $200ft$ *without sprinkler system" and "*$250ft$ *with sprinkler system" installed*

Table 4.1: Summary of IBC rules for "Means of Egress". Extracted from Chapter 10 of *International Building Code*, 2018/19, developed by the *International Code Council.*

user about its absence. It is so the designer can add the missing semantics in environment spaces.

Egress routes are computed using the shortest paths on a graph (G) of the environment layout where nodes (N) and edges (E) represent rooms and doors in the graph, respectively. Whenever semantics are added or removed, the graph is updated. If any room space is prohibited from passing through during egress as per IBC rules for *Means of Egress*, edges connected to the node of that room become untraversable in the graph, and hence, they do not participate in egress routes. An example of such a room could be Kitchen, Electricity, or Storage room.

4.2.3 Human Behavior Simulations

Agent-based simulations are used to model human–building interactions, which yields a time-based representation of dynamic behaviors of occupants in the environment space. Such analysis requires a specification of the *environment layout* (e.g., walls, pillars, obstacles, and doors), the *occupants* to populate the environment (e.g., spawn regions for the crowd, one or more target destinations, and walking speed) and the *activities* they engage in (e.g., emergency evacuation). SteerSuite (Singh, Kapadia, Faloutsos, & Reinman, 2009a) is used to perform human-building simulations using a social forced based crowd steering technique. The presented tool itself, however, is not bound to use a single kind of crowd steering model. More steering techniques can be integrated. Further details on human-building simulation processes are discussed in Appendix A.

In order to spawn virtual occupants in built-spaces, the tool automatically iterates over all the closed-spaces (e.g., rooms) in the given environment model. It then maps the number of virtual occupants to be spawn within these closed spaces using a standard qualitative classification, Level of Service (LoS) (Fruin, 1971b), as per the area of these spaces. There are six Levels of Service. LoS has been used in traffic and crowd simulations to measure the quality of movement flow both for automotive and pedestrian applications. LoS classes are generally given a grade level (from A–F), which are summarized in Table 4.2. These classes are further categorized into three levels: *LoS Low* – it is an average of grade A & B (representing a sparse crowd), *LoS Medium* – average of grade C & D (a moderate crowd) and *LoS High* – average of grade E & F (a dense crowd). Figure 4.2 shows two sample simulation snapshots for egress.

Human–building simulations yield not just the traveled distances from the starting position of virtual occupants to the nearest exit, but also the evacuation times. Unlike static egress planning, which only relies on the distance information, with simulation-powered occupant movements, more efficient egress planning can be done, and more safe environment layouts can be designed. The tool also allows users to compute an average *Egress Flow*, which represents the rate at which virtual occupants vacate the environment (the higher, the better).

Level of Service	Crowd Density	Selected Levels
A	≤ 0.27	*Low*
B	0.43 to 0.31	
C	0.72 to 0.43	*Medium*
D	1.08 to 0.72	
E	2.17 to 1.08	*High*
F	≥ 2.17	

Table 4.2: Level of Service (LoS) values and the respective crowd density mapping. The density is measured in occupants per square meter.

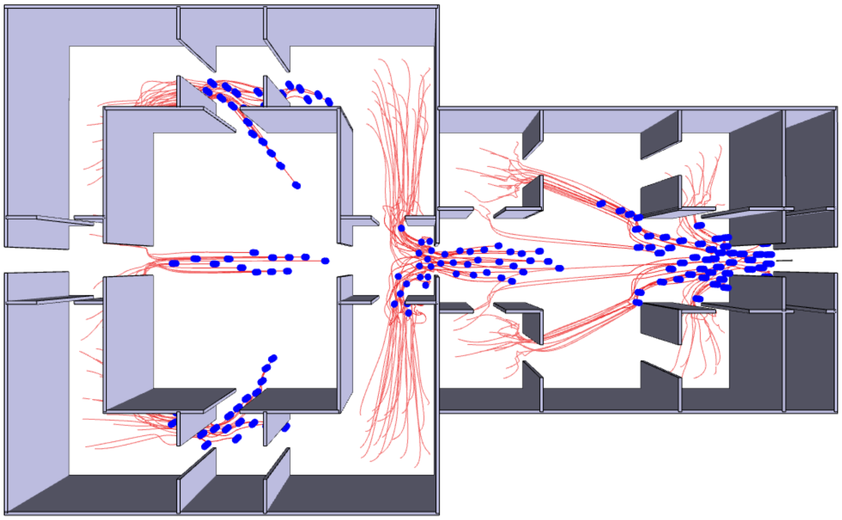


Figure 4.2. A sample snapshot of crowd simulation during egress at $t = 234^{th}$ frame. The circular disks represent virtual occupants, whereas *Red* line segments represent crowd trajectories.

4.3 Case Study

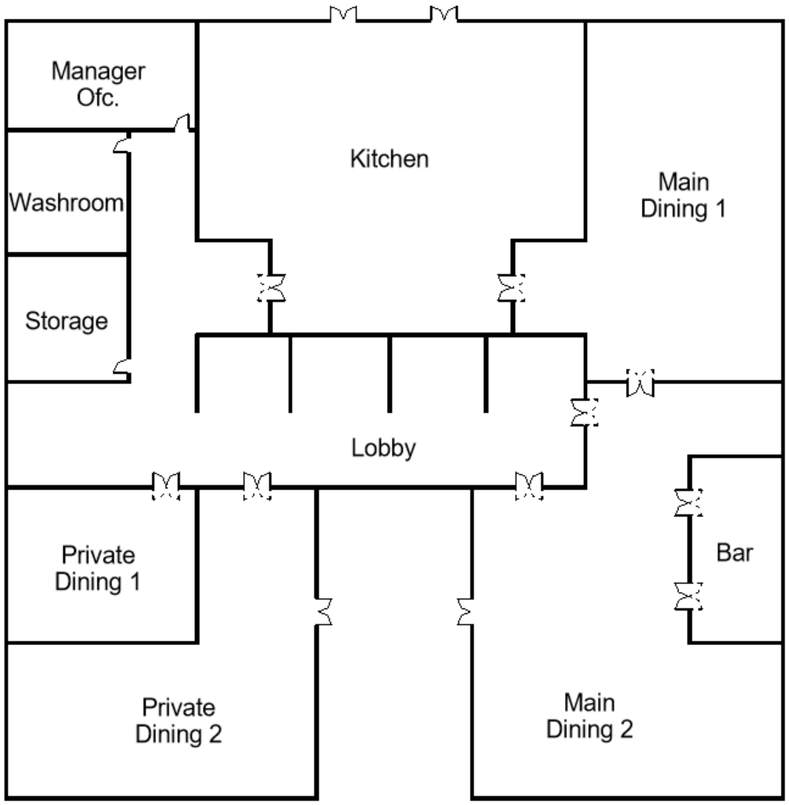
The presented case study first investigates the standard egress-planning workflow as per IBC rules (e.g., Section 1016/1017, Chapter 10, IBC 2018), which illustrate the requirements for egress paths in case of an emergency evacuation of a building. It then highlights the limitation of standard egress-planning workflow, which does not take into account space semantics and relies on a static distance measure to compute egress routes. The case study then shows how crowd simulations can provide a time-based dynamics of potential human–building interactions (e.g., by providing traveled distances and evacuation times of the agents) which may be of assistance in designing safer egress plans. Finally, it demonstrates that using human–building simulation workflows, users can account for different levels of crowd occupancies in different areas of the environment to understand the dynamics of design space for a range of crowds.

4.3.1 Environment

A restaurant layout is used in the case study (Figure 4.3). There are 10 rooms and 4 external exits in the design layout. The overall area of the environment space is approximately 7545 meters.

4.3.2 Static Egress Analysis without Semantics

First, the egress plan is computed for the selected environment using the standard workflow without semantics. In the standard workflow, only the static environment elements



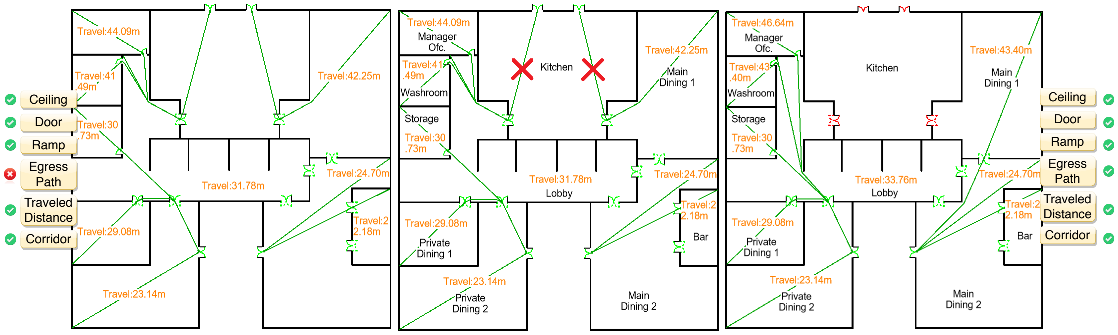
Environment Layout with Space Semantics

Figure 4.3. The restaurant layout used in the case study with semantaic information (e.g., room labels).

like rooms, exits, corridors, and ramps are considered while planning for the egress routes. Therefore, for a given environment model, an egress plan simply consists of paths from rooms to their nearest exits, relying on the geometric information of the given model alone, and missing any semantic information or route evacuation times during the planning of egress routes.

The IBC rules for *Means of Egress* state that travel distances to exits are to be measured from the most remote location of each room (Section 4.1), therefore, to devise an egress plan, the farthest point is selected in every room. We then calculate the shortest routes from that farthest point in each room to its nearest exit.

Figure 4.4 (Left) shows an egress plan for static analysis in the absence of space semantics, which is a default workflow. Room and environment exits in *green* showcase that there is absolutely no restriction on these spaces (e.g., associated rooms), and they can be part of egress routes. However, such a standard workflow might lead to an egress plan which violates certain IBC rules for *Means of Egress*. It is because one of the rooms in the built-environment is to be used as "Kitchen", and as per the IBC rules, such a space can not be a part of the egress plan. This egress planning violation can be seen in Figure 4.4 (Middle). Besides, in a standard workflow, only a static "distance" information is available to designers for egress routes.



No Semantics (default workflow)

IBC Violation *Means of Egress*

Semantics (presented workflow)

Figure 4.4. Emergency egress plan of the selected environment. Left: routes are computed using default egress planning workflow (i.e. in absence of space semantics). Middle: adding room labels to the egress plan shown in (Left). Right: routes are computed by taking into account the space semantics (i.e. semantics are defined). For both analyses, traveled distances are reported from the farthest point in every room to the nearest exit. Doors in red represent the entrance to areas which are not to be considered as part of egress routes under *Means of Egress* rules defined in building codes.

4.3.3 Static Egress Analysis with Semantics

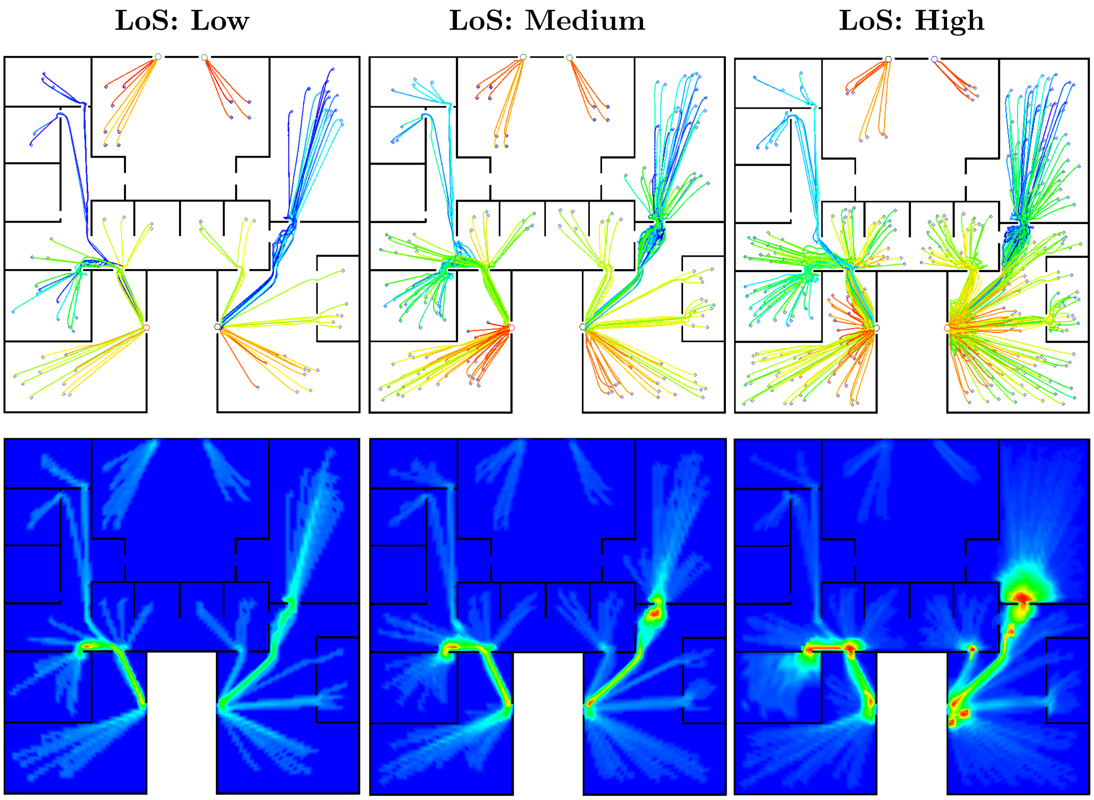
Next, *Space Semantics* are introduced in the environment and used in static rule checking for egress. These semantics include *Kitchen*, *Main Dining* (2), *Private Dining* (2), *Bar*, *Washroom*, *Storage*, *Lobby* and *Manager's Office*, for the selected restaurant environment. Such representations allow users to label the spaces (e.g., rooms) based on their potential usage. As a result, the presented tool can now compute an egress plan which could not be computed in the absence of semantic information. For example, now, while computing the egress routes, it ensures that no egress route passes through certain restricted environment areas that are not allowed to be passed under IBC rules for *Means of Egress*. Hence, maximizing the quality assurances of environment layouts for human safety.

Figure 4.4 (Right) shows an egress plan for static analysis in the presence of design space semantics. In the presented workflow, individual rooms or areas which are to be used as "Kitchen", "Electricity room", or "Storage areas" are constrained not to participate in egress routes. The exits of such rooms are highlighted in *red* to showcase that these are restricted entrances, and as per IBC rules, not allowed to pass through during egress evacuation. As a result, avoiding any of IBC rule violations for *Means of Egress*, and empowering designers to further enhance the safety of potential environment occupants by considering space semantics in preparing for egress plans. The travel distances are also reported along with egress routes to further help in making informed design decisions. However, the egress decisions are still relying on static distance information alone, even after incorporating space semantics in the planning.

4.3.4 Dynamic Egress Analysis with Semantics

In the static egress planning, egress routes are computed by relying on a static distance measure alone (i.e., travel distances from rooms to nearest exits). However, the environment space itself is static, but the potential occupants of the built-environment are not. Therefore, in the dynamic egress analysis workflow, agent-based simulations are used to compute egress routes as well as to understand the dynamics of potential human–building interactions for different levels of crowd occupancies. As a result, designers can make egress plans by not just considering travel distances but the evacuation times as well for the egress routes. Besides, they can analyze exit flows for different levels of crowd occupancies in their environments, empowering them to design realistic and more human-aware environments.

Figure 4.5 shows egress analytics for different crowd occupancies. In each example, a different crowd occupancy behavior is tested (e.g., Left–Right: LoS Low, LoS Medium, and LoS High). Egress trajectories of the occupants are shown as a color gradient from *Red* to *Blue*. Trajectories in *Red* show shorter traveled distances and evacuation times, whereas in *Blue* show longer distances and long evacuation times. Average exit flow values are also shown for all the agents. In the second row, crowd-density heat maps are shown where problematic areas are highlighted in *Red* compared to *Blue* ones, which are comparatively less congested. *LoS High* exhibits multiple bottlenecks at the lobby, main dining 1 & 2, and near the exits. These heat maps are to assist designers further in understanding the dynamics of potential human–building interactions in planning egress.

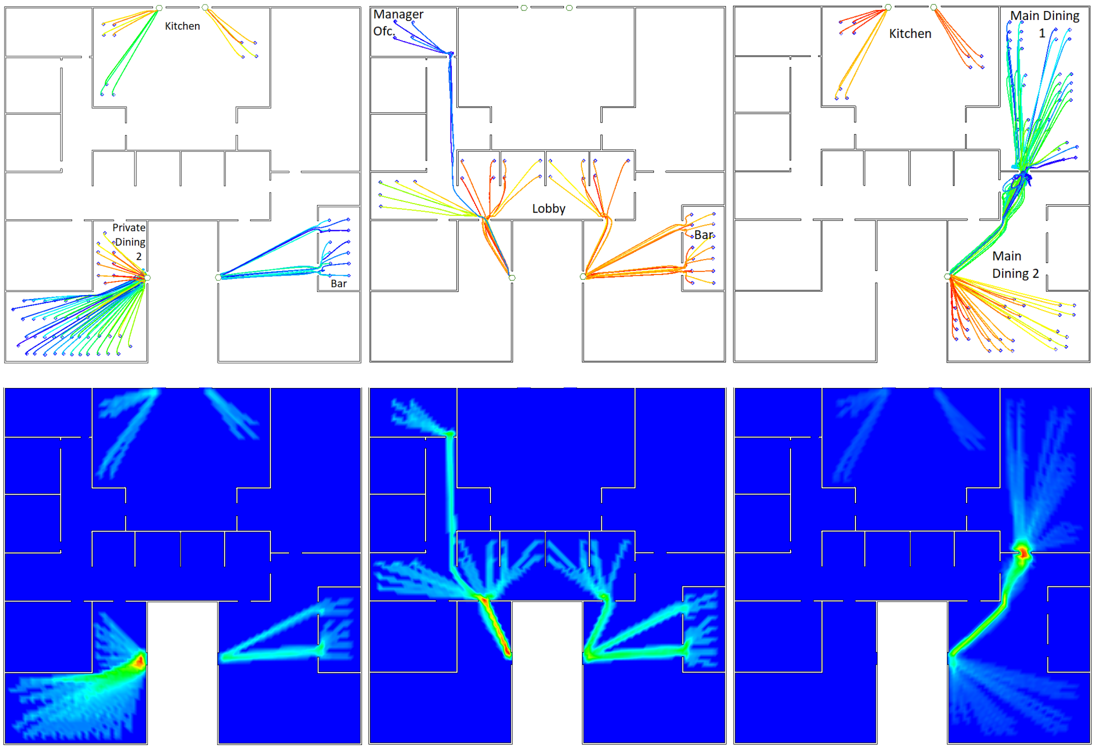


LoS: Low **LoS: Medium** **LoS: High**

Crowd Flow = 4.34 **Crowd Flow** = 9.00 **Crowd Flow** = 17.90

D = 24.04m — **T** = 20.17s **D** = 23.04m — **T** = 24.10s **D** = 24.19m — **T** = 24.25s

Figure 4.5. Crowd-based egress analysis for varied crowd occupancies. Each example maps a different crowd occupancy level (e.g. Level of Service). Top: color-coded (Red–Blue) trajectories of occupants during egress are shown based on average of evacuation times (**T**) and traveled distances (**D**). Trajectories in *Red* show shorter traveled distances and evacuation times, whereas in *Blue* show longer distances and high evacuation times. Average exit flow values (**Crowd Flow**) (i.e., exit rate of occupants per second) are also shown. Bottom: crowd density heat maps with high density in red (problematic areas) and low in blue.



Crowd Flow = 6.82 **Crowd Flow** = 2.24 **Crowd Flow** = 4.02

D = 12.36m — **T** = 10.42s **D** = 29.24m — **T** = 24.10s **D** = 23.13m — **T** = 24.57s

Figure 4.6. Crowd-based egress analysis for varied user-selected areas within the environment using *Medium LoS*. In each example, different rooms in the environment are populated with varied count of occupants. Top: color-coded (Red–Blue) trajectories of occupants during egress are shown based on average of evacuation times (**T**) and traveled distances (**D**). Trajectories in *Red* show shorter traveled distances and evacuation times, whereas in *Blue* show longer distances and high evacuation times. Average exit flow values (**Crowd Flow**) (i.e., exit rate of occupants per second) are also shown. Bottom: crowd density heat maps with high density in red (problematic areas) and low in blue.

As another example, selected room spaces in the environment are populated with a varied count of occupants. Figure 4.6 shows egress analytics of such a scenario. As in Figure 4.5, egress trajectories and crowd-density heat maps are shown here as well. Using such a tool, designers can also analyze the dynamics of handpicked areas within the environment with their selected crowd occupancy behaviors (e.g., LoS Low, LoS Medium, and LoS High).

4.4 Summary

This chapter presented a semantic-based simulation-guided computational workflow to compute egress plans and validate IBC rules for *Means of Egress.* The case study results indicate that the standard egress planning workflow does not take into account space semantics, violates certain IBC rules for *Means of Egress*, and rely on a static distance measure alone for egress routes. Thus, it poses threats to human safety in built-designs. However, by taking into account semantics of potential space usage and using human–building simulations, a more secure egress plan can be achieved, which relies on evacuation times as well in planning for egress routes. The crowd density heat maps for different crowd occupancies may further help in making more realistic and safe egress planning decisions. The presented workflow (tool) is integrated into a mainstream environment design platform (e.g., Autodesk Revit) for demonstration purposes.

Chapter 5

A Cross-Platform Approach to Simulate Human–Building Interactions

In Chapter 4, I presented interactive workflows to perform spatial analytics for human-building interactions. Using these workflows, in Chapter 5, I presented an automated tool to perform semantic-based rule checking of the *International Building Code* (IBC) rules for *Means of Egress*, and the analysis of egress scenarios using human-behavior simulations for different levels of crowd occupancies. However, with just a few exceptions (e.g., the research presented in Chapters 3 & 4), human–building simulation frameworks are often decoupled from environment modeling tools. They usually require specific hardware and software infrastructures and expertise to be used. Hence, hindering the designers' abilities to seamlessly simulate, analyze, and incorporate human-centric dynamics into their design workflows.

To this end, this chapter presents a generalized workflow to simulate and analyze human–building interactions. It is achieved by developing a cross-browser cloud-based platform to run human–building simulations as a service (e.g., on-demand from a client-side web-browser), and perform crowd-aware analytics to analyze environment designs for human-occupancy and activity. This chapter serves as the third contribution under the research bin “Environment Design Analysis”.

5.1 Overview

Analyzing how an environment layout impacts the movement and activities of its prospective inhabitants is a critical aspect of the environment design process. Traditional methods to evaluate an environment's design performance, such as cost, structure, energy, and lighting mostly rely on static space representations. The analytics from crowd simulations, on the other hand, account for the dynamic movement of people and their spatiotemporal impact on user experience, operational efficiency, and space utilization. Human–Building simulation processes, however, present high integration costs into environment design pipelines. Prior solutions to run human–building simulations demand deep expertise in a particular simulation platform. They require solving sophisticated interoperability challenges to import environment geometries, annotate spaces with semantics, define crowd behavioral parameters, generate simulation results, and visualize spatiotemporal data maps of space utilization. Besides, often designers have preferences towards specific environment design workflows that might not support human–building analytics.

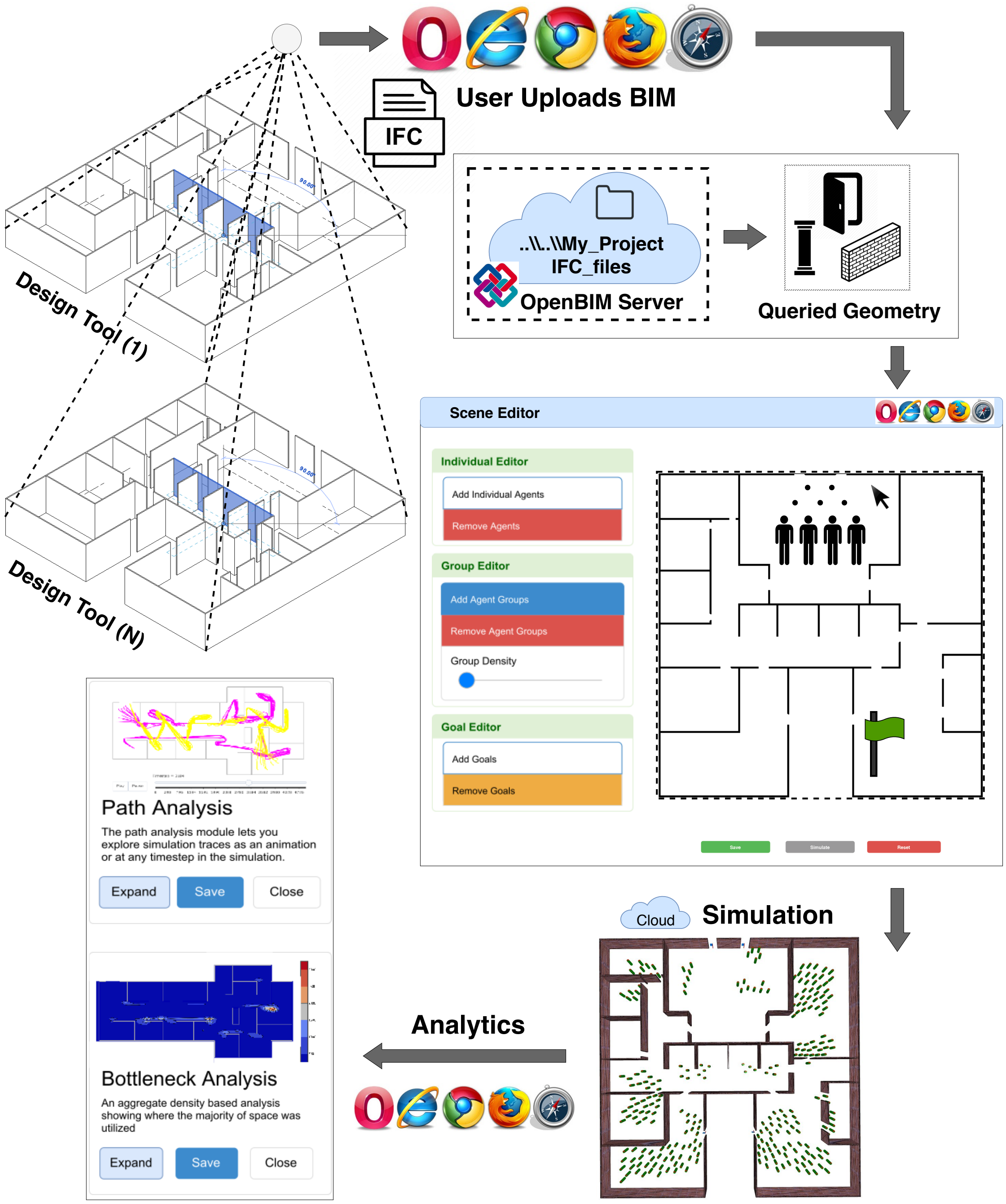
To address these challenges, a Software-as-a-Service (SaaS) paradigm is adopted for software distribution and licensing using cloud computing (M. Turner, Budgen, & Brereton, 2003). The SaaS approach has gained popularity in recent years and has several advantages both as a business model, but also for its users. It enables deep integration levels with other software in the work process to achieve targeted goals often in a cross-platform manner. In this way, explicitly utilizing web-based and cloud services, allows tools to be used on-demand and across platforms without reconfiguring core processes.

This chapter demonstrates how the SaaS approach may be used in a particularly challenging domain to support highly valuable processes. Often, firms that produce environment designs have a particular focus or set of focuses, which is referred to as design domains. The design domains tend to be clearly defined by the environment uses, such as outdoor urban settings, high-density housing, school/academic services, public services, commercial retail, industrial fabrication, warehousing, games, commercials, digital media, and film. Often the set of underlying tools used in the design process are the same or look the same. In early stages, procedural or prefabricated environment design processes are used to get numerous draft designs prepared quickly (e.g., using Grasshopper (*Grasshopper*, n.d.)). Within the design pipeline, advanced environment drafting tools are used to generate complete designs, retool, and reconfigure in an iterative process (e.g., using Autodesk Revit (Autodesk, n.d.)). Finally, designs are converted to engineering blueprints and models using a variety of approaches (e.g., AutoCAD, 3D Printing, and Model Services). In both, the beginning and middle stages of the pipeline, design firms make use of their staple tools and configurations. These processes are often rigid and/or design domain-specific. Adding tools to any one of these design domain processes can be difficult or prohibitive for a variety of reasons. A preliminary survey, including structured and unstructured questions, to experienced architects at three different firms with three different primary design domains, revealed that tool adoption is very challenging and attrition is high for tools that do not seamlessly integrate into already existing pipelines or are prohibitively expensive to do so (either monetarily, time expenditure, or acquiring expertise).

A generalized solution is presented to perform cross-platform design-domain agnostic integration of human–building simulations and analysis into the environment design pipeline. It offers: (1) seamless BIM and 3D environment model import, (2) domain-specific crowd authoring in a domain-agnostic experience, (3) dynamic agent-based crowd simulations, and (4) data-driven visualizations and analytics on designs in an interactive workspace. Figure 5.1 showcases the workflow overview.

5.2 Software-as-a-Service for Simulations

Software-as-a-Service (SaaS) is a paradigm that is progressively gaining more traction in the industry because it separates the ownership, deployment, and maintenance of the software products from the end-users (e.g., clients). This lets users utilize the software



The path analysis module lets you explore simulation traces as an animation or at any timestep in the simulation.

An aggregate density based analysis showing where the majority of space was utilized

Figure 5.1. System architecture for simulation-as-a-service to analyze human-building interactions.

services on-demand utilizing some client-side infrastructure (e.g., Application Program Interface (API), or Web Interfaces) often via the internet (Laplante et al., 2008). A survey on modeling and simulation as a service discussed the advantages, limitations, and risks involved in using cloud-based simulation services–extracting the difference between Software and Simulation-as-a-Service paradigms while noting the elasticity and ease of technical administration of the approach (Cayirci, 2013). The work presented in (Cayirci & Rong, 2011) discusses cloud computing and virtualization platforms used for civilian and military modeling and simulation applications. A distributed architecture is presented that uses a model-driven engineering technique to extract geometric information of building models from CAD/BIM tools. This architecture is then used as a remote service to run simulations and provides 3D visualization, which can be visualized through an external third-party software tool (e.g., 3ds Max) (Wang & Wainer, 2015).

In contrast, the workflow presented in this chapter is simulator agnostic in the sense that it uses a robust and modular underlying crowd simulation platform that specializes in continuous models. Allowing the user to choose what form they want their simulation to take. (Zehe et al., 2015) presented an approach to model and simulate urban system simulations on high-performance cloud clusters. A cloud-based framework is presented to remotely run simulations for studying the deployment of sensors in large facilities (Pax et al., 2018).

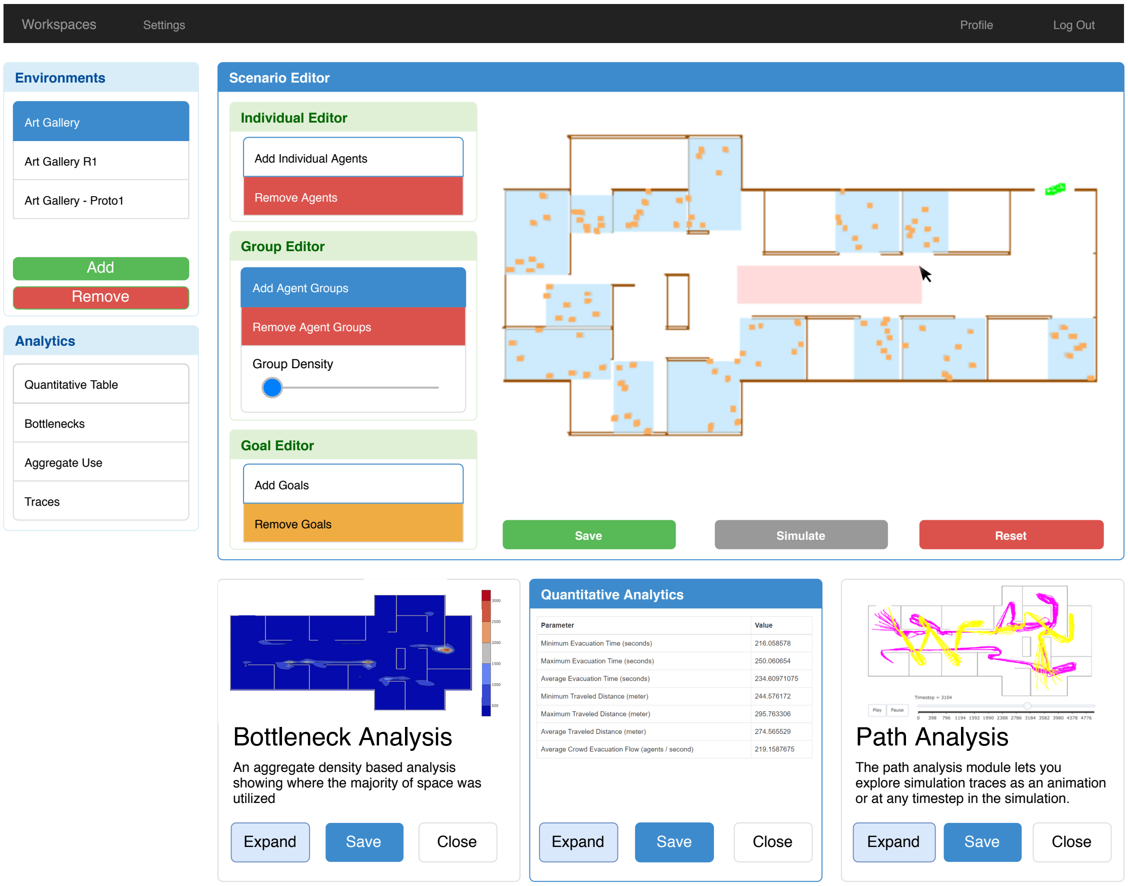
5.3 System Architecture

The presented workflow enables designers (e.g., users) to upload 3D environment models, author human-behavior simulation scenarios, run human–building simulations, and visualize crowd-aware analytics and feedback for their designs.

Figure 5.2 shows user interface of the simulation service platform accessed via client-side web-browser. It enables designers to upload 3D environment models, author human–building simulation scenarios, run human behavior simulations, and visualize crowd-aware analytics and feedback for their designs. It allows users to visualize environment designs both in 2D and 3D. The 2D visualization is presented as an orthographic projection of the environment model (i.e., top–down view), whereas the 3D visualization is a perspective projection from the top. Users can interact with their models by means of rotation and zooming around model's origin or using a fly through mode. A "Reset" functionality is also available to reset the camera to default view in 3D. The uploaded environment models and their respective crowd-aware analytics generated by the simulation service get saved to users' profile directories and can be accessed at a later time. Further details on the individual functions of the UI and simulation service are discussed in the following sub-sections.

5.3.1 Environment Specification and Model Support

The platform allows users to upload environments as Industry Foundation Classes (IFC), a standard BIM format. For an IFC, the system supports both IFC2x3 and IFC4



Bottleneck Analysis

An aggregate density based analysis showing where the majority of space was utilized

Quantitative Analytics

Parameter	Value
Minimum Evacuation Time (seconds)	216.058578
Maximum Evacuation Time (seconds)	250.060654
Average Evacuation Time (seconds)	234.60971075
Minimum Traveled Distance (meter)	244.576172
Maximum Traveled Distance (meter)	295.763306
Average Traveled Distance (meter)	274.565529
Average Crowd Evacuation Flow (agents / second)	219.1587675

Path Analysis

The path analysis module lets you explore simulation traces as an animation or at any timestep in the simulation.

Figure 5.2. The user interface of the simulation service which can be accessed via client-side web-browser. It includes a workspace to manage environment models (e.g., projects), a scenario editor to set up crowd activities, and a section to visualize crowd-aware feedback.

certifications (schema). The system does not limit users to use any particular environment design tool to generate their 3D environment models. Rather, IFCs can be sourced via any mainstream environment modeling platform. When an IFC file is uploaded, it is sent to an internally hosted open-BIM server and queried for geometric information of the environment. The open-BIM server stores the model and sends back environment specifications (e.g., walls, doors, pillars, and floors) to the simulation service in an XML format (e.g., environment configuration as discussed in Appendix A). These environment specifications are then used to visualize the environment models in the user's web-browser as well as to run human–building simulations.

5.3.2 Crowd Configuration and User Interaction

The platform allows users to define crowd configurations for design-specific human behavior simulation scenarios to run with their environment models. The "Scenario Editor" in Figure 5.2 summarizes a crowd configuration process. On the right is an environment layout of exhibition space (e.g., art gallery). On the Left are the allowable actions a user can perform in the scenario editor. These include adding and removing individual occupants as well as occupancy groups, setting crowd-density levels (LoS) (i.e., number of occupants to spawn within an occupancy group), and adding and removing targets or goals for the occupants to walk to (e.g., crowd activities). An occupancy group is added by drawing a rectangle into the scene (Figure 5.2 – *Pink* region) and the number of occupants to spawn within that group is calculated by multiplying the area of that drawn region with selected crowd-density LoS level. On double-clicking an individual occupant or an occupancy group shows a list of available targets in the current configuration. Users can then select one or more targets from the list for the occupants (or occupancy groups). Once a crowd configuration is created, the user can then save it by selecting a “Save Config” action. The crowds and their activities are saved in an XML format similar to crowd configuration, as discussed in Appendix A.

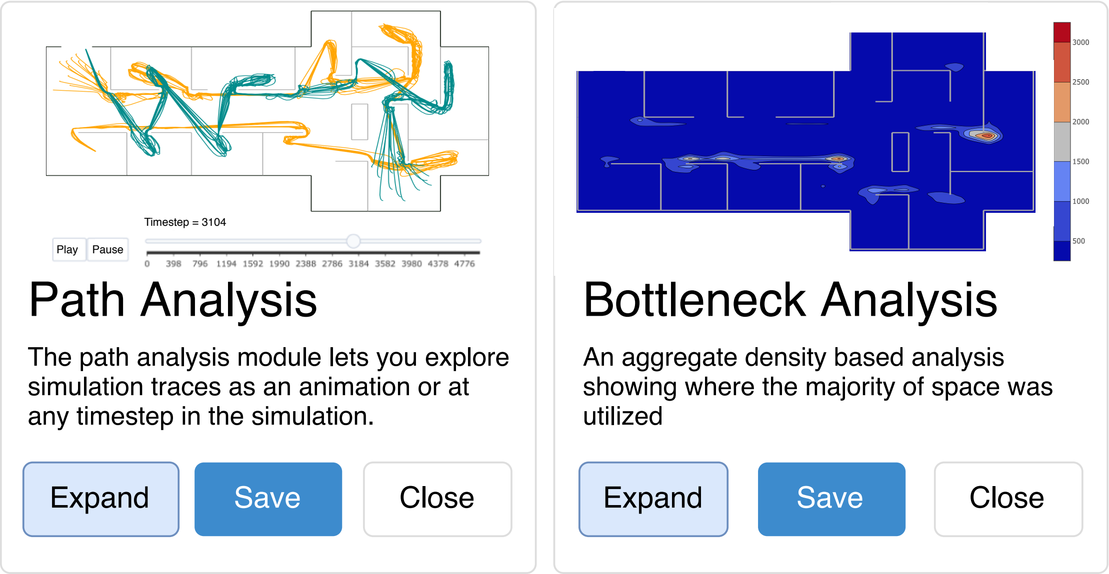
5.3.3 Human Behavior Simulations

A simulation scenario contains the specification of the environment layout (e.g., geometric information like positions and attributes of walls, doors, pillars, and floors) and the virtual crowds (e.g., individual and group agents, their desired activities, behavioral parameters, and crowd steering technique). When the user selects a “Simulation” action, the system communicates the current simulation scenario with both environment and crowd specifications to SteerSuite (i.e., a human–building simulation framework, hosted as a cloud server by the simulation service platform) in an XML representation. Further details on human–building simulation processes can be found in Appendix A. Once the simulation is completed, occupant trajectories and other crowd-aware simulation statistics are sent back to the user’s web-browser.

5.3.4 Simulation Feedback

After a simulation is completed, crowd-aware simulation statistics are sent back to the user's web-browser. The simulation service platform then allows users to analyze their environment designs by selecting from an ever-expanding list of dynamic crowd analysis and visualization approaches. It allows users to visualize spatial quantitative and qualitative feedback from the human–building simulation. Figure 5.3 shows occupants' trajectories (path analysis – Top) and density contours (bottleneck analysis – Bottom) respectively. The traces are shown in *Blue*, from the starting position to the final target, for all the occupants. In order to make the simulation experience intuitive for users, the simulation service platform playbacks the crowd traces, allowing the users to go back-and-forth in simulation timesteps with the help of a slider. The heat map for bottleneck analysis is a color-coded representation of an average occupant density per square meter, calculated for the whole design space of the environment and for all the occupants, over the course of the simulation. *Red* regions in the heat map show areas of high density (e.g. potential bottlenecks), whereas *Blue* shows less dense areas.

The service platform also reports simulation statistics as quantitative numbers. These include minimum, maximum and average evacuation times and traveled distances over the course of the simulation, as well as an average *Exit Flow* of occupants. The exit flow is calculated by dividing average evacuation time with the total number of occupants completed the simulation.



Path Analysis

The path analysis module lets you explore simulation traces as an animation or at any timestep in the simulation.

Bottleneck Analysis

An aggregate density based analysis showing where the majority of space was utilized

Figure 5.3. The Qualitative tools to afford quick exploration of human–building simulation results and problematic areas. The bottleneck analysis thresholds aggregate occupancy maps to bring focus to various types of flow bottlenecks in designs.

5.4 Case Study

In this section, a series of cases are presented to demonstrate the effectiveness of the simulation service workflow. Three different design domains are selected as cases, with their environment models that are sourced from three different environment modeling pipelines. This is to demonstrate how the SaaS approach can be effectively and seamlessly used as a single solution to inform decision making in the environment modeling workflows.

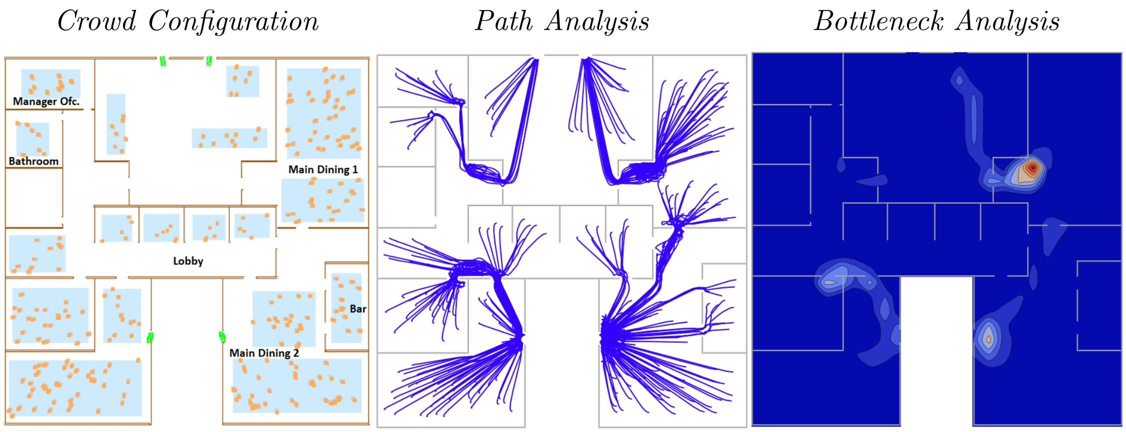
5.4.1 Eatery Design

An eatery layout, whether being designed for a restaurant, a food court, or a cafeteria, has to comply with numerous applicable codes, including accessibility, flow, and egress. For an egress, however, accounting for potential human–building interactions for future inhabitants is of vital importance.

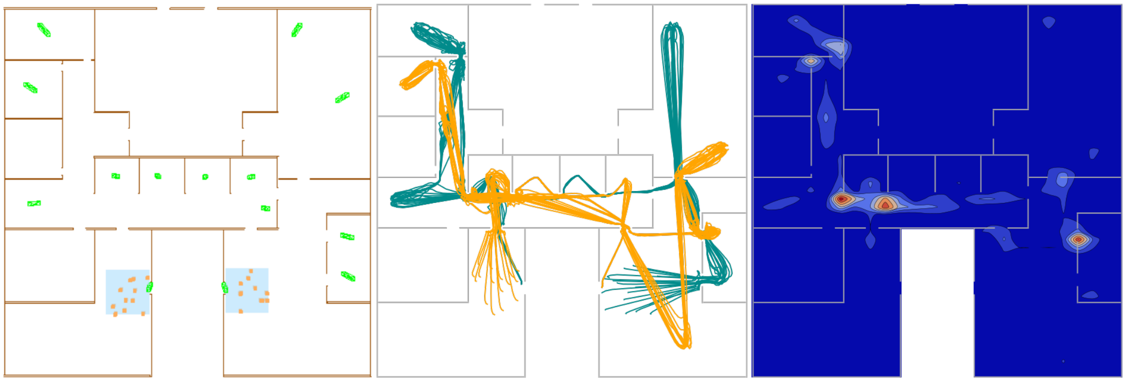
This use case demonstrates how the presented workflow can be used to analyze crowd dynamics of potential human–building interactions for two utterly different simulation scenarios. A real-world restaurant-style environment is created using Autodesk Revit. Figure 5.4 shows analytics for a restaurant environment for an emergent egress evacuation and a group dine-in scenario. For an egress evacuation (top row), using the presented service controls, virtual customers are interactively added in different spaces of the restaurant with an objective (e.g., target) to move towards the nearest exit. Crowd trajectories are shown in Blue, highlighting the paths virtual customers followed while moving towards exits. The color-coded heat map highlights the bottlenecks in space, which appeared during the evacuation, providing visual insights on potential human-safety hazards. For group dine-in scenario (bottom row), two different groups of virtual customers are added, entering the restaurant from different entrances, waiting in the lobby to be attended by a receptionist, moving to the bar, dining-in in the main dining hall, going to the bathroom, visiting the manager, and heading back towards exits. Crowd trajectories are shown in different colors for each group to differentiate their activities and the paths they followed along with them. The heatmap shows potential bottlenecks at the bar entrance and in the lobby. Average exit flow, traveled distances, and evacuation times are also shown in the figure.

5.4.2 Exhibition Design

A real-world exhibition-style environment (e.g., an art gallery) is created using Rhinoceros. Figure 5.5 shows the analytics for an egress evacuation and a group-based exhibition exploration scenario. For egress evacuation (top row), virtual visitors are interactively added at different exhibit points in the art gallery with an objective to move towards the nearest exit. Path analysis reveals that the obstacle in the middle hallway towards the left-side helped in forming multi-lanes in the left-side of the gallery. The heat map shows a bottleneck in the middle hallway towards right-side of the gallery near the exit. These analyses highlight that a designer might want to consider adding an obstacle in the hallway towards right-side of the gallery as well, to help the formation of lanes for egress,



Evacuation: **Flow** = 19.31agents/s, **Distance** = 20.76m, **Time** = 19.75s



Group Dining: **Distance** = 198.7m — **Time** = 182.0s

Figure 5.4. Crowd analytics for a restaurant layout. Two different scenarios are presented: Top – an egress evacuation where customers from different spaces in the restaurant moving towards nearest exit, and Bottom – a group dining where two different groups of people come to the restaurant, wait in the lobby, go to the bar, dine-in, go to the washroom and leave. In the left column, crowd configurations are shown with agents' spawn region in light blue and goals in green. Crowd trajectories are shown in *Blue* for egress and multi-colored for the group dining scenario. Crowd-density analysis is also shown as color-coded heat map (Red–Blue) where denser crowd areas (bottlenecks) are highlighted in dark red.

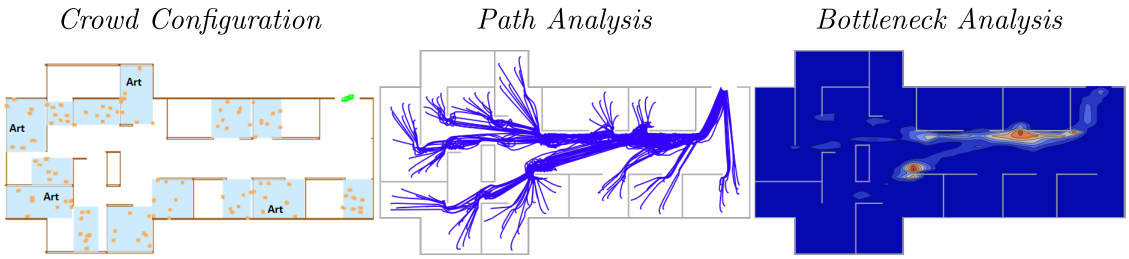
or make other design improvements accordingly. For group-based exhibition exploration (bottom row), two different groups of agents are added to explore the gallery from one exhibit point to another, making stops, and then moving to the next.

5.4.3 Workplace Design

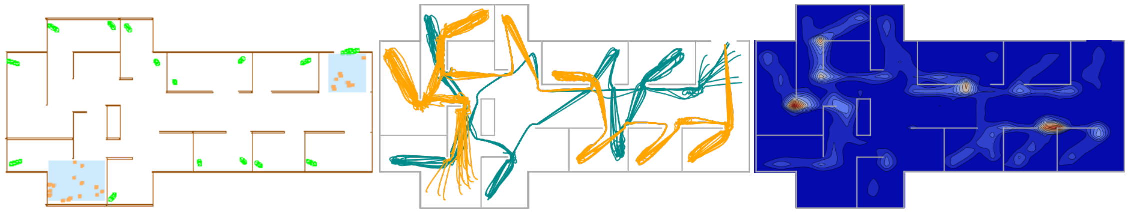
A workplace environment (e.g., an office) is created using SketchUp. Figure 5.6 shows analytics for egress and a daily work-routine scenario of two different teams. In the egress scenario (top row), virtual employees are added in different spaces in the office with an objective to move towards the nearest exit. Path and bottleneck analyses are presented. The heat map reveals multiple bottlenecks in the hallways near meeting rooms and cafeteria. For the daily routine scenario, two different teams are added to different spaces in the office. Their work-routine activities are shown, including attending meetings, visiting colleagues' cabins, and going to the cafeteria. Several bottlenecks in the design space are revealed in the heat map.

Count	Mean	Median	Standard Deviation
6	72.91	73.75	6.20

Table 5.1: A summary of results for SUS to evaluate the usability of the simulation service platform, where the score range is from 0 to 100.

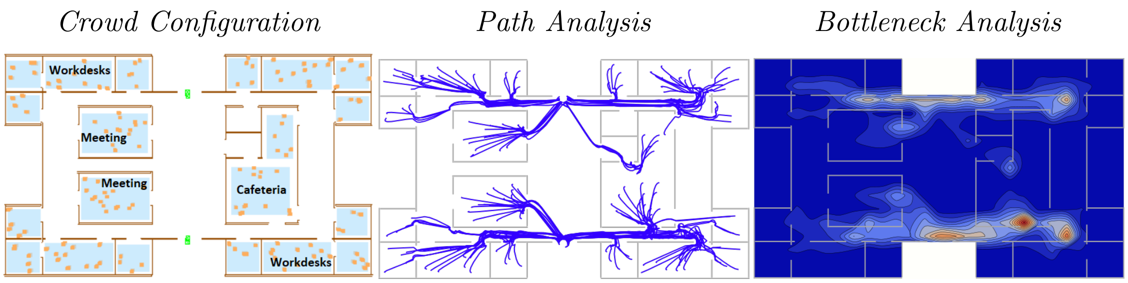


Evacuation: **Flow** = 27.45agents/s — **Distance** = 37.03m — **Time** = 36.12s

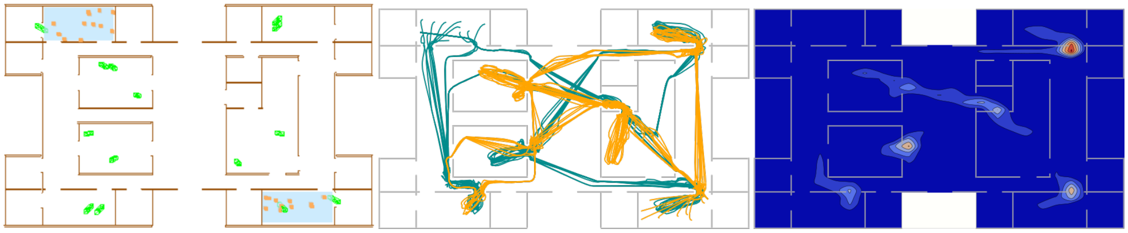


Group Exploration: **Distance** = 209.8m — **Time** = 208.6s

Figure 5.5. Crowd analytics for an exhibition environment (e.g., an art gallery). Two different scenarios are presented: Top – an egress evacuation where visitors from different spaces in the gallery moving towards nearest exit, and Bottom – a group exploration where two different group people exploring the gallery from one exhibit point to another. Crowd trajectories are shown in *Blue* for egress and multi-colored for group exploration scenario. Crowd-density analysis is shown as color-coded heat map (Red–Blue) where denser crowd areas (bottlenecks) are highlighted in dark red. Crowd exit flow for egress evacuation, average evacuation time (**T**) and traveled distance (**D**) for both evacuation and group dining scenarios are also reported. *Green* cylinders are the targets for agents, whereas *Orange* represent agent groups.



Evacuation: **Flow** = 22.45agents/s — **Distance** = 23.23m — **Time** = 25.65s



Work Routine of Teams: **Distance** = 235.8m — **Time** = 224.3s

Figure 5.6. Crowd analytics for a corporate work space (e.g., an office). Two different scenarios are presented: Top – an egress evacuation where employees from different spaces in the office moving towards the nearest exits, and Bottom – a daily work routine of two different teams attending meetings, going to cafeteria and visiting colleagues.

5.5 System Usability

A pilot user study is conducted to evaluate the usability of the presented simulation service platform. Six senior-level graduate students voluntarily participated in the experiment. All the participants reported prior experience with CAD tools to analyze building structures. Participants were tasked with using the simulation service platform to author crowd configurations in a given residence environment (e.g., a house), and analyze the environment space for human occupancies. All participants used the system for a fixed amount of time (e.g., 20 minutes). Afterward, participants completed a System Usability Scale (SUS) (Brooke, 2013) survey which is an established method in the literature to evaluate the usability of a system, and can be scaled to the range of 10 to 100, with a score higher than 68 to be considered above average and admissible (Sauro & Lewis, 2011). SUS score is a compound measure of usability for a system which has been proved to be reliable. The summary of SUS scores from the pilot study is reported in Table 5.1. The mean and median scores from SUS fall within the adjective range of "good" and "excellent" (Bangor, Kortum, & Miller, 2009) for the presented simulation service platform.

5.6 Summary

In this chapter, a generalized approach is presented to simulate and analyze human–building interactions. A cross-browser cloud-based simulation service platform is developed to eliminate all the hardware and software infrastructure dependencies. This way, a single solution is presented to bring the environment layouts from different environment modeling tools (e.g., Autodesk Revit, SketchUp, or Rhinoceros) into an interactive crowd authoring workspace. The workspace then let the users set up design-specific crowd scenarios, remotely run human–building simulations, and analyze crowd-aware environment design feedback. A series of case studies are presented to showcase the effectiveness of this approach by analyzing environments for different design-domains with respect to human-occupancy. The usefulness of the service platform is evaluated with a system usability study (SUS) survey where participants rated their confidence between “good” and “excellent”.

Chapter 6

Parametric Modeling of Humans, Building, and Activities

Earlier in Chapter 4, an interactive workflow was presented to perform analytics for human–building interactions. This workflow, however, was integrated into a specific environment modeling platform (e.g., Autodesk Revit), limiting the user-base (i.e., designers who do not use Autodesk Revit) to incorporate the dynamics of human–building interactions into their designs. Following this, in Chapter 6, a democratized solution was presented to run human behavior simulations for crowd-aware analytics of environments as an on-demand service from clients' web-browsers. However, this approach is most useful at later stages of the design process, when models require slight modifications to accommodate human-related factors. Often, in the early stages of the environment design process, designers use parametric exploration tools to perform most of the engineering tasks. Therefore, in order for the crowd-aware analytics to be useful in early environment modeling stages, human–building simulation processes must be well coupled with modeling tools. This way, designers can use crowd-aware simulation feedback to adjust their designs iteratively from the very beginning.

To this end, this chapter presents a platform that enables the parametric representation of (a) an environment design and the bounds of its permissible alterations, (b) a crowd that populates the environment, and (c) the activities that the crowd engages in. Using this approach, users can systematically run human behavior simulations with their environment designs and analyze the results in the form of data-maps (e.g., spatialized representations of human-centric analyses). The presented platform combines Revit–Dynamo (*Dynamo BIM*, n.d.) with SteerSuite (Singh et al., 2011), two established tools for parametric environment design and human behavior simulations, to create a familiar node-based workflow. This chapter serves as the first contribution under the research bin "Environment Design Exploration".

6.1 Overview

Environment modeling involves the systematic exploration of design options to identify solutions for a given social, physical, and environmental context (Kalay, 2004; Simon, 1969). This is an iterative process that involves the progressive refinement of design solutions to achieve a target performance (Rittel, 1971). Inadequate assessments at the early design stage can lead to under-performing environment designs and diminished user satisfaction or productivity.

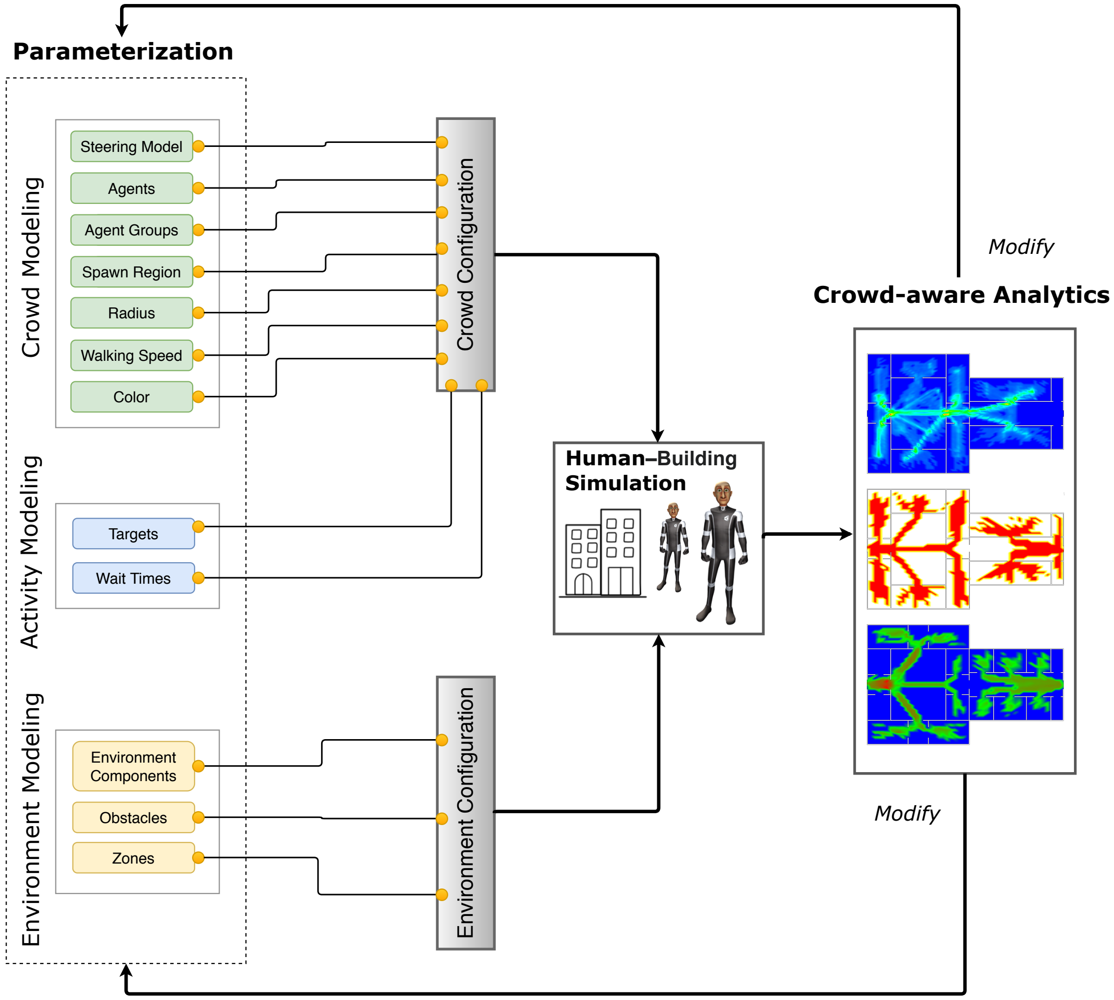


Figure 6.1. An overview of the framework for parametric modeling and analysis of environments, crowds, and their activities.

In this chapter, a parametric representation of environments and crowds is introduced for modeling design options, simulating human behaviors, producing human-centric analyses, and incorporating the findings in the designs. In conventional approaches, designers modify an environment to generate a unique design solution. *Parametric modeling* explicitly encodes the relationship between environment components. In this way, a designer can explore the vast possibilities by simply modifying component parameters (Woodbury, 2010). The presented platform directly embeds the traditional environment modeling features as well as the modeling of crowds and their activities within a parametric design framework. In this way, designers can leverage the node-based visual data-flow of parametric design tools to model the relationships and constraints between environment elements, crowd properties, and activities to perform iterative human-centric analyses. This way, designers can make informed decision-making in their environments. The platform combines Dynamo – a BIM-based parametric modeling tool embedded into Revit, with SteerSuite – an established crowd simulator (Singh et al., 2011). With newly modeled Dynamo nodes and pre-existing SteerSuite capabilities, it provides an integrated framework to analyze crowd-aware analytics for human–building interactions.

The first step of the framework involves generating a parameterized representation of (a) an *environment*, which includes bounds of permissible alterations and additional data to support human behavior simulations (e.g., space semantics, spawning regions, and movement targets); (b) the *crowd* that populates the environments (e.g., number of agents, agent groups, steering method for agent navigation, crowd distributions, agent radius, and color); and (c) the *activities* crowds are engaged in (e.g., day-to-day or emergency evacuations). The designer can then simulate a broad range of parametric behaviors and activities and then quantitatively analyze the crowd-aware feedback. The framework provides several human-centric analyses such as crowd measures (e.g., evacuation times, traveled distances, and crowd movement flow) or spatiotemporal data-maps (e.g., aggregated density, speed, and movement map (Morad, Zinger, Schaumann, Putievsky Pilosof, & Kalay, 2018)). Figure 6.1 shows the overview of the presented framework.

6.2 System Architecture

The platform combines Revit–Dynamo, an established node-based tool for parametric design modeling, with SteerSuite, an established crowd simulator.

6.2.1 Revit–Dynamo

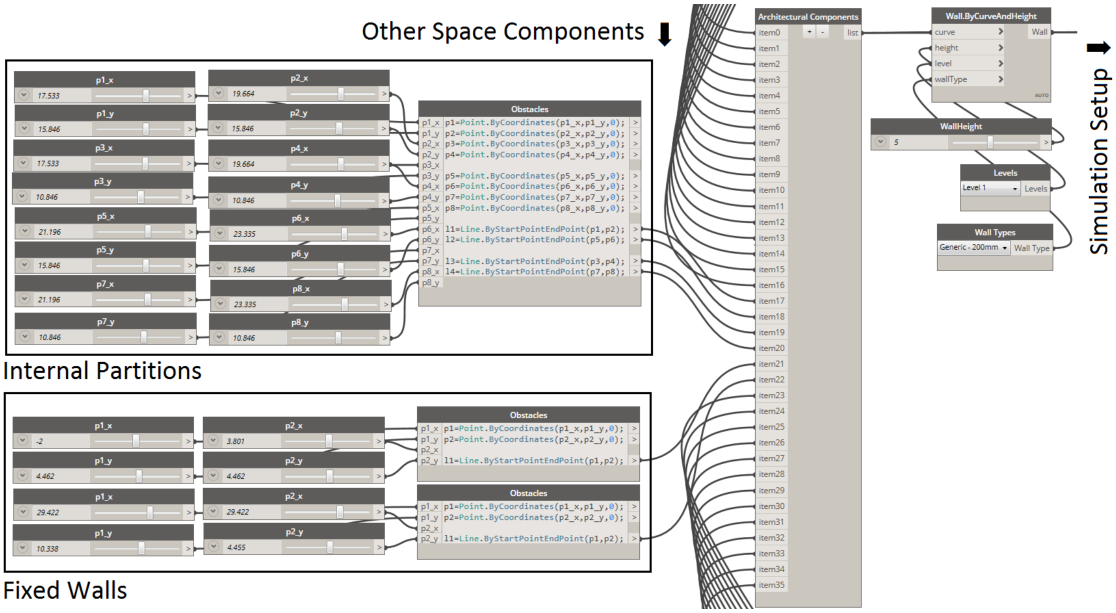
Dynamo is a visual programming interface embedded within Autodesk Revit that enables visual programming of environment components and the relations between them. Each visual component in Dynamo is represented as a node. Each node encodes a script that can create a geometry in Revit, read/write data from a file, perform operations on BIM data, or communicate data with another program or other nodes in the graph. Nodes can be connected through wires to share data among them. A dynamo program is also called a graph or a network. The execution of a dynamo program flows through the network of wires across different nodes. As a result, we get a visual representation of all the steps that lead to an end environment design. Different from other parametric modeling approaches, such as Grasshopper, Dynamo is coupled directly with Revit. BIM models represented in Dynamo – beyond geometric data – can also store metadata that can be used to perform static and dynamic human-centric analyses such as the work presented in Chapter 3.

6.2.2 Human Behavior Simulations

SteerSuite (Singh et al., 2011) is used to simulate virtual agents in the environments using established agent navigation and collision avoidance technique (e.g., Social Forces (Helbing et al., 2000)). There are other crowd steering techniques supported in SteerSuite as well. The presented work is not bounded to use only social forces kinds of agent steering, and other techniques can also be used. The parametric modeling processes of environment, crowds, and activities, generate their respective configurations (e.g., environment configuration and crowd configuration), which then communicated to SteerSuite to run human behavior simulations. The details on human–building simulations are presented in Chapter 3. Custom Python-language nodes are developed to facilitate communication between SteerSuite and Dynamo.

6.2.3 Environment Modeling

An environment layout is composed of architectural components, also known as environment features (e.g., walls, doors, pillars, floors, and equipment) as well as *zones* – discrete



```
p1=Point.ByCoordinates(p1_x,p1_y,0);
p2=Point.ByCoordinates(p2_x,p2_y,0);
p3=Point.ByCoordinates(p3_x,p3_y,0);
p4=Point.ByCoordinates(p4_x,p4_y,0);

p5=Point.ByCoordinates(p5_x,p5_y,0);
p6=Point.ByCoordinates(p6_x,p6_y,0);
p7=Point.ByCoordinates(p7_x,p7_y,0);
p8=Point.ByCoordinates(p8_x,p8_y,0);

l1=Line.ByStartPointEndPoint(p1,p2);
l2=Line.ByStartPointEndPoint(p5,p6);

l3=Line.ByStartPointEndPoint(p3,p4);
l4=Line.ByStartPointEndPoint(p7,p8);
```

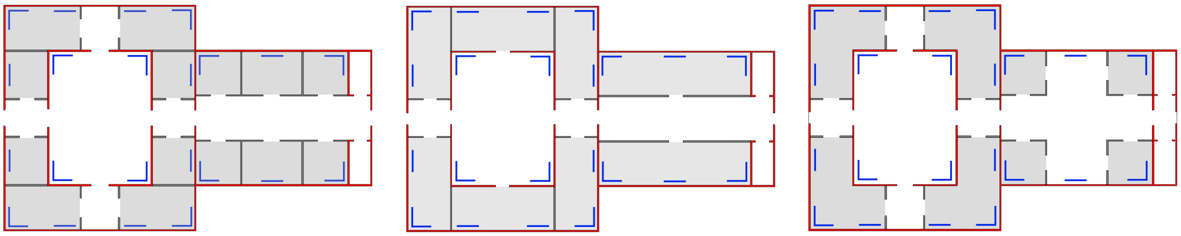
```
p1=Point.ByCoordinates(p1_x,p1_y,0);
p2=Point.ByCoordinates(p2_x,p2_y,0);

l1=Line.ByStartPointEndPoint(p1,p2);
```

```
p1=Point.ByCoordinates(p1_x,p1_y,0);
p2=Point.ByCoordinates(p2_x,p2_y,0);

l1=Line.ByStartPointEndPoint(p1,p2);
```

Parametric Building Model



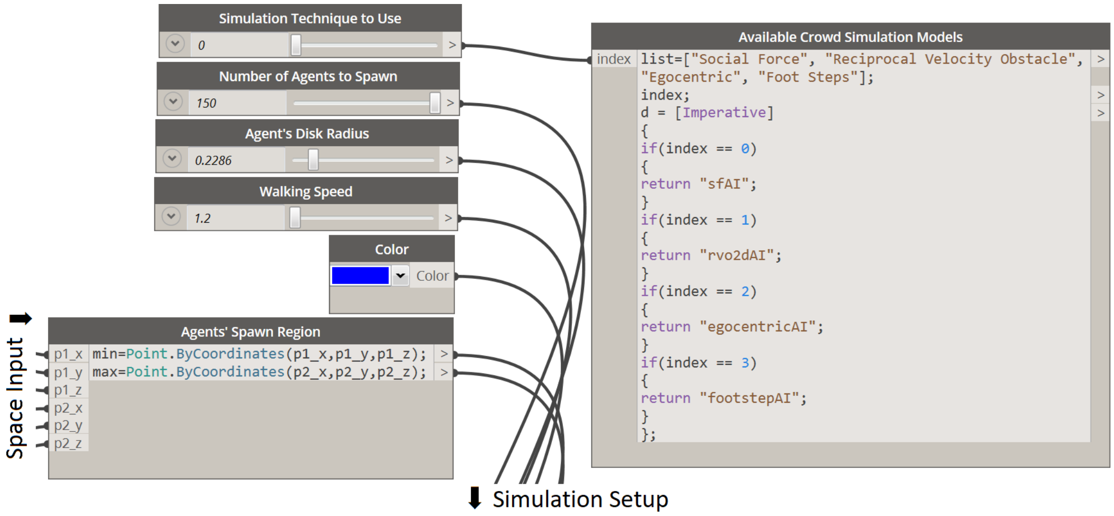
Building Design 1 (B1) *Building Design 2 (B2)* *Building Design 3 (B3)*

Figure 6.2. Top: A node-based graph for parametric environment modeling of an art galley, created and visualized in Dynamo. The environment model is composed of a set of fixed and movable partitions (e.g., walls), for which the parameters can be tuned to generate different environment layouts. Bottom: three variants of the art gallery created by tuning the parameters of the internal partitioning walls. Grey regions indicate the spawn regions of the crowd; red lines indicate the fixed walls; dark-gray lines indicate the partitioning walls (e.g., tunable walls); and blue-lines represent the art works (i.e., potential targets for the crowd).

sections of space that host different kinds of activities (Brodeschi, Putievsky Pilosof, & Kalay, 2015). Both types of entities, which can be modeled using traditional CAD and BIM approaches, are defined as sets of adjustable parameters using nodes and can be used as input to define additional crowd parameters. For instance, the environment components can be used as obstacles that the agents must avoid. Zones can be used to define regions where agents are spawned at the beginning of the simulation or are associated with behaviors. Figure 6.2 shows a parametric environment model of an art gallery designed and visualized in Revit–Dynamo with different possible layouts generated by tuning environment parameters.

6.2.4 Crowd Modeling

A crowd is composed of a user-defined number of agents that move in the environment space. Additional parameters include the speed at which agents move, one or more targets (goals), the color and radius of the disk, which represents a virtual agent in the simulation scene, and a steering model (e.g., Social Forces). The presented parametric modeling workflow enables first to define the environment parameters and then use them as input for defining crowd parameters. For instance, parameterization of zones in an environment can be used as spawning regions were agents are initialized at the beginning of the simulation. Depending on the use case, there can be one or multiple crowd modeling nodes in the parametric workflow to analyze the same or different areas in an environment. Figure 6.3 shows a parametric crowd model designed and visualized in Revit–Dynamo.



Simulation Technique to Use: 0

Number of Agents to Spawn: 150

Agent's Disk Radius: 0.2286

Walking Speed: 1.2

Color: Color

```
min=Point.ByCoordinates(p1_x,p1_y,p1_z);
max=Point.ByCoordinates(p2_x,p2_y,p2_z);
```

```
list=["Social Force", "Reciprocal Velocity Obstacle",
"Egocentric", "Foot Steps"];
index;
d = [Imperative]
{
if(index == 0)
{
return "sfAI";
}
if(index == 1)
{
return "rvo2dAI";
}
if(index == 2)
{
return "egocentricAI";
}
if(index == 3)
{
return "footstepAI";
}
};
```

Parametric Crowd Model

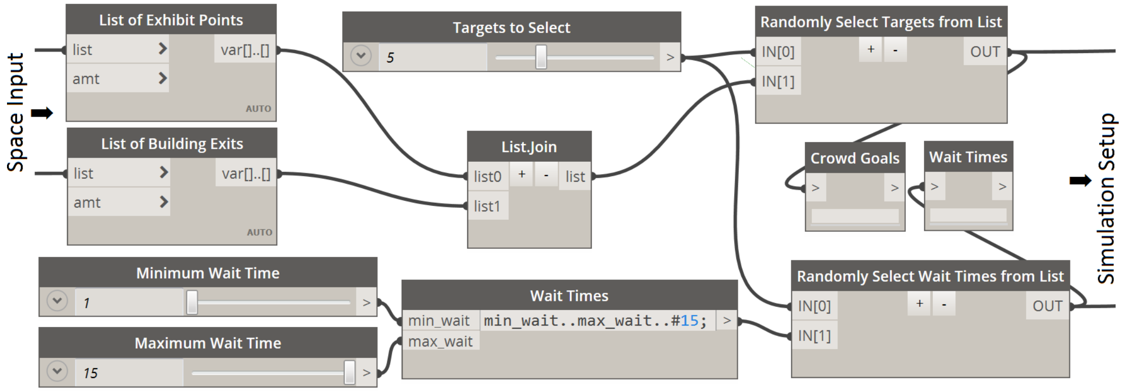
Figure 6.3. A parametric crowd model that allows a user to tune different crowd parameters. It gets input from the environment model for the specifications of zones to spawn/originate the virtual agents.

6.2.5 Activity Modeling

A crowd can be engaged in different activities, such as the day-to-day use of environment space or emergency evacuation. Specifying agent movement targets can model such activities, or behaviors, and the duration of their performance at each destination. One example of defining an activity model could be to specify environment exits as the final destinations for the agents, thus modeling a simplified evacuation scenario. More complex scenarios can be modeled by defining a series of destination targets in the environment space (e.g., the location of the artworks) or behaviors (e.g., behavior trees, or zone dependent behaviors) where agents move in space from one location to another. In the parametric modeling workflow, a user first defines the environment parameters and then use them as input to define the activity parameters for crowds. For example, the location of the artworks specified in the environment model can be used to define destination targets for the agents in the activity model. Figure 6.4 shows a parametric activity model designed and visualized in Revit–Dynamo.

6.2.6 The Simulation Phase

The environment, crowd, and activity models generate their respective user-defined parametric representations, which is used as input in the simulation phase. Custom nodes are defined to take inputs from the environment, crowd and activity models, aggregate all the input parameters, and generate environment and crowd configurations as XMLs. These XMLs are then communicated to SteerSuite to run the actual human–building



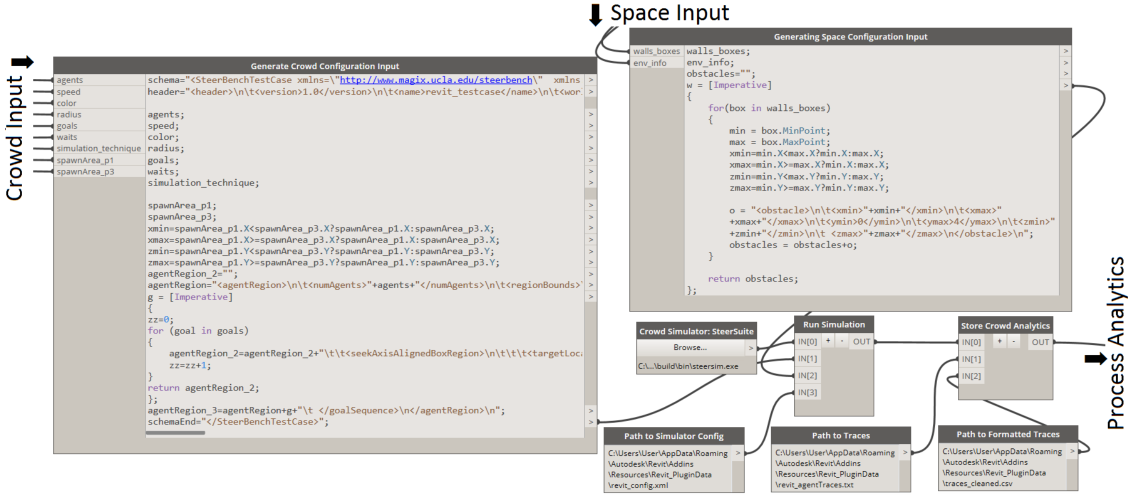
```
min_wait..max_wait..#15;
```

Parametric Activity Model

Figure 6.4. The crowd activity model visualized in Dynamo. The parameters can be tuned to generate different activities, such as evacuations or day-to-day scenarios in explore an art gallery.

simulations.

The platform allows visualizing human–building simulations in real-time. Furthermore, it updates the simulations in real-time as the user changes the defined parameters in the environment, crowd, or activity models. Once a simulation is completed, the time-based dynamics of human–building interactions (e.g., Spatio-temporal trajectories of crowds during the simulation, as well as other crowd-aware statistical measures) are communicated back to Dynamo as input to the analysis phase. This process closes the loop of crowd-aware environment design modeling without breaking the standard early-stage modeling workflows of the designers. Figure 6.5 shows the simulation nodes designed and visualized in Revit–Dynamo, as well as a sample snapshot from a human–building simulation.



```
schema="<SteerBenchTestCase xmlns=\"http://www.magix.ucla.edu/steerbench\"  xmlns
header="<header>\n\t<version>1.0</version>\n\t<name>revit_testcase</name>\n\t<wor

agents;
speed;
color;
radius;
goals;
waits;
simulation_technique;

spawnArea_p1;
spawnArea_p3;
xmin=spawnArea_p1.X<spawnArea_p3.X?spawnArea_p1.X:spawnArea_p3.X;
xmax=spawnArea_p1.X>=spawnArea_p3.X?spawnArea_p1.X:spawnArea_p3.X;
zmin=spawnArea_p1.Y<spawnArea_p3.Y?spawnArea_p1.Y:spawnArea_p3.Y;
zmax=spawnArea_p1.Y>=spawnArea_p3.Y?spawnArea_p1.Y:spawnArea_p3.Y;
agentRegion_2="";
agentRegion="<agentRegion>\n\t<numAgents>"+agents+"</numAgents>\n\t<regionBounds>
g = [Imperative]
{
zz=0;
for (goal in goals)
{
    agentRegion_2=agentRegion_2+"\t\t<seekAxisAlignedBoxRegion>\n\t\t\t<targetLoc
    zz=zz+1;
}
return agentRegion_2;
};
agentRegion_3=agentRegion+g+"\t </goalSequence>\n</agentRegion>\n";
schemaEnd="</SteerBenchTestCase>";
```

```
walls_boxes;
env_info;
obstacles="";
w = [Imperative]
{
    for(box in walls_boxes)
    {
        min = box.MinPoint;
        max = box.MaxPoint;
        xmin=min.X<max.X?min.X:max.X;
        xmax=min.X>=max.X?min.X:max.X;
        zmin=min.Y<max.Y?min.Y:max.Y;
        zmax=min.Y>=max.Y?min.Y:max.Y;

        o = "<obstacle>\n\t<xmin>"+xmin+"</xmin>\n\t<xmax>"
        +xmax+"</xmax>\n\t<ymin>0</ymin>\n\t<ymax>4</ymax>\n\t<zmin>"
        +zmin+"</zmin>\n\t <zmax>"+zmax+"</zmax>\n</obstacle>\n";
        obstacles = obstacles+o;
    }

    return obstacles;
};
```

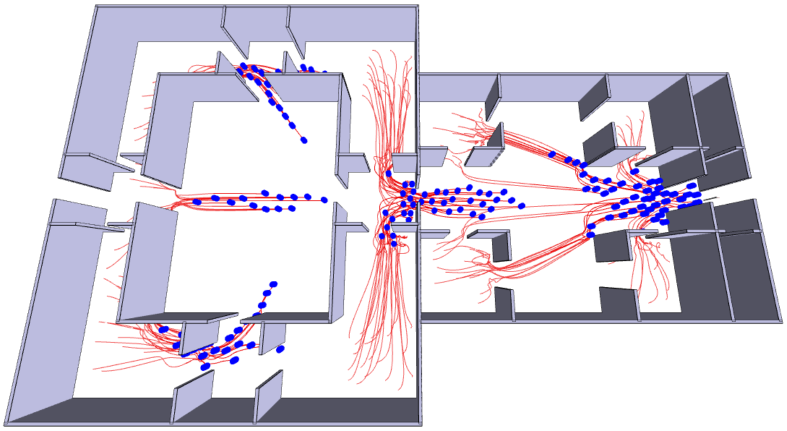
C:\...\build\bin\steersim.exe

C:\Users\User\AppData\Roaming
\Autodesk\Revit\Addins
\Resources\Revit_PluginData
\revit_config.xml

C:\Users\User\AppData\Roaming
\Autodesk\Revit\Addins
\Resources\Revit_PluginData
\revit_agentTraces.txt

C:\Users\User\AppData\Roaming
\Autodesk\Revit\Addins
\Resources\Revit_PluginData
\traces_cleaned.csv

Simulation Setup



Human–Building Simulation

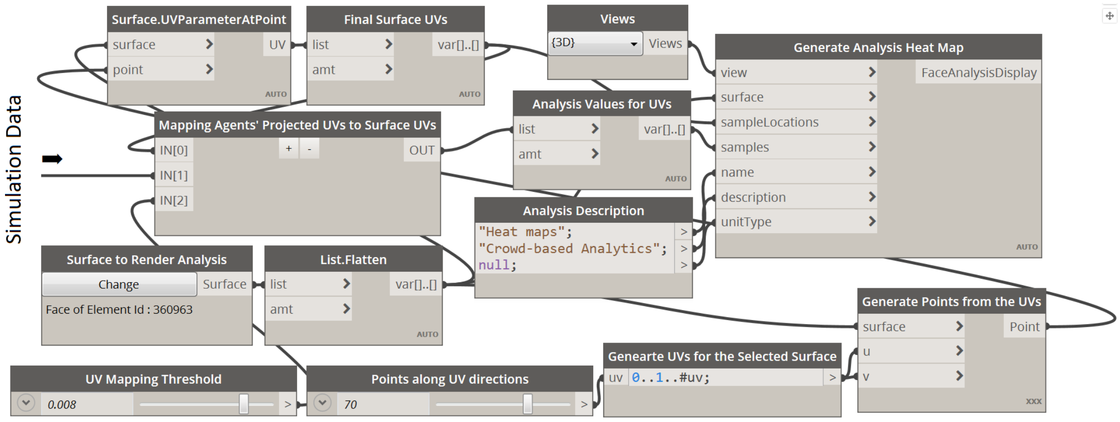
Figure 6.5. Top: a parametric workflow to setup and run human–building simulations designed in Revit–Dynamo. Bottom: a snapshot from human–building simulation of an evacuation activity. The human behavior simulation is run using SteerSuite. Blue circles represent the virtual agents, whereas the red lines represent crowd trajectories.

6.2.7 The Analysis Phase

Users can visualize the simulation feedback for different analysis methods, including (but not limited to) density, trajectory, and speed data maps within Revit–Dynamo. The *density* map is computed as the number of agents within a square meter space, average over the period of simulation. *Trajectory* map is the collection paths the agents follow while navigating the environment. Lastly, the *speed* map is defined as the distance traveled over time by an agent. It is computed for all the paths traveled by the agents during the simulation. Figure 6.6 shows the node-based workflow for the analysis phase, parameterized and visualized in Revit–Dynamo. The figure also shows the output of each of the three analysis methods. Designers can use this visual feedback to examine the dynamics of human–building interactions more systematically and during the early stages of environment design modeling.

6.3 Case Study

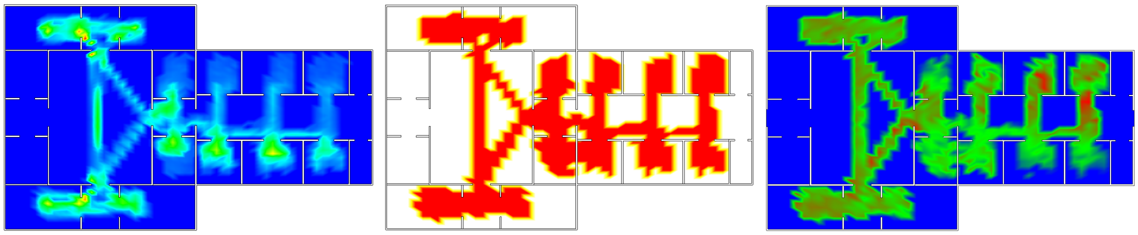
A case study is presented to showcase the functionality and effectiveness of the presented parametric-design workflow. The study systematically iterates over several human–building simulations to test the impact that an environment, crowd, and their activities produce on the overall environment occupancy of an art gallery space.



```
"Heat maps";
"Crowd-based Analytics";
null;
```

```
0..1..#uv;
```

Dynamo Script



Density (D) *Path Traces (T)* *Speed (S)*

Figure 6.6. Top: parametric modeling of crowd-aware analyses designed and visualized in Revit–Dynamo. Bottom: examples of human-centric analyses (e.g., spatial crowd-aware feedback) for an exhibition environment with an artwork exploration activity. Left to Right: Density (red regions are the most congested areas compared to blue ones), Trajectory (red regions are the spaces traveled by virtual agents during the course of simulation), and Speed data maps (red regions are the areas where agents traveled with high speeds compared to blue ones), respectively.

6.3.1 Setup

Environment parameters. Three environment variants are created by tuning the parameters of the adjustable partitions of an art gallery space (Figure 6.2 – Bottom). In the remainder of this section, these variants are named *B1*, *B2* and *B3* respectively.

Crowd parameters. A total of 150 autonomous agents are randomly distributed and initialized in 14 different spawn regions for environment (B1), 8 different regions for environment (B2) and 8 different regions for environment (B3), as shown in Figure 6.2 – Bottom (gray-colored). Crowd movements are parameterized into two categories in terms of walking speed. *Adults (C1):* represents adult walking. A speed of 1.2 m/s is considered an average walking speed of an adult with normative gait and without the use of mobility aids (Bohannon, 1997; LaPlante & Kaeser, 2004). *Mix-Adults (C2):* represents mix-adult (heterogeneous) walking. Depending on the age, height, weight, and health conditions, a human can walk with a wide speed range. In this study, *C2* adults walk in a range of 1.1 – 1.8 m/s. In the remainder of this paper, crowd heterogeneity levels will be referred to as *C1*, and *C2*, respectively.

Activity parameters. Two different simulation activities are considered. *Day-to-day (A1):* represents a day-to-day scenario where people come to an art gallery and walk from one exhibit point to another until they have seen all the exhibits or those aligned with their interest. Agents spend a random time between 5 – 20 seconds with each exhibit before moving to the next. *Evacuation (A2):* represents an emergency scenario (e.g., fire egress) where all the crowds vacate the environment through their nearest exits.

Implementation details. All case study experiments are run on a Lenovo laptop with the following specifications: Intel(R) Core i7-6700HQ CPU @ 2.60GHz (8 CPUs), 16 GB of RAM (DDR4), Nvidia GeForce GTX 1060 (Graphics Card) and Microsoft Windows 10 Home (OS).

6.3.2 Results

Data maps are shown for density, trajectory, and speed analyses, for the three environment variants (B1, B2, and B3), for adult (C1) and mix-adult (C2) crowds, and both day-to-day (A1) and evacuation activities (A2).

Figure 6.7 shows spatial feedback from the simulation for environment variant (*B1*). For the adult crowds (*C1*), in the density map (D) for exhibition activity (*A1*), the red regions in the corridors and hallways are more congested as they are common passages to connect different exhibit points. However, in evacuation activity (*A2*), this congestion is mostly found near the environment exits due to bottlenecks near egress points. For the trajectory map (T) during day-to-day activity (*A1*), a complex trajectory structure is observed because the crowd was moving from one exhibit point to the other in order to explore different exhibitions. In contrast, in the evacuation activity (*A2*), more symmetric trajectories are seen as the agents tried to vacate the environment from their nearest exits. For the speed map (S) during exhibition activity (*A1*), the higher walking speed is recorded in the corridors and hallways. In contrast, in evacuation activity (*A2*), the highest speed is recorded only near the environment exits.

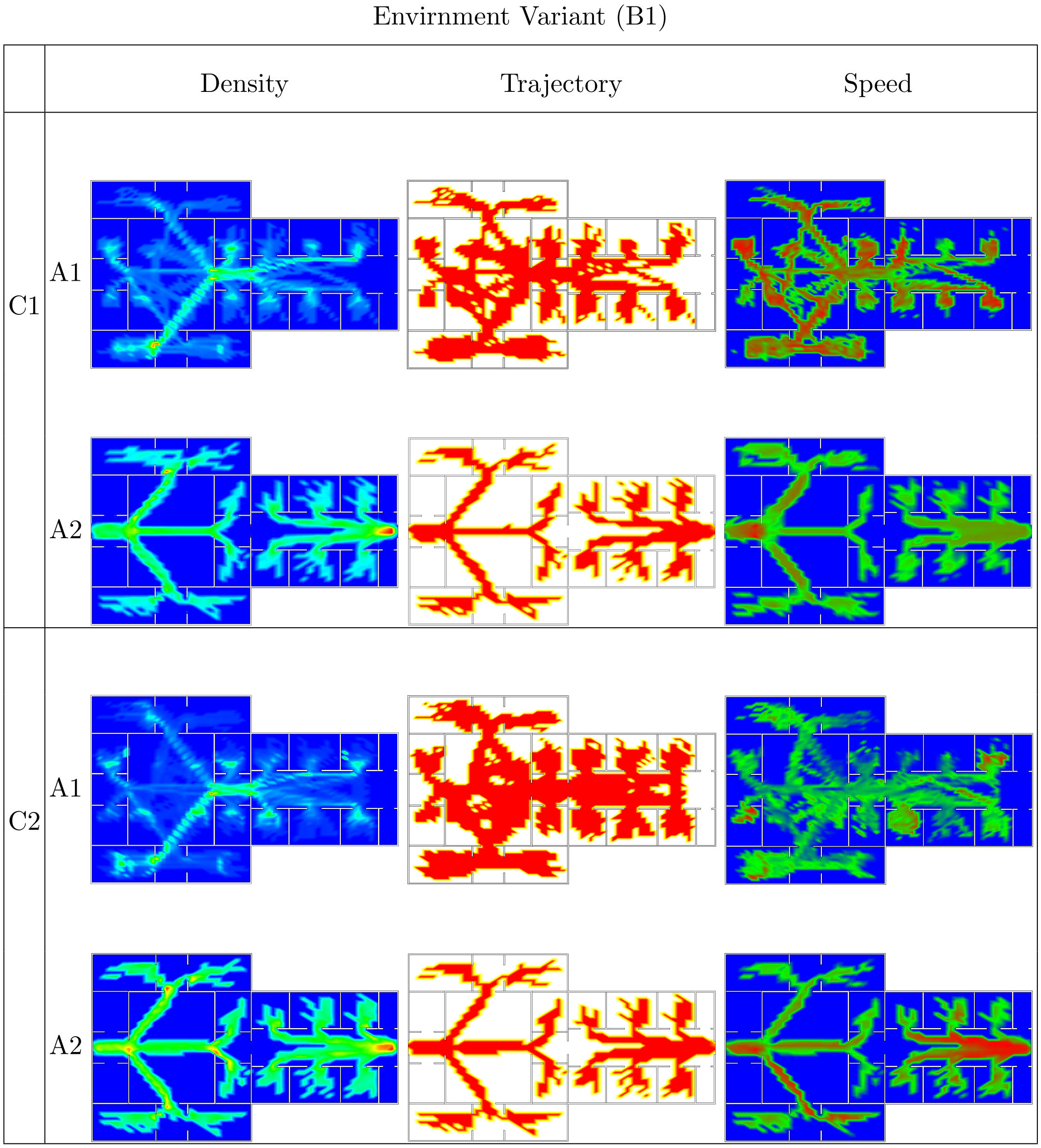


Figure 6.7. The crowd-aware analyses for the environment variant (B1). Density (D), trajectory (T) and speed (S) data maps are shown for both crowd instances (e.g., adult (C1) and mix-adult (C2) walkings), and for both day-to-day (A1) and evacuation (A2) activities.

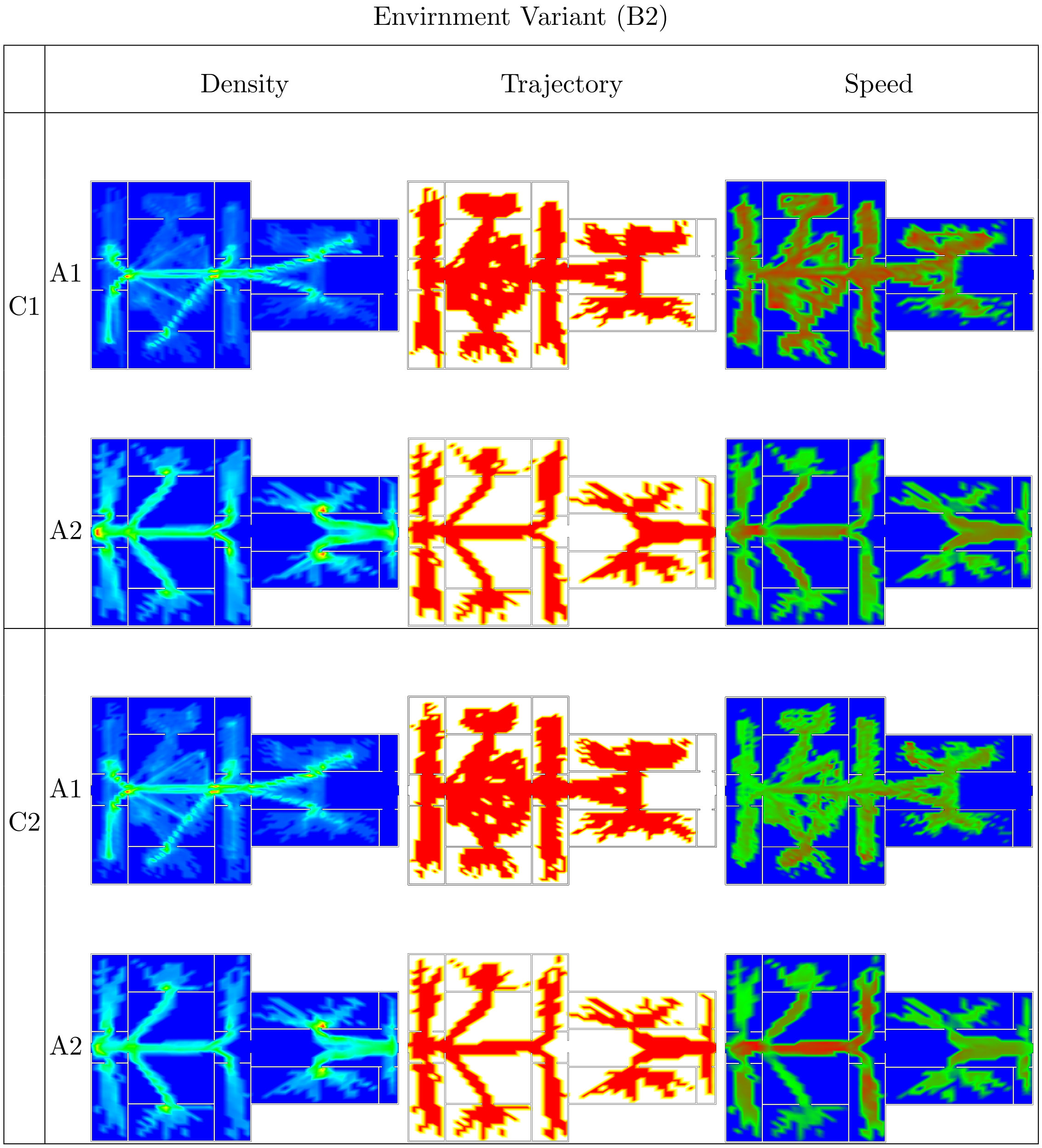


Figure 6.8. The crowd-aware analyses for the environment variant (B2). Density (D), trajectory (T) and speed (S) data maps are shown for both crowd instances (e.g., adult (C1) and mix-adult (C2) walkings), and for both day-to-day (A1) and evacuation (A2) activities.

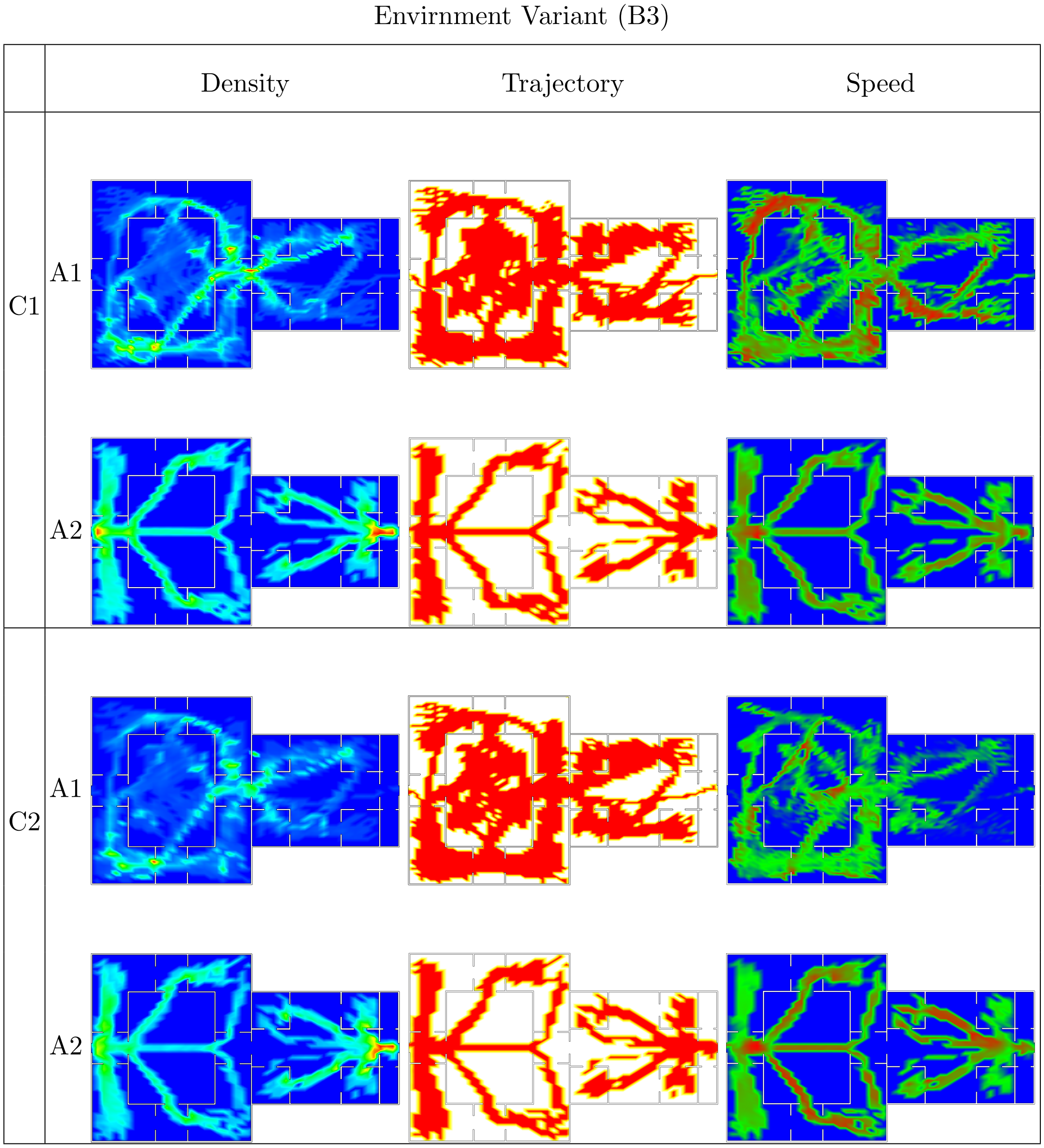


Figure 6.9. The crowd-aware analyses for the environment variant (B3). Density (D), trajectory (T) and speed (S) data maps are shown for both crowd instances (e.g., adult (C1) and mix-adult (C2) walkings), and for both day-to-day (A1) and evacuation (A2) activities.

Figure 6.8 shows spatial feedback from the simulation for environment variant (*B2*). For the adult crowds (*C1*), in the density map (*D*) for exhibition activity (*A1*), the regions in the middle corridor are comparatively more crowded especially at the very center of the hallway. In contrast, in evacuation activity (*A2*), this congestion is found near egress points as well as around the regions connecting the middle hallway and the exhibit areas. For the trajectory map (*T*) during exhibition activity (*A1*), comparatively more complex trajectories are seen. For evacuation activity (*A2*), the symmetric trajectories are found as the agents vacated the environment from their nearest exits. However, for both activities, the trajectories show that crowds traveled more areas compared to areas traveled in the environment (*B1*). For the speed map (*S*) during exhibition activity (*A1*), the higher walking speed is recorded not just in the corridors but also in the exhibit areas. In contrast, in evacuation activity (*A2*), high walking speed is only recorded near the egress points.

Figure 6.9 shows spatial feedback from the simulation for environment variant (*B3*). For the adult crowds (*C1*), in the density map (*D*) for exhibition activity (*A1*), the areas at exhibit points, as well as the middle corridor exhibit, increased density levels, whereas, during the evacuation activity (*A2*), the congestion is only found near the egress points. For the trajectory map (*T*) during exhibition activity (*A1*), complex trajectory structures are seen in the middle corridor as well as at the exhibit points with multi-route trajectories. For evacuation activity (*A2*), the symmetric trajectories are seen as agents moved to the nearest environment exit. For the speed map (*S*) during exhibition activity (*A1*), since there are multiple routes to the exhibition rooms, high walking speed is recorded around the exhibit areas as the agents moved in from one side of the room and exit from the other side. However, in evacuation activity (*A2*), high walking speed is only recorded in the middle hallway near the environment exits.

The speed analysis also reveals interesting patterns. In evacuation activities (*A2*) the mix-adult crowd (*C2*) shows more variation and asymmetry in speed than adult crowd (*C1*). Interestingly, the more uniform crowd (*C1*) seems to exhibit more speed variation and slower regions in everyday exhibit browsing (*A2*).

The above analyses are simply for the proof-of-concept. In a realistic setting, a user would use multiple levels of analysis to identify and analyze further areas of interest or patterns. For example, a trajectory analysis could identify the most visited areas, where a subsequent speed analysis could identify the specific use patterns in those areas.

6.4 Summary

In this chapter, a parametric design workflow is presented where users can specify a parameterized representation of (a) an environment (with bounds of permissible alterations of design space), (b) the crowds that populate the environment, and (c) the activities of the crowds they engaged in. Such a representation can be used to run human–building simulations and fine-tune the environment, crowd, and activities parameters based on visual feedback of human-centric analyses (e.g., density, trajectory, and speed maps) to achieve the desired performance. The presented workflow enhances the existing capabilities of a mainstream parametric modeling pipeline (e.g., Revit—Dynamo), enabling users to utilize crowd-centric dynamics of human–building interactions into the early stages of their designs.

Towards the end, a case study is presented to showcase the functionality and the effectiveness of the presented parametric workflow. While in this study, a selected number of environment, crowd, and activity configurations are analyzed, the parametric platform, however, can simulate infinite variations of these parameters in a systematic fashion.

Chapter 7

Joint vs. Sequential exploration of Parameters for Human–Building Analysis

In Chapter 6, a parametric workflow was presented to analyze human–building interactions by manually setting up parameters for the environment, crowds, and their activities. This approach is particularly useful to assist designers to incorporate human-focused factors into their designs during the early stages of the environment modeling. However, methods based on manually configuring an environment and a corresponding human behavior simulation are not practical for exploring the potentially vast number of design solutions that satisfy human-centric environment goals and requirements. Often, for practical reasons, designers may consider standard crowd configurations that do not capture the behavior of diverse occupants that may exhibit different locomotion abilities, movement patterns, and social behaviors.

To this end, this chapter presents a series of experiments to investigate automated joint and sequential parameter exploration workflows for human–building analysis. Exploring environment and crowd features are necessary to more accurately capture the mutual relations between buildings and the behavior of their occupants. This chapter serves as the second contribution under the research bin "Environment Design Exploration".

7.1 Overview

One of the significant challenges in environment modeling is the exploration of a wide range of design-space alternatives and the identification of those that best satisfy design goals while adhering to constraints (Kalay, 2004). Often, running human–building simulations using some standard crowds do not always account for the systematic impact that different environment designs produce on occupant movement and activities. Therefore, it is necessary to investigate the environment and crowd parameters in relation to each other, sequentially (e.g., exploring environment parameters first, keeping the crowd constant, and vice versa), and as a joint exploration effort.

This chapter uses the parametric workflow presented in Chapter 6 that allows users to manually adjust the environment and crowd parameters, run human–building simulations, and analyze the simulation feedback in the form of spatialized data maps. A series of experiments are conducted that use high-value thresholding and an unsupervised pattern recognition technique to automatically explore the vast number of environment-crowd parameter configurations. The hypothesis is that a joint exploration of the environment–crowd parameters (also known as features), is necessary to comprehensively capture the mutual relations between environments and the behavior of their occupants. By sequentially exploring environment and crowd features one after the other, designers may fail to identify design solutions that satisfy human-centric environment goals. This may lead designers to ill-posed designs that do not accurately capture the high dimensional design-space. To test the hypothesis, environment and crowd parameters are systematically explored to find out their impact on the flow of people (e.g., crowd flow) in an evacuation scenario. More specifically, 5 different experiments are run as follow:

1. Exploring environment configurations keeping constant the crowd parameters
2. Exploring crowd parameters keeping constant the environment configuration
3. Exploring crowd parameters while using salient environment configurations found in experiment (1)
4. Exploring environment configurations while using salient crowd parameters found in experiment (2)
5. Jointly exploring environment and crowd parameter configurations.

Further details on each of these experiments are given in the following sections.

7.2 Experiment Setup

7.2.1 Overview

A series of experiments are conducted to explore a large set of environment and crowd parameter configurations in "isolation" (i.e., environment/crowd only) as well as "jointly" to analyze the mutual relationship between the environment and crowd behaviors for the said two workflows. The parameter exploration in isolation is called as "sequential" exploration process. A sequential parameter exploration approach is more common and often used in traditional environment modeling.

The dimensionality of environment and crowd parameters (features) significantly impact an environment's solution space. If the environment and crowd parameter are explored in isolation, their dimensionality will be high, depending on the number of features. However, if they are explored jointly, their dimensionality will be multiplicatively large. This makes exhaustive exploration of design solutions intractable–especially with continuous parameter spaces. To explore such an enormous solution space, a machine learning technique is adopted for finding patterns in high-value designs of the exhaustive solution space.

First, environment–crowd parameter spaces are discretized regularly. Next, the highest value environment solutions are threshold with respect to some given metric (e.g., crowd flow) using only the 95th percentile of solutions. Finally, unsupervised pattern recognition is performed to identify salient patterns in the remaining high-value design solutions–referred to as templates. The templates are captured by clustering similar parameters for the environment–crowd configurations using an unsupervised pattern recognition technique (e.g., k-means++ using the squared Euclidean distance) (Arthur & Vassilvitskii, 2007; Hartigan & Wong, 1979). The k-means++ uses a heuristic approach to seeding the cluster centroids and improves the quality of pattern solutions.

An environment template is the centroid of a cluster, which represents the mean performance of all of the environment parameter configurations contained in that cluster with respect to the given performance criterion, i.e., *Crowd Flow*. Similarly, a crowd template represents the mean performance of all the crowd parameter configurations in that cluster. The parameterized environment and crowd configurations are generated using the parametric design workflow presented in Chapter 6.

Table 7.1 shows an overview of the experimental setup. A total of five (5) experiments are conducted. First, we tested the sequential exploration approach by means of experiments (E1–E4). *E1* explores the environment feature space using the default crowd parameterization. *E2* explores the crowd feature space using the default environment parameterization. Then, using the environment templates found in *E1*, *E3* explores the crowd features. Similarly, using the crowd templates found in *E2*, *E4* explores the environment features. This gives the best of environment and crowd parameter templates from *E4* & *E3*, respectively, which are found via sequential parameter exploration process. Finally, we jointly explore the environment and crowd parameters by testing all of the environment configurations using all of the crowd configurations (E5).

Experiments (E)	**# Input Environments**	**# Input Crowds**	**# Configurations (Env. x Crowd)**	**Top 5% Configurations (Flow-based)**	**# Configurations to K-MEANS**	**# Output Environments**	**# Output Crowds**
# 1 Sequential Environment (v1)	Diverse (19,683)	Default (1)	19,683	✓	984	Salient Environment Templates (3)	
# 2 Sequential Crowd (v1)	Default (1)	Diverse (27)	27		27		Salient Crowd Templates (2)
# 3 Sequential Crowd (v2)	Templates from Exp #1 (3)	Diverse (27)	81		81		Salient Crowd Templates (2)
# 4 Sequential Environment (v2)	Diverse (19,683)	Templates from Exp #2 (2)	39,366	✓	1,968	Salient Environment Templates (3)	
# 5 Joint Environment/ Crowd	Diverse (19,683)	Diverse (27)	531,441	✓	26,572	Salient Environment Templates (3)	Salient Crowd Templates (3)

Table 7.1: An overview of the experimental setup. For experiments E1,E4 and E5, top 5% of the flow-based sorted configurations (i.e,. only the 95th percentile of solutions) are selected. Light-Gray colored cells highlight the best performing environment and crowd templates found via sequential exploration. Dark-Gray colored cells highlight the best environment–crowd templates found via joint parameter exploration workflow.

7.2.2 Environment

Figure 7.1 shows the default configuration of a real-world office space currently under construction. There are seven rooms (R1 – R7) and two exits (one on each side) in the environment. Gray regions are the spawning areas for agents. Black solid lines are the boundary as well as interior walls. The main hallway (corridor) width is $3.5m$ in the default configuration. Red and blue dotted lines are hallway variants of $3.0m$ and $2.5m$ widths, respectively. Openings in the walls facing the hallway are the default door placements. Black line-segments parallel to the walls facing the hallway are the alternate locations for the placement of doors.

Table 7.2 shows the environment parameters and their values, selected for the experiments. A default (D) environment configuration features doors placed in the middle of the walls, hallway width of $3.5m$, and exits on both (LEFT/RIGHT) sides of the environment. In the experiments, the geometric symmetry of the default environment is maintained. The permissible discretized parameterizations for the environment features are chosen to affect crowd movement without introducing major changes in the environment design.

Parameter	**Permissible Values**		
Door Placements	Left	Middle (D)	Right
Hallway Width	3.5m (D)	3.0m	2.5m
Exits	Left/Right (D)	Left only	Right only

Table 7.2: The environment parameters and their permissible values. In the default (D) environment configuration, doors are placed in the middle, hallway width is $3.5m$, and exits are on both (LEFT/RIGHT) sides of the environment.

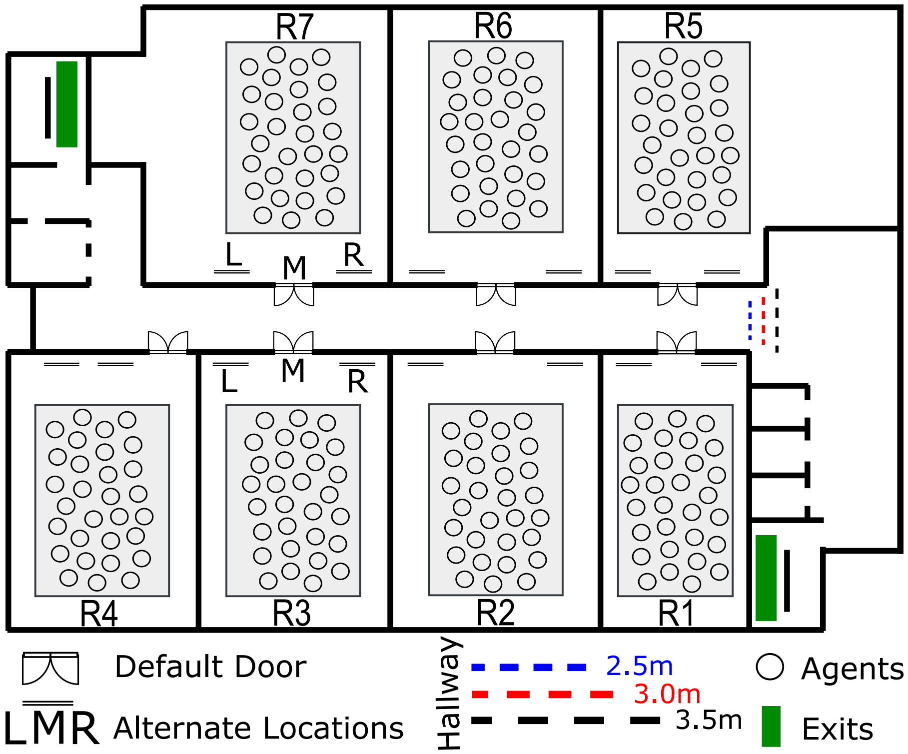


Figure 7.1. The default environment design used in experiments. GREEN regions are the exits. GRAY regions are the spawning areas for agents. BLACK solid lines are the boundary as well as interior walls. Default hallway (corridor) width is 3.5m. RED and BLUE dotted lines are hallway variants with 3.0m and 2.5m of width, respectively. Openings in the walls facing the hallway are the default door placements. BLACK line-segments parallel to the walls facing the hallway are the alternate locations for door placements.

7.2.3 Crowds

A variant of the social forces model (Helbing & Molnar, 1995) is used for agent navigation and collision avoidance. In the presented experiments, crowd activities are mapped to evacuations, and social forces models are known to exhibit panic behaviors (which may be shared during an emergency evacuation). Further details on human–building simulation processes are presented in Appendix A.

Table 7.3 shows crowd parameters and their permissible values. A default (D) crowd configuration contains 200 agents, which are equally distributed within all seven rooms. In every room, agents are equally mapped to a set of three walking speeds, 1.0 m/s, 1.3 m/s, and 1.6 m/s. These values are chosen to capture the desired walking speeds of a diverse crowd. Figure 7.2 shows a snapshot of simulation at 137$^{\text{th}}$ frame for the default environment and crowd parameters.

7.2.4 Measures

Crowd Flow is used as a metric for evacuation simulations. It has been defined in several different ways (Johansson, Helbing, Al-Abideen, & Al-Bosta, 2008; Helbing, Johansson, & Al-Abideen, 2007). In this chapter, the crowd flow is defined as the rate at which the agents reach their final goal or target position:

$$F_{Exit} = \frac{|A_c|}{t_c}, t_c = t_l - t_0 \tag{7.1}$$

where A_c is the agents count, and t_0 and t_l are the completion times for the first and

Parameter	**Permissible Values**		
Occupancy	100 agents	200 agents (D)	300 agents
Agents Distribution	Equal (D)	66% equal 33% random	33% equal 66% random
Speed (meter/sec)	33% agents (1.0)	66% (1.0)	17% (1.0)
	33% agents (1.3) (D)	17% (1.3)	17% (1.3)
	33% agents (1.6)	17% (1.6)	66% (1.6)

Table 7.3: The crowd parameters and their permissible values. A default (D) crowd configuration has crowd parameters such that occupancy is 200 agents, which are equally distributed within all seven rooms. In every room, agents are equally mapped to a set of three walking speeds, 1.0 m/s, 1.3 m/s and 1.6 m/s.

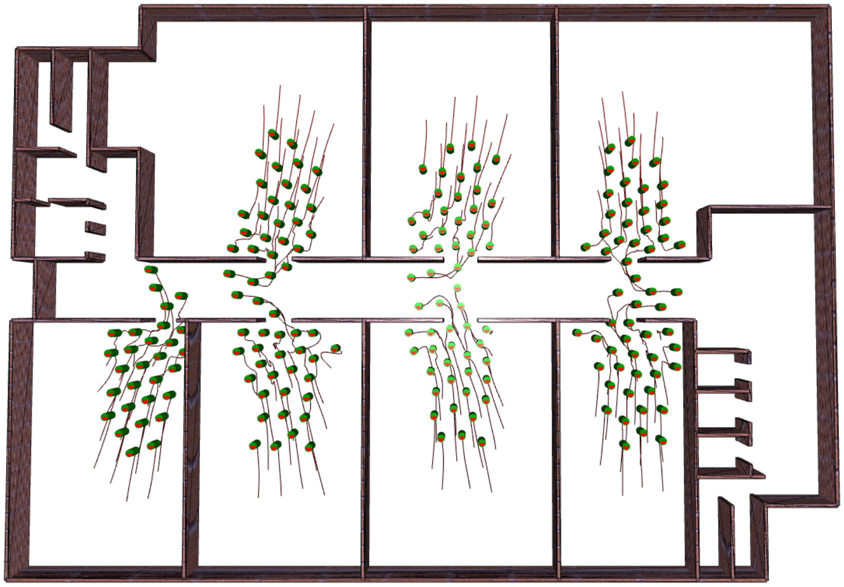


Figure 7.2. A snapshot of human–building simulation at 137^{th} frame for the default environment and crowd parameterizations.

last agents to reach their target positions respectively.

7.3 Cases

There are 5 experiments in total (E1–E5). E1–E4 explore the environment–crowd parameterizations sequentially, whereas *E5* explores these parameterizations as a joint effort.

7.3.1 Sequential Environment Exploration using Default Crowd Parameters

This experiment (E1) aims to explore and find salient environment parameters which maximize the exit flow of occupants during emergency evacuations. In this experiment, default crowd model parameters are used for running simulations while exploring the environment configurations (Table 7.1).

Procedure. All the environment configurations are simulated with default crowd parameters (i.e., walking speed (1.3 m/s), occupancy (200 agents), and distribution (equal)). The crowd flow values from these simulations are stored. Environment configurations are then sorted based on their corresponding crowd flows from higher to lower. Figure 7.3 (LEFT) shows histogram of *Crowd Flow* distributions. Only the top five percent of environment configurations with space parameters that yield higher crow flows are selected. Environment parameters of these selected configurations are then fed into *K-MEANS* to find out representative environment space parameters (also called centroids or templates) that yield higher crowd flows. The selection of "K=3" for the clustering is done based on *Sum of Squared Error* (SSE) elbow analysis, Figure 7.3 (RIGHT).

Results. Figure 7.4 (LEFT) shows the representative environment parameters (i.e., centroids of 3 clusters) from the clustering procedure. These centroids serve as environment templates and are used in *E3* to explore diverse crowd configurations.

7.3.2 Sequential Crowd Exploration using Default Environment Parameters

This experiment (E2) aims to explore and find salient crowd parameters which maximize the exit flow of occupants during emergency evacuations. It uses default environment parameters while exploring a diverse set of crowd configurations (Table 7.1).

Procedure. All crowd configurations are simulated with default environment parameters (e.g., door placements: middle, hallway width: $3.5m$ and exits: both sides (Left/Right)). The crowd flow values from these simulations are stored. Crowd configurations are then

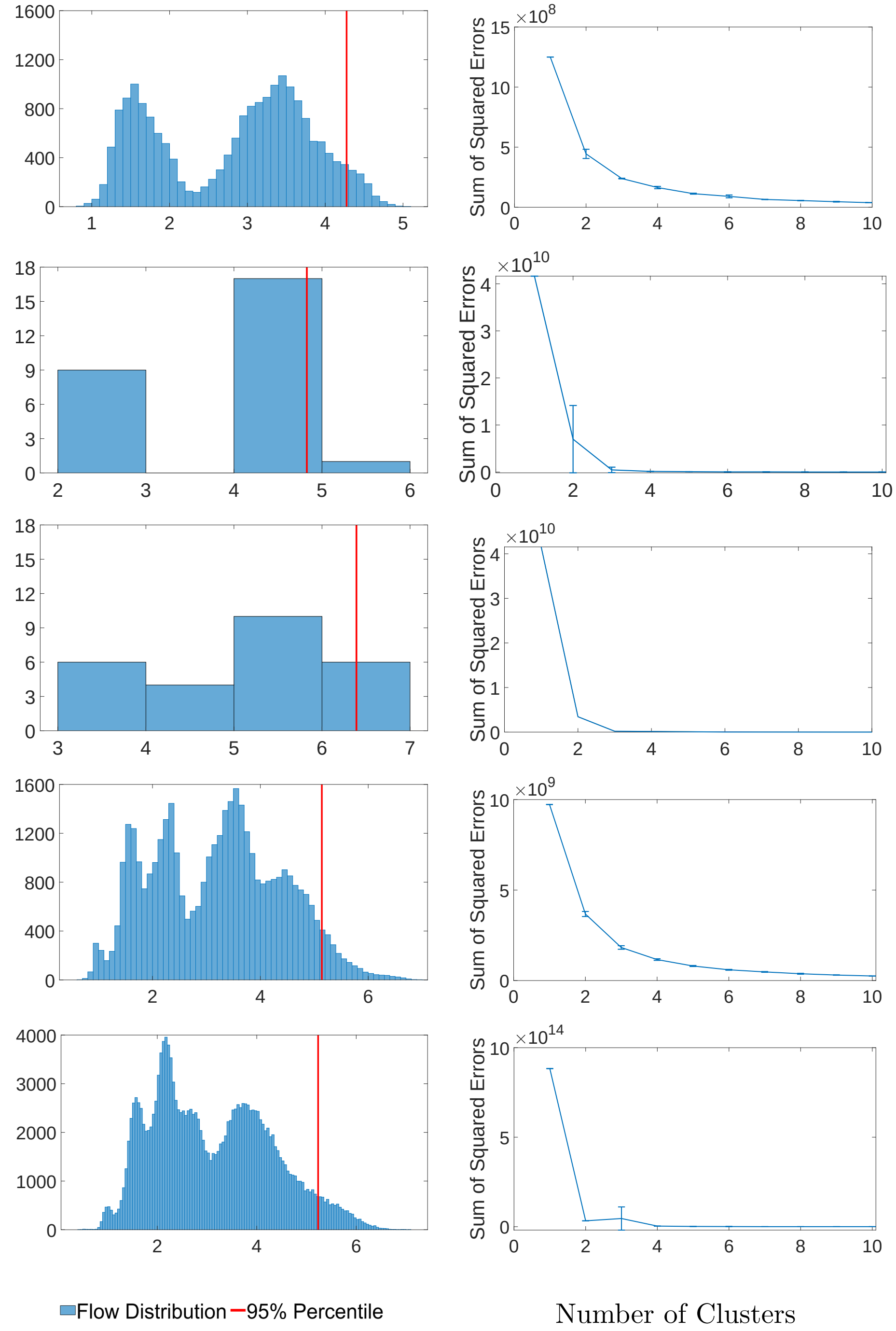
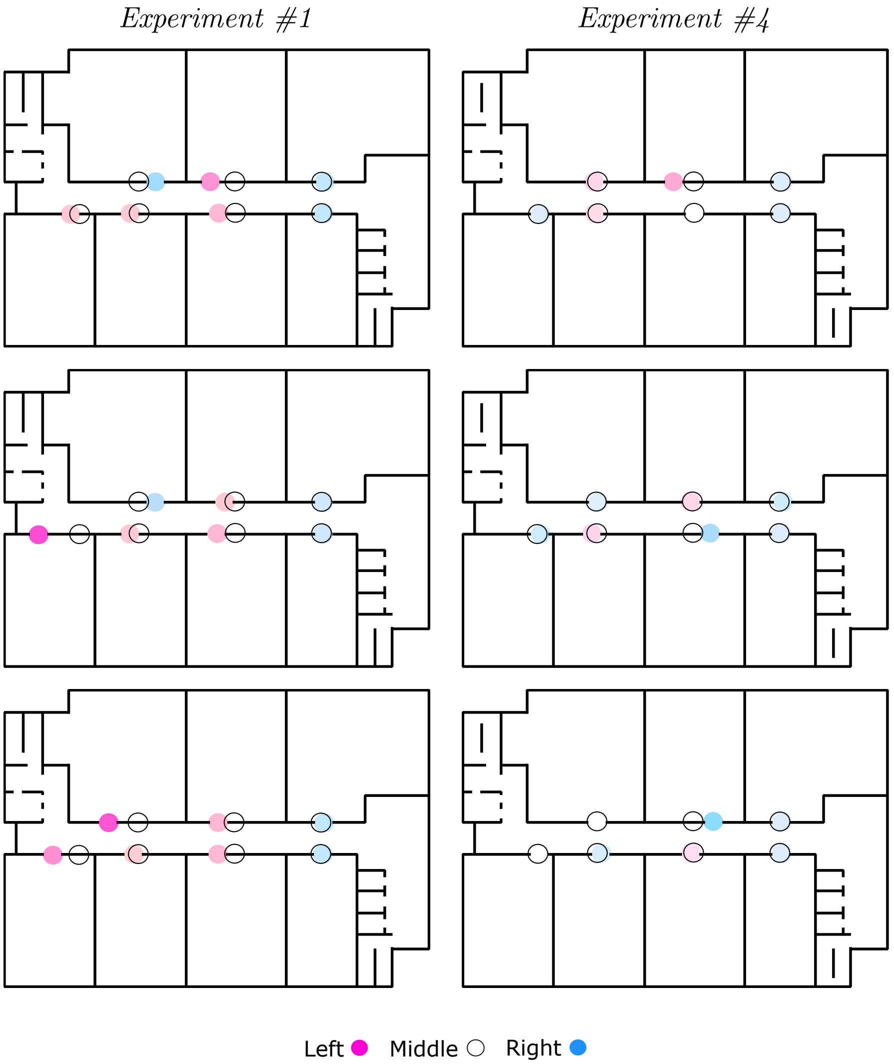


Figure 7.3. LEFT: Distribution of crowd flow for the environment configurations in each experiment. RIGHT: Sum of squared errors from elbow analysis for the selection of K for clustering. Rows: Top (E1) – bottom (E5), respectively.


Experiment #1

Experiment #4

Figure 7.4. Results for E1 & E4 – Representative environment parameters (i.e., centroids of clusters) from the clustering analysis. These are salient environment configurations found by simulating all the environment configurations using the default crowd parameters for experiment E1 (LEFT), and with salient crowd configurations (e.g., crowd templates) found in *E2* for experiment E4 (RIGHT). Door placements can be seen in the design layouts. Hallway widths of $3.325m$, $3.327m$ and $3.327m$, and $3.37m$, $3.39m$ and $3.38m$ for $E1$ and $E4$, respectively – (TOP–BOTTOM). In both experiments, exits are found on both sides of the environment.

sorted based on their corresponding flow from higher to lower. Figure 7.3 (LEFT – second row) shows histogram of *Crowd Flow* distribution. Since there are only fewer crowd configurations (e.g., 27), therefore, all of them are selected, and their respective crowd parameters are fed into *K-MEANS* to find out representative crowd templates which yield higher exit flows. The selection of "K=2" for the clustering is done based on *Sum of Squared Error* (SSE) elbow analysis, Figure 7.3 (RIGHT – second row).

Results. Table 7.4 (LEFT) shows the representative crowd parameters (i.e., centroids of 2 clusters) from the clustering analysis. These centroids are the crowd configurations that improve the desired performance objective (e.g., movement flow) and are used in *Experiment # 4* to explore a wide range of environment parameter configurations. The centroids are also called "Templates".

7.3.3 Sequential Crowd Exploration using Environment Templates from (E1)

This experiment aims to explore and find salient crowd parameters which maximize the crowd flow of occupants during emergency evacuations. Instead of using default environment parameters, in this experiment, the 3 environment templates are used which are found in *Experiment # 1*, while exploring diverse crowd configurations (Table 7.1).

Procedure. The 3 environment templates (found in *Experiment # 1*) are simulated with all of the crowd configurations. The crowd flow values from these simulations are stored. The configurations are then sorted based on their corresponding flows from higher to lower. Figure 7.3 (LEFT – third row) shows histogram of *Crowd Flow* distribution.

Crowd Parameters	**C # 1**	**C # 2**
Occupancy	150 agents	300 agents
Agents' distribution	Equal	Equal
Walking speed	39% (1.0 m/s) 22% (1.3 m/s) 39% (1.6 m/s)	39% (1.0 m/s) 22% (1.3 m/s) 39% (1.6 m/s)

Table 7.4: Results for E2: Representative crowd parameters (e.g., centroids of clusters) from the clustering analysis in *Experiment #2*. These centroids are the crowd templates that improve the desired performance objective (e.g., movement flow) and are used in *Experiment # 4* to explore a wide range of environment parameter configurations.

Since these are a small number of samples (e.g., 81 configurations), therefore, all of them are selected and fed into *K-MEANS* to find out representative crowd templates which yield higher exit flows. The selection of "K=2" for the clustering is done based on *Sum of Squared Error* (SSE) elbow analysis, Figure 7.3 (RIGHT – third row).

Results. Table 7.5 shows the representative crowd parameters (i.e., centroids of 2 clusters) from the clustering analysis. These centroids are the best of crowd templates found through sequential parameter exploration process that improve the desired performance objective (e.g., crowd flow).

Crowd Parameters	**C # 1**	**C # 2**
Occupancy	200 agents	200 agents
Agents' distribution	Equal	Equal
Walking speed	66% (1.0 m/s)	24.5% (1.0 m/s)
	17% (1.3 m/s)	24.5% (1.3 m/s)
	17% (1.6 m/s)	50% (1.6 m/s)

Table 7.5: Results for E3: Representative crowd parameters (e.g., centroids of clusters) from the clustering analysis in *Experiment #2*. These centroids are the best of crowd templates found through sequential parameter exploration process that improve the desired performance objective (e.g., crowd flow).

7.3.4 Sequential Environment Exploration using Crowd Templates from (E2)

This experiment (E4) aims to explore and find salient environment parameters that maximize occupants' flow. Instead of using default crowd parameters, in this experiment, the 2 crowd templates are used (found in *Experiment # 2*) while exploring a wide range of environment configurations (Table 7.1).

Procedure. All of the environment configurations are simulated with the 2 crowd templates found in *Experiment # 2*. The crowd flow values from these simulations are stored. The environment configurations are then sorted based on their corresponding crowd flows from higher to lower. Figure 7.3 (LEFT – fourth row) shows histogram of *Crowd Flow* distribution. Since we are looking for certain environment configurations with the space parameters that maximize the exit flow, therefore, only top-five percent of the flow-based sorted configurations are selected. The parameters from these top-five percent selected environment configurations are then fed into *K-MEANS* to find out representative environment templates which yield higher exit flows. The selection of “K=3” for the clustering is done based on *Sum of Squared Error* (SSE) elbow analysis, Figure 7.3 (RIGHT – fourth row).

Results. Figure 7.4 (RIGHT) shows the representative environment parameters (i.e. centroids of 3 clusters) from the clustering analysis. These centroids are the best of environment templates through a sequential parameter exploration process.

7.3.5 Joint Exploration of Environment–Crowd Parameters

This experiment (E5) aims to “jointly” explore environment–crowd parameters to find salient parameter configurations for both environment and crowds that maximize occupants’ flows. In this experiment, all of the environment configurations are simulated with all of the crowd configurations (Table 7.1).

Procedure. All of the environment configurations are simulated with all the crowd parameter configurations. The crowd flow values from these simulations are stored. Configurations are then sorted based on their corresponding exit flows from higher to lower. Figure 7.3 (LEFT – fifth row) shows histogram of *Crowd Flow* distribution. Since we are looking for a certain combination of environment and crowd parameters that maximize the occupants’ flow, therefore, we only selected top-five percent of the flow-based sorted configurations. Environment and crowd parameters of those top-five percent jointly explored configurations are then fed into *K-MEANS* to find out a combination of representative environment and crowd templates which yield higher exit flows. The selection of "K=3" for the clustering is done based on *Sum of Squared Error* (SSE) elbow analysis, Figure 7.3 (RIGHT – fifth row).

Results. Figure 7.5 and Table 7.6 show the environment and crowd templates respectively that improve the desired performance objective (e.g., crowd flow), discovered by jointly exploring the environment–crowd parameters from the clustering analysis. These environment–crowd templates are the best of environment and crowd parameters, which are found through the joint parameter exploration process.

Crowd Parameters	**C # 1**	**C # 2**	**C # 3**
Occupancy	200 agents	300 agents	300 agents
Agents' distribution	Equal	Equal	Equal
Walking speed	39% (1.0 m/s) 22% (1.3 m/s) 39% (1.6 m/s)	66% (1.0 m/s) 17% (1.3 m/s) 17% (1.6 m/s)	25% (1.0 m/s) 26% (1.3 m/s) 49% (1.6 m/s)

Table 7.6: Results for E5: Representative crowd parameters (e.g., centroids of clusters) from the clustering analysis in *Experiment #5*. These crowd templates are the best of crowd parameters which are found by jointly exploring environment–crowd parameters that improve the desired performance objective (e.g., crowd flow).

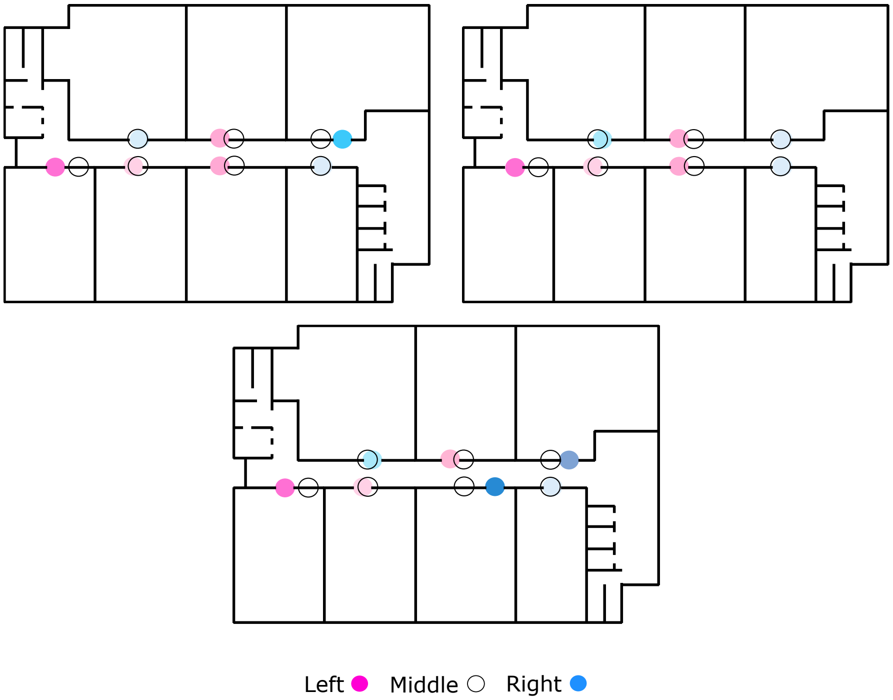
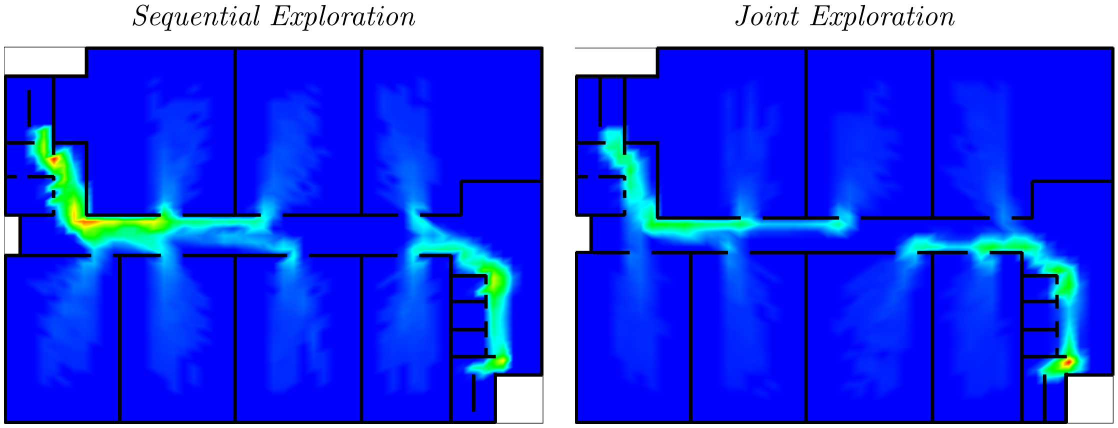


Figure 7.5. Results for E5: Representative environment parameters (i.e., centroids of 3 clusters) from the clustering analysis. These environment templates are the best of environment parameters which are found by jointly exploring environment–crowd parameters. Door placements can be seen in the layouts. Hallways have $3.075m$, $3.125m$ and $3.125m$ of widths, respectively. In addition, exits are found on both sides of the environment.

7.4 Sequential vs Joint Comparison

This section compares the crowd flow values for the environment–crowd templates found via joint and sequential parameter exploration processes. For the "sequential" process, the environment templates from E4 are simulated with the crowd templates from E3. Similarly, the environment–crowd templates which are "jointly" found in E5 are also simulated with each out.

Figure 7.6 shows crowd-density data maps for the best environment–crowd parameters from each parameter exploration process. The data map for the sequential exploration process is shown on the Right, whereas for joint exploration is shown on the Left. Their respective crowd flow values are also reported. The jointly discovered environment–crowd template configuration yield the highest exit flow of 6.488 agents/second, whereas for the sequential process, the flow of 5.762 agents/second is recorded. Parameterization from joint exploration produced 27.6% increased in crowd flow compared to sequential exploration. Overall, joint exploration process produced better environment–crowd parameters which yield higher flow values. In addition, with joint parameter exploration, door placements are made such that they are offset to each other (i.e., not opposite), creating a sort of zipper effect in the crowd movements, hence, less congestion in the hallway and better exit flows.



Sequential Exploration *Joint Exploration*

$Flow = 5.398\ agents/s$ $Flow = 6.488\ agents/s$

Figure 7.6. Density data maps for the best combination of environment–crowd parameters from sequential (LEFT) and joint (RIGHT) parameter explorations. *Crowd Flow* values are also reported for both data maps.

7.5 Summary

This chapter presented a series of experiments to demonstrate that a joint exploration of the high-dimensional environment and occupancy parameters provides a broader view of the relationship between environments and their occupants' behaviors. A total of 5 simulation experiments (*E1–E5*) were performed. The comparison of environment and crowd templates from sequential exploration (*E3–E4*) against those of the joint exploration (*E5*), revealed strong indications toward the necessity of joint parameterization and exploration. The results indicate that the joint exploration of space-crowd parameters produces significantly more accurate results compared with sequential exploration processes that consider default design or crowd features, allowing designers to investigate the relationship between spaces and their occupants comprehensively. In addition, the joint exploration produced environment layouts where doors are positioned offset to each other as opposed to opposing doors found in the sequential parameter exploration, which resulted in smooth crowd movements in the corridor, and hence yielded higher exit flows. The opposing door placements in joint exploration are the known results from both theoretical crowd simulation, and pedestrian movement analysis works (Hoogendoorn & Daamen, 2005; Nicolas, Bouzat, & Kuperman, 2017).

Chapter 8

Perceptual Evaluation of Environment Spaces

In the previous chapter, I presented environment–crowd parameter exploration processes to derive optimal environment configurations that satisfy a diverse range of crowd movements. Now a question arises that how spatial features of these environment configurations can be communicated to other stakeholders (e.g., to someone who is not a designer or an architect). It is to evaluate how well the end-users, policymakers, or government officials can perceive the spatial characteristics (e.g., visibility, accessibility, or organization) of an environment's design space.

In this chapter, I will investigate how well the novice and expert users perceive the spatial characteristics of environment spaces and whether their perception depends on the way they explore these spaces. Note that the presented work in this chapter is a preliminary exploration of the visual modes for communicating spatial environment

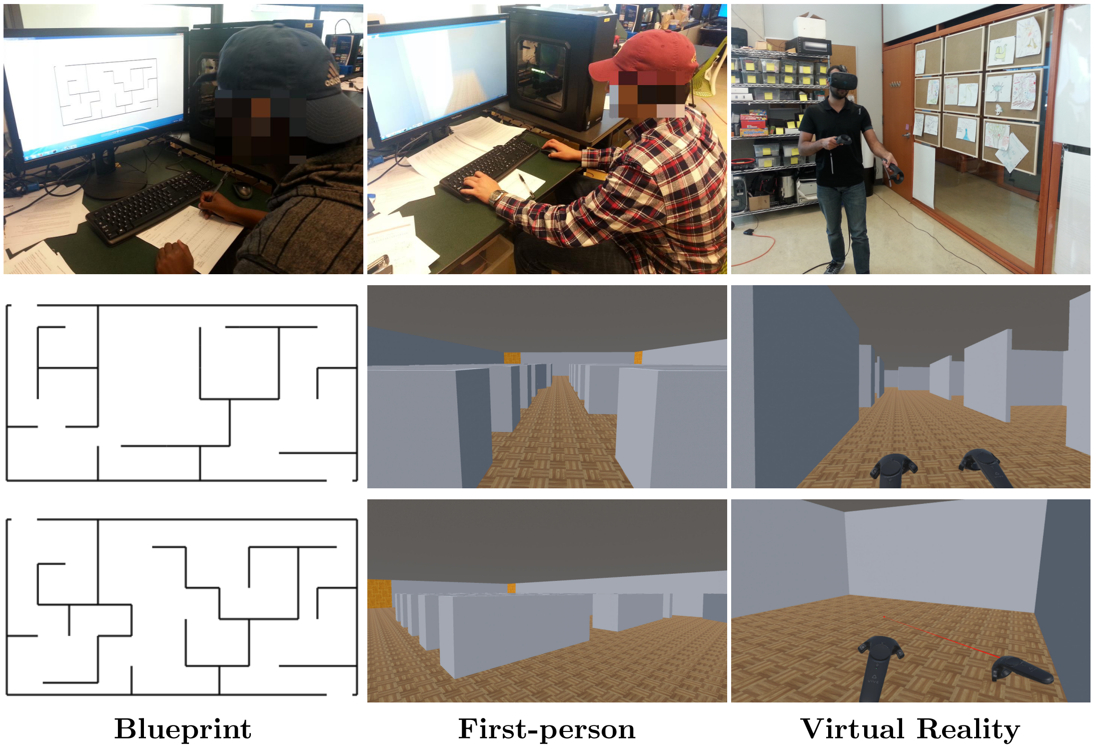


Figure 8.1. An overview of the perceptual study showing noivce participants completing study tasks.

information to the end-users. There can be different ways of communicating spatial information related to environment designs, and this chapter only touches upon one of the aspects (e.g., visual exploration of the design spaces). An in-depth research is needed to conclusively approve or disapprove the hypothesis of the presented study, which needs to be investigated in the future. This chapter is contributed under the research bin “Environment Design Communication”.

8.1 Overview

Environment layouts contain complex, high dimensional information that often must be communicated to decision-makers that are not designers or architects. Conveying such high dimensional information using low dimensional abstractions is difficult and may lead to a loss of critical information. In general, people have a difficult time comparing spatial layouts to which they cannot relate from experience (Eliot, 2002; Golledge, 1997). It is of particular interest in building and environment design modeling, which is still primarily based on 2D projections, such as blueprints, and more recently first-person views and 3D renderings with computer game-like interfaces.

As described in Section 3.3 of Chapter 3, the spatial measures from Space-Syntax analysis (i.e., *Accessibility*, *Visibility*, and *Organization*) provide a computational way of understanding and comparing designs for particular aspects of the environment. However, while these metrics can assign numerical values to environment configurations, it can be challenging for a person to understand why the environment is performing in some particular way without some context or experience with the design. It has been shown that people better understand information supplied to them in a format more in-line with their everyday experience (Magana, Brophy, & Bryan, 2012; Magana, 2014).

I will investigate whether novice users can perceive the spatial characteristics of an environment space properly and whether their perception depends on the way they explore the space. To do so, I will use the measures defined in Space-Syntax analysis (i.e., Visibility, Accessibility, and Organization of space) as the basis for the perceptual study, as they are well understood and have been extensively studied by the environment modeling and spatial cognition communities. They are considered correlated to, and therefore indicative of, human behaviors as they relate to navigation and spatial understanding of environment spaces (Bafna, 2003). The Space-Syntax methodology is already explained in-detail in Chapters 2 & 3. Therefore, in this chapter, I will only present a summary of Space-Syntax and its measures for recall purposes. The perceptual study I will present in this chapter focuses on three visual modes of environment space exploration. These visual modes are (1) 2D blueprints (**2D**), (2) 3D first-person walkthrough (**FP**), and (3) virtual reality (**VR**) walkthrough.

I will present two user studies. In the first study, novice participants are asked to rate environment spaces for their spatial characteristics (e.g., Accessibility, Visibility, and Organization of space) when exploring the environments in different modes of display (e.g., 2D, FP, and VR). Purposely, each environment design is presented in two variations: one that minimizes and one that maximizes the Space-Syntax measures. It is to investigate if the users can correctly perceive the difference in spatial characteristics of the environment space, and if so, in which visual mode. In the second study, expert users are asked to compare the same environment variations through 2D blueprints only and select the environment variation that they believe has higher values of the spatial measure. The purpose of this study is to investigate if experts are able to correctly perceive the difference in spatial characteristics of the presented environments when they evaluate a design space using 2D blueprints.

8.2 Perception and virtual reality in environment design

Environment features (e.g., architectural components) are one of the key factors in planning and navigating through space. In (Hölscher & Dalton, 2008), alternative designs of building corridors were presented to experts and non-experts as blueprints and videos of simulated walkthroughs to investigate the visual perceptions of users. They found that the users' inputs from the videos of simulated walkthroughs have strong correlations with the ground truth environmental measures, whereas no correlation is found for blueprint views. However, there is evidence that people using head-mounted displays may underestimate distance depending on measurement protocol (Grechkin, Nguyen, Plumert, Cremer, & Kearney, 2010). Furthermore, the navigation technique may play an essential role in the spatial understanding of environment spaces (Zanbaka, Lok, Babu, Ulinski, & Hodges, 2005).

The work presented in this chapter is highly motivated by an experiment to measure the perceptual judgments of experts and novice users in designs of complex corridors across different visual modes (Dalton, Hoelscher, Peck, & Pawar, 2010). In the referred experiment, users were asked to complete the experiment using three different modes: by looking at blueprint views of corridor designs, videos of simulated walkthroughs, and 3D in a CAVE-based virtual reality system (Cruz-Neira, Sandin, & DeFanti, 1993). However, these experiments were specific to wayfinding or navigation tasks. They do not focus on or take into account human-focused spatial measures such as visibility, accessibility, and organization of an environment space. Also, they do not compare and validate measures with respect to perception or design preferences of expert users.

8.3 Spatial Measures from Space-Syntax

The spatial measures from Space-Syntax analysis used in the user study include accessibility, visibility, and organization of space.

A node with low accessibility is connected to other regions of the visibility graph through a longer sequence of nodes. Intuitively, this measures the difficulty of navigating from a particular standpoint and is related to how many turn decisions are required to move from one point to another. Nodes with a high degree in the visibility graph are the regions with high visibility, and provide a better field of view and are considered more connected with the surrounding space. Visibility can also be thought of as the feeling of "openness" from a particular standpoint in space. Organization relates to how easy it is for an individual to plan and navigate through space. If a node in the visibility graph has low organization value, then the steps required to reach other regions in the environment from that node is unbalanced, in the sense that the number of options along the path varies widely.

The two user studies presented in this chapter use these measures as evaluation metrics of users' perception of design spaces. Further details on Space-Syntax methodology, and its measures are discussed in Sections 2.3 & 3.3.

8.4 User Study: Novice Users

Spatial measures provide architects and designers with fast computational means of analyzing an environment space. However, displaying or showcasing environment layout to a novice user has traditionally been done using blueprints, and more recently, digital first-person views (typically using computer game or rendering engines). This user study evaluates how well the novice users perceive spatial environment design information in different visual modes.

Null Hypothesis. All three visual modes (e.g., blueprint, first-person walkthrough, and 3D VR walkthrough) convey the spatial environment information to the users equally well.

8.4.1 Material and Methods

Measures. Three spatial measures (accessibility, visibility, and organization of space) from Space-Syntax analysis are used in this study.

Environments. A variety of real-scaled environments, including an art gallery, a grocery store, and an office are used to illustrate the effect of spatial measures from Space-Syntax analysis. Each environment is chosen to exemplify a particular spatial measure. That is, the art gallery is tuned for ‘Accessibility’, the grocery store is tuned for ‘Visibility’, and the office is tuned for ‘Organization’ of the space. All three environments have been tuned to produce two design variations (design conditions) representing extremes, the low average value (MIN), and the high average value (MAX) of their respective spatial measure.

Figure 8.2 shows the three environments with two design variations. The first two rows show the MAX condition with high values of spatial measures, while the next two rows show the MIN condition with low values. Environment layouts are shown with and without their associated spatial measure displayed as an overlaid heat map. The art gallery (left) is tuned for accessibility, the grocery store (middle) for visibility, and the office environment (right) for organization of space.

Table 8.1 shows the pre-computed values of the spatial measures for each environment variation. Since the MIN/MAX design variations of each environment are tuned for a specific spatial measure, they may have conflicting MIN/MAX values for metrics that they are not tuned for.

Apparatus. Three visual modes of environment exploration is used (Figure 8.3). The study experiments are completed using all three modes, including a 2D blueprint, interactive 3D first-person walkthrough, and a virtual reality (VR) system with teleportation. The 2D blueprints are skeletal views of the designs of the environments. Each blueprint displays wall and scale information to the participant. The participant viewed the blueprints on a high resolution (1080p) widescreen (16:9) computer monitor. The 3D first-person walkthroughs are interactive 3D models with basic ambient lighting (no shadow) built in the Unity3D game engine. The participants were given a mouse (look direction) and keyboard (translation) to control a virtual camera. The participant viewed the environments on a high resolution (1080p) widescreen (16:9) computer monitor. The

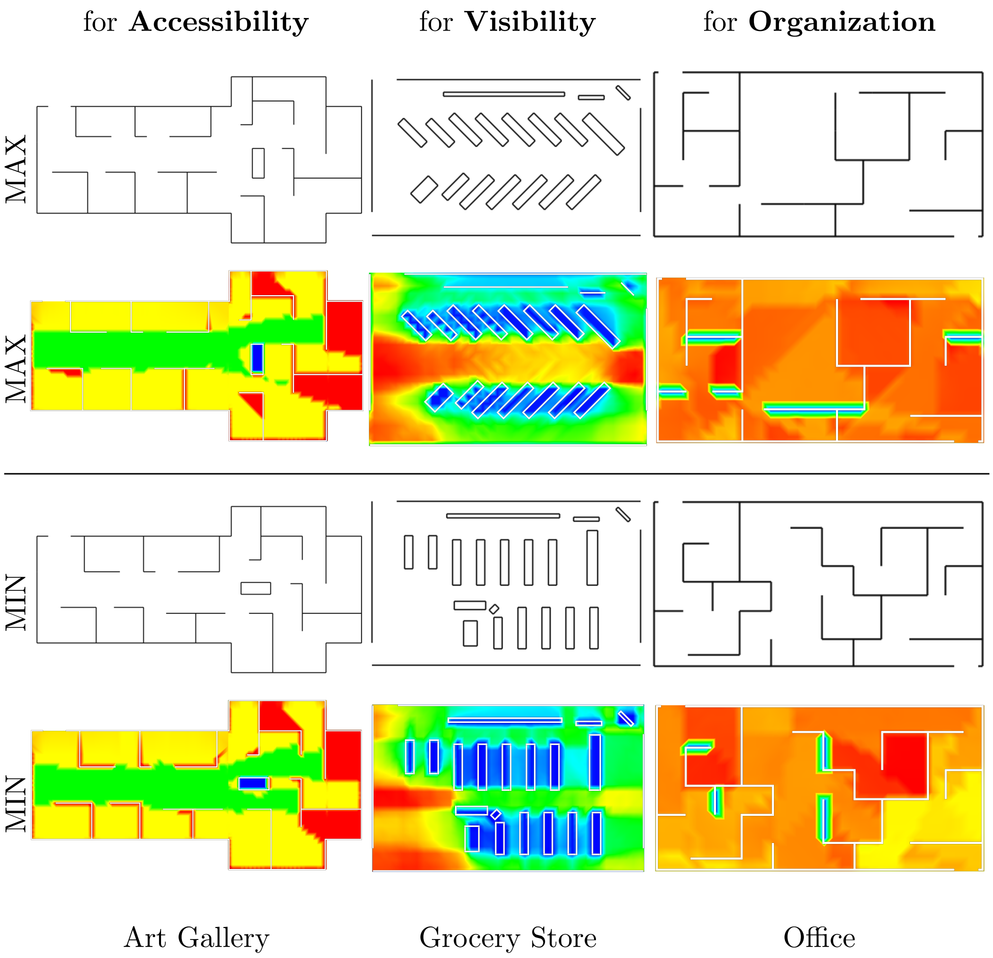


Figure 8.2. A set of three environments and their two design variations with the associated spatial measure shown as an overlaid heat map (red area in the environments show the high values and blue show the low values of the spatial measure). Top: design variation with higher metric value (MAX). Bottom: design variation with lower metric value (MIN). Art Gallery is tuned for accessibility, grocery store for visibility, and office for the organization of space.

Environment	**Accessibility**	**Visibility**	**Organization**
Art Gallery-min	**3.758**	395.926	1.4655
Art Gallery-max	**3.8037**	392.5512	1.4326
Grocery Store-min	3.0133	**141.56**	1.1192
Grocery Store-max	3.054	**149.3974**	1.1335
Office-min	5.6132	98.3605	**2.1219**
Office-max	6.9855	74.4237	**2.5361**

Table 8.1: Pre-computed spatial measures from Space-Syntax analysis for the three environments. The art gallery, grocery store, and office, each has two design conditions (MIN/MAX) for extreme values of accessibility, visibility, and organization of the space.

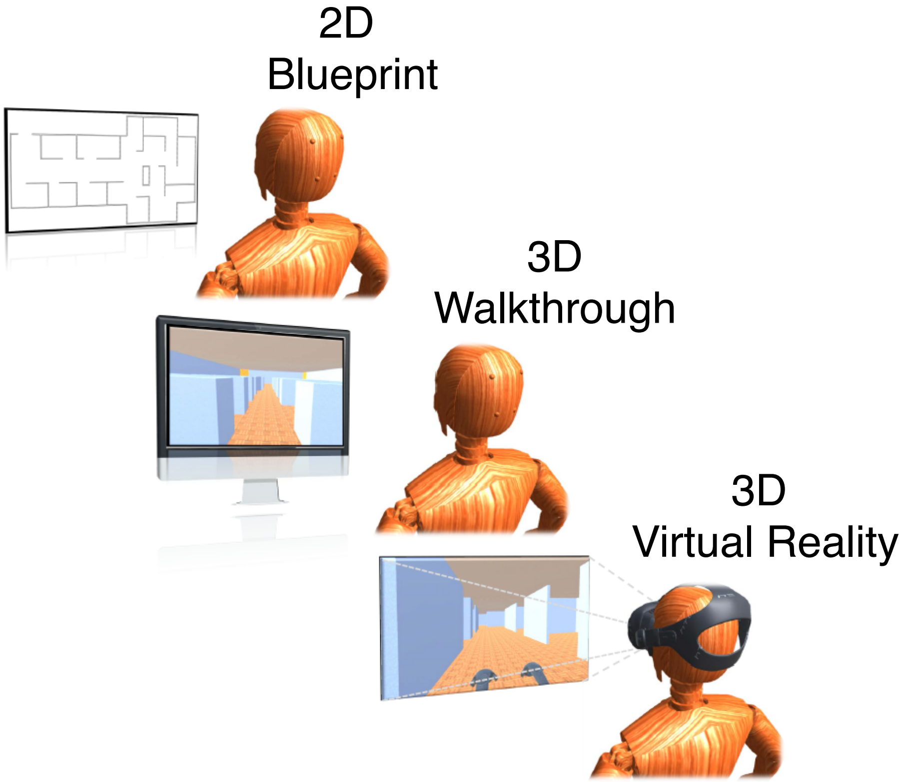


Figure 8.3. The visual modes of environment space exploration: 2D blueprints, 3D first-person view, and virtual reality with teleportation.

latest consumer-level VR system, the HTC Vive, is used in the study. This system affords room-scale interaction and navigation using two hand-held controllers. The participants view the world using a head-mounted display (HMD) OLED screen affording 1080x1200 pixel resolution per eye at a 90Hz refresh rate and a latency of 22ms.

Participants. 18 users (4 female and 14 male between 22 and 35 years of age) voluntarily participated in the experiment. They were paid 10 dollars per hour. The participants were mostly university students studying in computer science, digital media, or closely related fields. In order to recruit novices for this experiment, only those participants who reported no prior understanding of environment design and Space-Syntax concepts were selected.

Procedure and task. The study is delivered in three parts. In each part, participants were provided with two different design variations (MIN/MAX) to explore. They were then asked to perceptually rate the environments for the three spatial measures (accessibility, visibility, and organization of space), based on their understanding, by assigning a rating value on a ten-point Likert scale (1 – 10) with 1 being 'very low' and 10 being 'very high'. Every participant was given 20 minutes for each visual mode to complete the tasks. To prevent any learning effect between participants, the experimental conditions are delivered with a balanced latin-square design for the selection of visual modes and environments. At the start of the experiment, each participant was briefly informed about spatial measures from Space-Syntax analysis and was shown examples of metric visualization (e.g., heat maps) for a sample environment.

It has been reported in the literature that working with VR may cause VR-induced sicknesses like eye strain, dizziness, nausea, and some other symptoms similar to motion sickness (Nichols & Patel, 2002). To minimize motion sickness, the teleportation navigation method is utilized in VR exploration. This method allows a user to jump to a new position in the environment from which they can explore locally. Furthermore, each participant's interpupillary distance (IPD) is measured, and the headset lenses are adjusted accordingly.

8.4.2 Analysis

Independent variables. The pre-computed spatial measures from Space-Syntax analysis for each design variation of each environment are the primary independent variables (also referred to as computed spatial measures or ground truth). As well, the apparatus for each visual mode is considered an independent variable.

Dependent variables. Users' ratings are captured during each part of the experiment on a ten-point Likert scale (1 – 10) for the three spatial measures: (1) Accessibility, (2) Visibility, and (3) Organization of the space.

To understand the relationship between participants' ratings and the pre-computed spatial measures of the environments, a Pearson product-moment correlation analysis is performed. A three-way repeated measures analysis of variance is conducted on the influence of independent variables (visual modes, spatial measures, design variations of environments) on the users' perceptual ratings. A one-way between-subjects analysis of variance is performed to statistically compare the ratings of novice participants among all three visual modes.

8.4.3 Results

On average, participants spend 9 *minutes* in blueprint, 12 *minutes* in first-person and 10 *minutes* in VR mode of exploration.

Mean of users' ratings. Figure 8.4 shows the mean values of the participants' rating over both MIN/MAX design variations of the environments in all three visual modes.

The vertical bars show the standard deviation.

Correlation analysis between users' ratings and pre-computed spatial measures. Figure 8.5 shows correlation between users' ratings and the pre-computed values of spatial measures for the environment design variations. *Art gallery:* The users' ratings positively correlated with accessibility in virtual reality ($r = +.38$, $p = .03$), but are not significantly correlated in first-person ($r = +.05$, $p = .86$) and 2D blueprint ($r = +.11$, $p = .76$) modes at confidence interval $\alpha = 0.05$. *Grocery store:* The users' ratings are not significantly correlated with visibility in first-person ($r = -.20$, $p = .63$) and 2D blueprint ($r = -.05$, $p = .88$) modes, but significantly correlated in virtual reality ($r = +.47$, $p = .01$) mode at confidence interval $\alpha = 0.05$. *Office:* The users' ratings significantly correlated with pre-computed organization values in 2D blueprint ($r = -.39$, $p = .03$) and virtual reality ($r = +.63$, $p = .04$) modes, but not significantly correlated in first-person ($r = -.06$, $p = .86$) mode at confidence interval $\alpha = 0.05$.

Comparison of users' ratings across all visual modes. A significant effect of visual modes on participants' rating is found at a significance level of $p < 0.05$ for the three conditions [$\mathrm{F}(2, 87) = 17.92 = 3.0341\mathrm{e}{-07}$] (Figure 8.6). A posthoc comparison is then performed using the Tukey HSD test to compare across conditions. The test indicates that virtual reality mode has higher effects than 2D blueprint and first-person modes.

Influence of independent variables on users' ratings. A three-way repeated-measures analysis of variance is conducted on the influence of independent variables on the users' perceptual ratings.

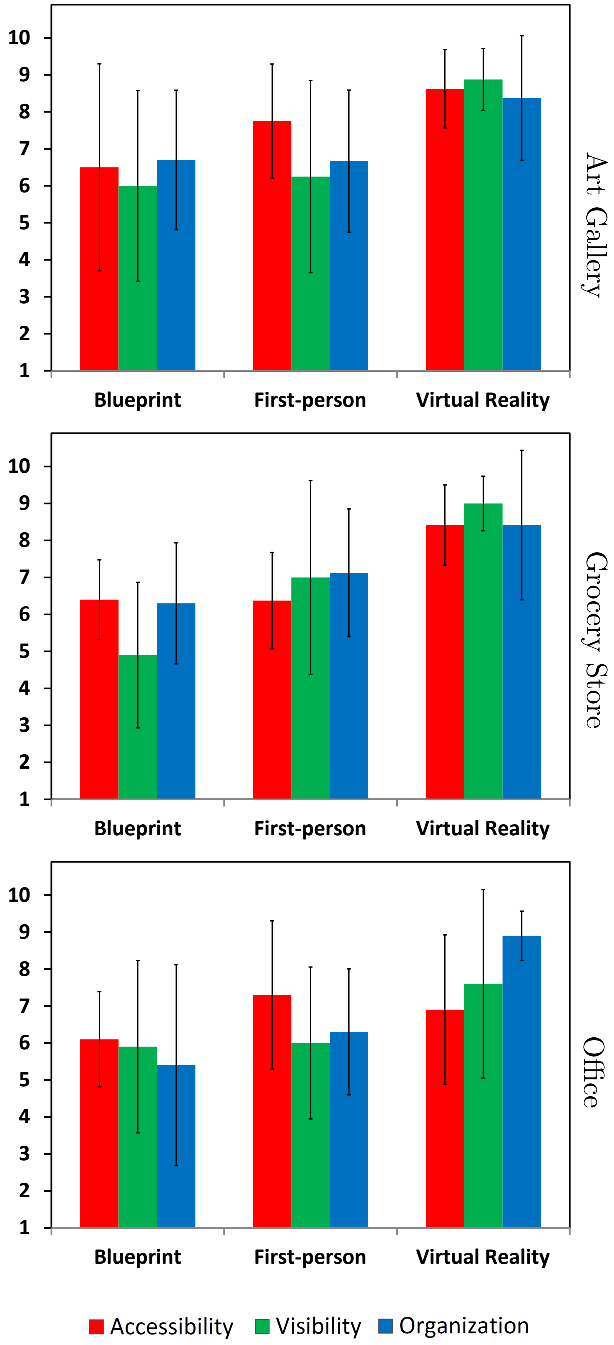


Figure 8.4. Mean user ratings for both MIN/MAX environment design variations. Vertical bars show standard deviation (SD). The VR mode has less SD and a higher mean than the other two visual modes.

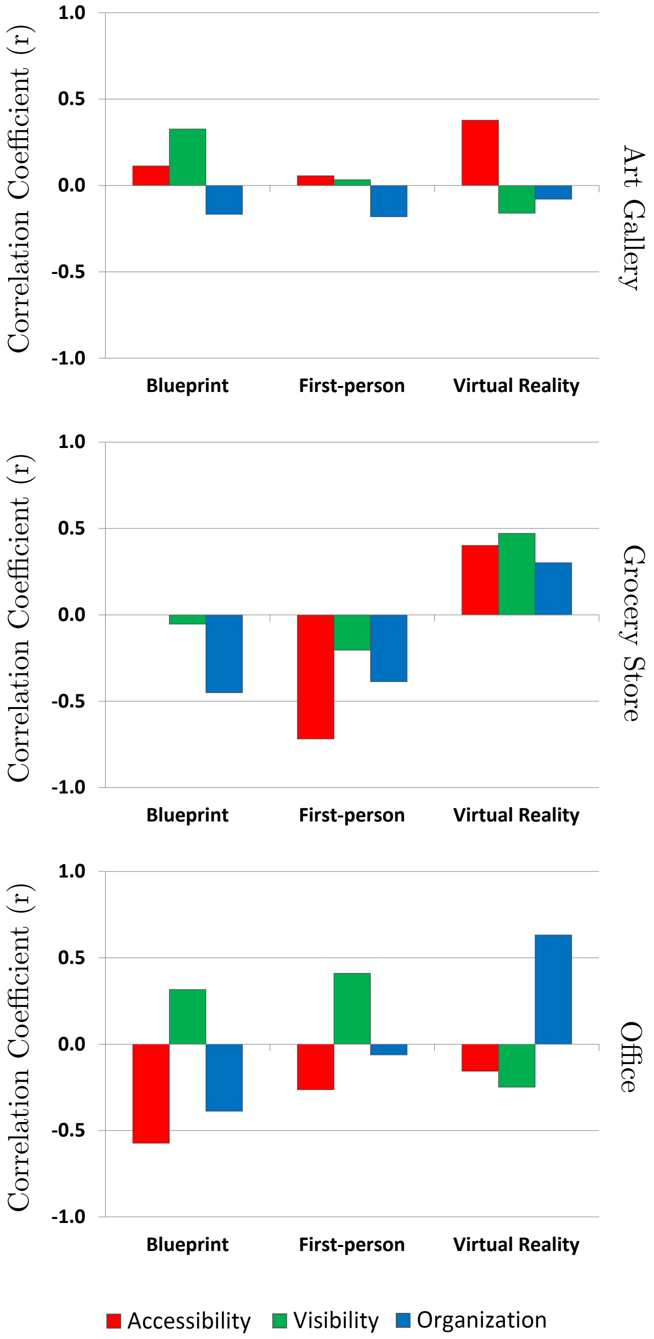


Figure 8.5. Linear correlation (r) between participants' perceptual ratings and spatial measures from Space-Syntax. VR shows a moderate positive correlation for the spatial measure every environment is tuned for.

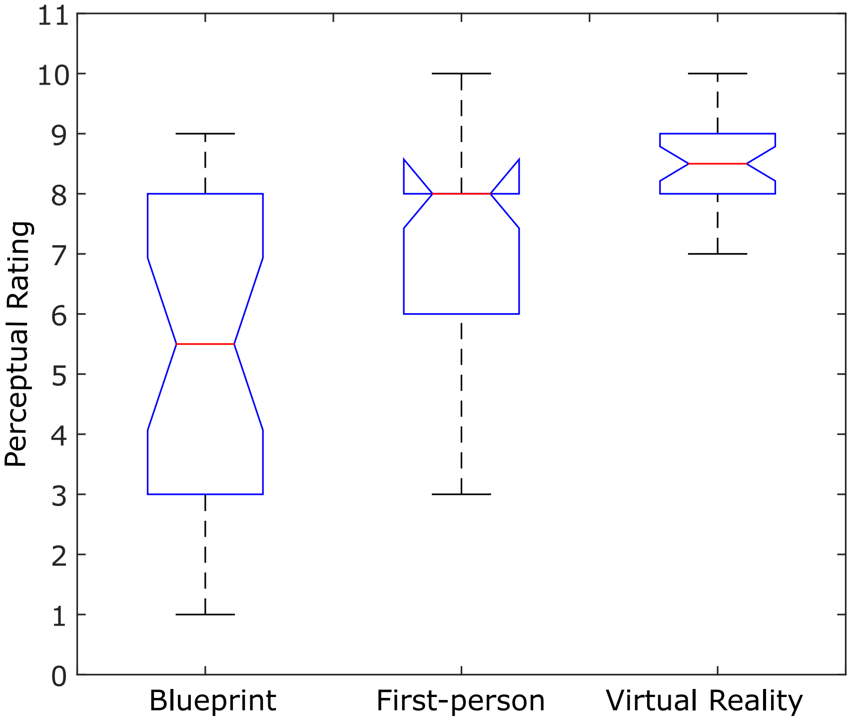


Figure 8.6. One-way analysis of variance (ANOVA) of perceptual ratings to analyze the differences among visual modes. The test indicates that virtual reality mode is significantly different from the other two. It has significantly higher perceptual ratings than blueprint and first-person. Bars show minimum and maximum rating values.

Art gallery: All effects are statistically significant at the 0.05 significance level. The main effect for visual modes yielded an F ratio of $[\mathrm{F}(2,28) = 14.29$, $p = 0.000]$ indicating a significant difference among Blueprint, First-person and VR modes. The main effect for spatial measures yielded an F ratio of $[\mathrm{F}(2,28) = 7.51$, $p = 0.002]$ indicating a significant difference among Accessibility, Visibility and Organization measures. The main effect for design variations of environments yielded an F ratio of $[\mathrm{F}(1,14) = 20.17$, $p = 0.001]$ indicating a significant difference between MIN and MAX variations. The interaction effects *visual modes * design variations* ($\mathrm{F}(2,28) = 14.45$, $p = 0.000$) and *visual modes * spatial measures * design variations* ($\mathrm{F}(4,56) = 3.680$, $p = 0.010$) are significant, whereas the interaction effects *visual modes * spatial measures* ($\mathrm{F}(4,56) = 2.177$, $p = 0.083$) and *spatial measures * design variations* ($\mathrm{F}(2,28) = 1.320$, $p = 0.283$) are not significant.

Grocery store: Only a single effect (visual modes factor) is statistically significant at the 0.05 significance level. The main effect for visual modes yielded an F ratio of $[\mathrm{F}(2,28) = 69.75$, $p = 0.000]$ indicating a significant difference among Blueprint, First-person and VR modes. The main effect for spatial measures and design variations of environments yielded an F ratio of $[\mathrm{F}(2,28) = 0.69$, $p = 0.510]$ and $[\mathrm{F}(1,14) = 0.50$, $p = 0.489]$ respectively, indicating no significant difference among Accessibility, Visibility and Organization measures and between MIN and MAX design variations. The interaction effects *visual modes * spatial measures* ($\mathrm{F}(4,56) = 6.89$, $p = 0.000$) and *visual modes * design variations* ($\mathrm{F}(2,28) = 4.24$, $p = 0.025$) are significant, whereas the interaction effects *spatial measures * design variations* ($\mathrm{F}(2,28) = 0.20$, $p = 0.813$) and *visual modes*

** spatial measures * design variations* ($\mathrm{F}(4, 56) = 0.72$, $p = 0.577$) are not significant.

Office: All effects are statistically significant at the 0.05 significance level except for the design variations factor. The main effect for visual modes and spatial measures yielded an F ratio of [$\mathrm{F}(2, 28) = 11.70$, $p = 0.00$] and [$\mathrm{F}(2, 28) = 14.23$, $p = 0.000$] respectively, indicating a significant difference among Blueprint, First-person and VR modes, and among Accessibility, Visibility and Organization measures. The main effect for design variations of environments yielded an F ratio of [$\mathrm{F}(1, 14) = 2.42$, $p = 0.142$] indicating no significant difference between MIN and MAX design variations. The interaction effects *visual modes * spatial measures* ($\mathrm{F}(4, 56) = 6.345$, $p = 0.000$) and *visual modes * design variations* ($\mathrm{F}(2, 28) = 3.47$, $p = 0.045$) are significant, whereas the interaction effects *spatial measures * design variations* ($\mathrm{F}(2, 28) = 0.89$, $p = 0.419$) and *visual modes * spatial measures * design variations* ($\mathrm{F}(4, 56) = 1.43$, $p = 0.235$) are not significant.

8.4.4 Discussion

The summary statistics indicate that participants had a better understanding of the spatial measures when exploring the environments using virtual reality over other visual modes. On the other hand, standard deviation values are much smaller for all three environments when using virtual reality. Furthermore, the first-person performed better than 2D blueprint. Overall, accessibility and organization were more highly rated spatial measures than visibility in all three visual modes.

Correlation analysis reveals several interesting insights. In particular, the benefits of using VR to understand the spatial features of an environment seem to be consistent in all three experiment cases. *Art Gallery:* The correlation coefficients show that the participants perceived the accessibility of the space most accurately in the virtual reality mode, and least accurately using the first-person mode. It is also interesting to note that for all three visual modes, the correlation between users' ratings and pre-computed accessibility values is positive, unlike the other two measures. *Grocery Store:* The correlation coefficients show a negative relation between the participants' ratings and pre-computed visibility values for both first-person and 2D blueprint modes. In contrast, the virtual reality mode has a moderate to low positive correlation. *Office:* The moderate positive correlation with virtual reality, as opposed to the low and weak negative correlations of blueprint and first-person, indicates that participants were able to perceive the organization of the space in agreement with its pre-computed values only using this mode.

Results from three-way (*visual modes* x *spatial measures* x *design variations of environments*) repeated-measures analysis of variance show that the main effect as well as interaction effect involving visual modes factor has greater influence on the users' ratings and has significant difference among blueprint, first-person and virtual reality modes. Figure 8.7 shows the estimated marginal means of users' perceptual ratings on the three visual modes.

The one-way analysis of variance shows that participants' perception and understanding of the spatial measures from one of the modes is considerably different from the other two, and therefore, rejects the null hypothesis (Obuchowski (Jr.) & Rockette (Jr.), 1995).

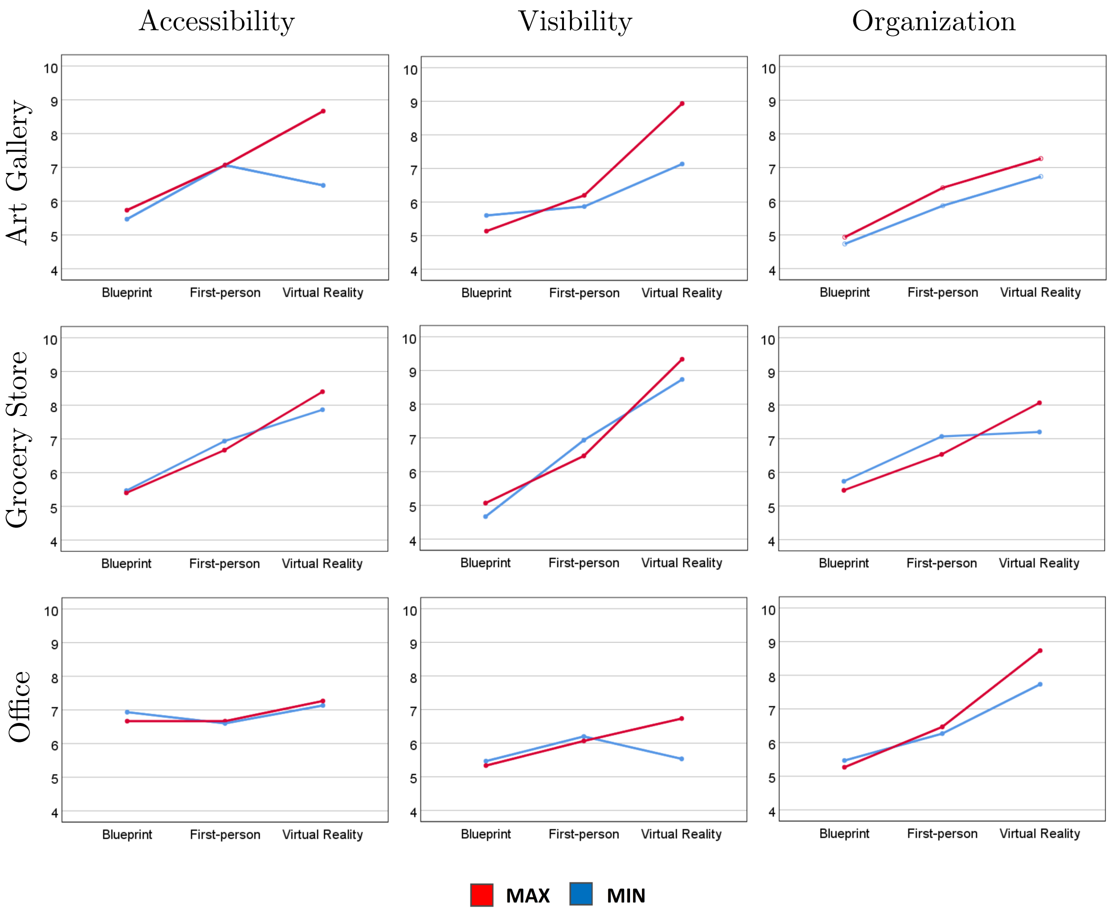


Figure 8.7. Estimated marginal means of users' perceptual ratings for the three visual modes. Virtual Reality shows the highest influence on user perception.

These results suggest that virtual reality does affect a person's perception and understanding of space. More specifically, the results suggest that when someone uses virtual reality as a mode to explore environments, the person's perception is more accurate for spatial measures from Space-Syntax analysis.

8.5 User Study: Expert Users

Blueprints are conventional means of conveying both draft and final configurations of environment designs. It is expected that experts are capable of inferring a large amount of information from these blueprints. However, it remains to be seen how well the computed spatial measures (e.g., from Space-Syntax analysis) conform to an expert's spatial intuition. The agreement between the two sources of spatial perception is key to validating the usefulness of spatial measures for the amount of design-time information they provide.

8.5.1 Material and Methods

Environments. The blueprints of the three environments, including an art gallery, a grocery store, and an office (maze), are used in this experiment (Figure 8.2).

Apparatus. 2D blueprints are the skeletal views of environment designs. Each blueprint displays wall and scale information to the participant. The participants viewed the blueprints using their computer monitors via an online survey with high-resolution images.

Participants. 14 experts (6 female, 7 male and 1 non-binary/third-gender) voluntarily participated in the experiment. Table 8.2 shows the demographic information of the participants.

Demographic Information

Gender	**Sex**	**Age**	**Country of Residence**
Female: 6 (42.9%)	Female: 6 (42.9%)	25 - 34 years old: 10 (71.4%)	Canada: 9 (64.3%)
Male: 7 (50%)	Male: 7 (50%)	35 - 44 years old: 4 (28.6%)	United Kingdom: 1 (7.1%)
Non-binary/Third-gender: 1 (7.1%)	Intersex: 1 (7.1%)		Pakistan: 4 (28.6%)

Table 8.2: Demographic information of expert participants (self-provided).

In order to recruit experts for this experiment, all participants self-evaluated their knowledge and skills in the area of environment design, urban planning, and Space-Syntax spatial measures on a five-point Likert scale-based assessment. On average, participants rated 4 and higher on a scale of 1–5 regarding their prior experience. Furthermore, participants were asked to rate their understanding of Space-Syntax spatial measures, for which the average recorded response is 3.43 on a scale of 1–5. This shows that the participants had above-average prior understanding of Space-Syntax spatial measures. To further increase this understanding, participants were briefly informed about the spatial measures from Space-Syntax with heat map visualization examples. Table B.3 (from Appendix B) shows the recorded domain knowledge responses from the participants.

Experiment procedure and task. This experiment is conducted as an online survey. Both MIN and MAX variations of the environments are presented in randomized order side-by-side as blueprints with scaling information. Each participant made a binary selection to identify the design variation they believe has the highest value (MAX) for each Space-Syntax spatial measure.

8.5.2 Analysis

Independent variables. The design variations of the environments are the primary independent variables. The pre-computed spatial measures from Space-Syntax analysis for each design variation are also the independent variables.

Dependent variables. The expert selections of the design variation of each environment are the only dependent variables.

8.5.3 Results

Figure 8.8 summarizes the results from experts' selections. The blue portion of the bars shows the percentage of experts who correctly identified the design variations of the environments that agreed with the pre-computed Space-Syntax spatial measures (Table 8.1). That is, the portion of experts which correctly identified the design variations which have

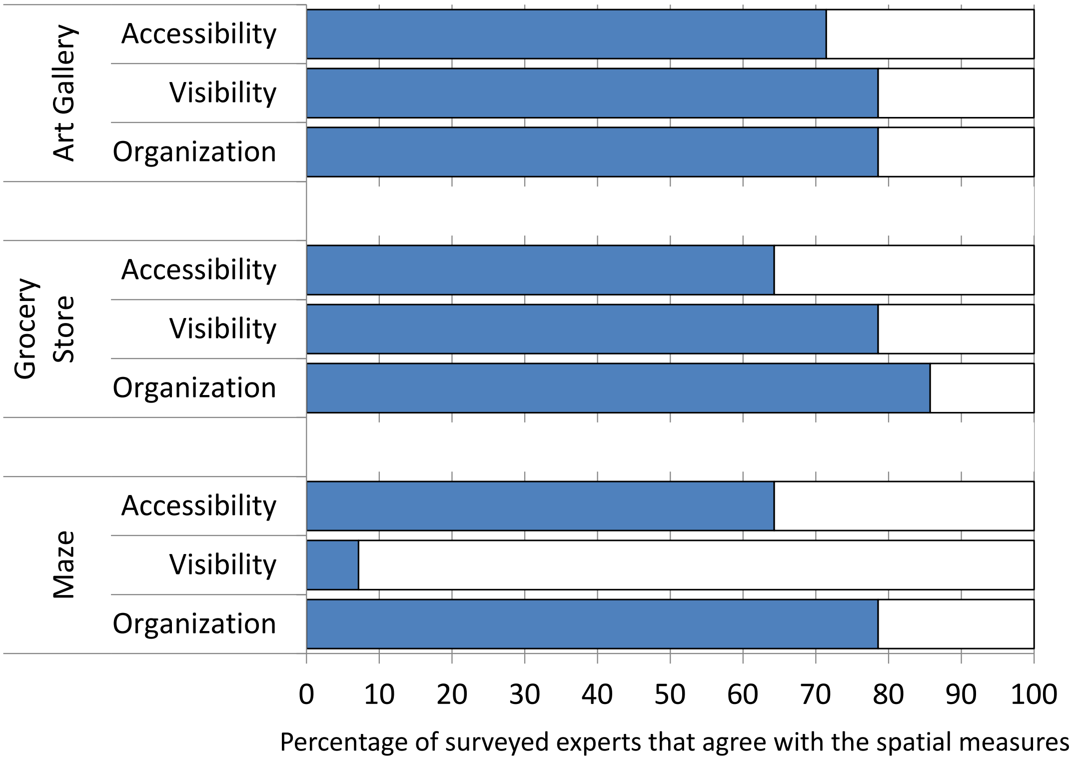


Figure 8.8. The blue portion of the bars shows the correctness of experts' identification of design variation that agrees with the pre-computed spatial measures.

the highest value (MAX) of visibility, accessibility, and organization. On average, 68% of the experts correctly identified the design variations.

8.5.4 Discussion

The results show that the majority of experts perceived the Space-Syntax spatial measures as intended and correctly differentiated between the two design variations (MIN/MAX). More specifically, the majority of the experts agreed with the pre-computed spatial measures in the cases of the art gallery and the grocery store. For the office environment, the majority correctly identified the accessibility and organization but did not agree with visibility of the space. It is therefore fair to conclude that even for experts is not easy to evaluate certain spatial characteristics of an environment from blueprints alone.

8.6 Summary

In this chapter, I presented a perceptual study to find out whether a novice user's perceptual understanding of an environment space agrees with established spatial measures such as those defined by Space-Syntax analysis, and whether that agreement depends on the mode of visual exploration. Experimental results indicate that using virtual reality to explore environment space results in better agreement between the users' perception of the space and the computed spatial measures. In most cases, virtual reality is the only mode that shows a significant positive correlation between the two. These results have implications for how the sharing and collaboration of environment design can be done most effectively. It appears that novices may gain a significantly better understanding of a potential environment design if they are allowed to experience it using VR. Intuitively, this means personal experience with a design is useful in communicating the attributes of the space. Though virtual reality is not reality, it provides an ad-hoc yet immersive means of approximating a person's experience without the need to be physically in the space. The results from three-way (*visual modes* x *spatial measures* x *design variations of environments*) analysis of variance showed significant differences among the three visual modes for the main effect as well as the interaction effects involving visual modes factor. Furthermore, the estimated marginal means showed that virtual reality is the most effective of the three visual modes.

In the second study, expert users with prior knowledge of spatial measures and with proficiency in environment designs were asked to identify design variations of the environments. The expert observations are mostly in agreement with the pre-computed environment variations for the spatial measures for accessibility and organization, but not entirely for visibility, indicating that even experts may have difficulty interpreting spatial measures from blueprints alone. Our results indicate that virtual reality may be the best method for analyzing three-dimensional spaces for environment design applications. These results motivate further investigation into the perception, evaluation, and communication of designs involving complex spatial forms.

These studies concluded that perceptual evaluation of an environment space is most effective in virtual reality, especially for novices, while 2D blueprints are complicated and understandable by experts only.

Note that the presented studies are the preliminary exploration of the visual modes for communicating spatial environment design information with limited user participants. An in-depth research is needed in the future that not only test the study conditions with a larger user base but only considers other aspects of space exploration, to conclusively approve or disapprove the hypothesis.

Chapter 9

Conclusion

This dissertation attempts to explore the dynamics of human–building interactions by means of human behavior simulations. It presents innovative solutions to integrate agent-based simulations into industry established CAD pipelines. Moreover, it offers the democratization of human behavior simulations as a cross-platform on-demand service. These solutions and platforms enable designers and architects to design crowd-aware environments that better support human-related factors by simulating movements of potential occupants. Several spatiotemporal analytics from human–building simulations are computed. These include (but not limited to) path/trajectory analyses, bottleneck analyses, time and distance-based traces, and speed and density data maps.

These crowd-aware analytics are to assist designers in improving their environment layouts by making crowd-informed decisions, not just at the end when the environment model is already matured, but from the very beginning in the environment design process.

This chapter reviews the findings and user evaluations of the presented workflows and discusses their applicability and acceptance in common environment design practices. Following these discussions, I explore the limitations of this work. In the end, I follow up with future works to address these limitations.

9.1 Findings and Observations

The presented research in this dissertation falls under three bins of research production, namely *Environment Design Analysis* (Chapters 4–6), *Environment Design Exploration* (Chapters 7–8), and *Environment Design Communication* (Chapters 9). This section repeats in summary form the findings of each chapter for convenience.

Environment design analysis. An interactive spatial analytics tool is presented as the first item of research under environment design analysis. Different from other simulation tools representing similar design metrics, this research is readily integrated into a mainstream environment modeling pipeline (e.g., Autodesk Revit). Beyond static spatial analyses, the tool also enables users to run dynamic crowd simulations to investigate the impact of the environment on its occupants, all interactively and in real-time. Results from the user study reveal that using such an interactive platform, the designers can progressively refine the design layouts of their existing models in terms of accessibility, visibility, organization, crowd flow, and walking distances. The users' questionnaire demonstrates the usability and effectiveness of the tool in supporting designers' decision-making. Following this work, an automated semantic-based International Building Code (IBC) checker is developed to compute egress plans and validate the IBC rules for means of egress. It uses human behavior simulations to evaluate egress routes. The presented case study results indicate that the standard egress planning workflow does not take into account space semantics, violates certain IBC rules for *Means of Egress*, and rely on a static distance measure to compute egress routes. Thus, poses threats for human safety as the egress plans lack the dynamic aspects of human movements. On the other hand, by taking into account semantics of potential space usage and evacuation times for egress routes, more secure egress plans can be achieved by making human-aware egress planning decisions. These works, however, are integrated into a specific mainstream environment modeling pipeline (e.g., Autodesk Revit). To make these crowd-aware solutions to be used by the broader audience, the last research item under environment design analysis presents a democratized workflow to run human–building simulations as an on-demand service via client-side web-browser. User participants rated their confidence on the usability of this approach as "above average". The mean and median scores from SUS fall within the adjective range of "good" and "excellent". This indicates a higher acceptance of such approaches in the environment design community as they enable deep integration levels with other software in the work process to achieve targeted goals often in a cross-platform manner.

Environment design exploration. The innovative solutions presented under the research bin 'environment design analysis' are mostly useful to analyze the environment models that are already matured (e.g., their BIM models have already been designed). This limits the designers to make any significant changes in their designs. It is because, by this time, many resources have already been spent to achieve the current environment draft. To this end, a parametric workflow is presented to enable users to specify a parameterized representation of (a) an environment (with bounds of permissible alterations of an environment), (b) the agents that populate the environments, and (c) the activities agents are engaged in. Such representation can be used to run human behavior simulations and fine-tune the aforementioned parameters based on visual feedback of human-centric analyses (e.g., density, trajectory, and average speed maps). This solution is embedded within a mainstream parametric design framework (e.g., Revit–Dynamo), which is used in the early stages of the environment design process. The results from the case studies reveal that such approaches hold promise to augment the iterative environment design process with human-related factors right from the early design stages. The study results also reveal that the joint exploration of the environment–crowd features yields higher value design solutions compared to sequential parameter explorations. For example, the joint feature exploration produced environment layouts where doors are positioned offset to each other – increases crowd flow, as opposed to opposing doors – causes congestion and slows down the crowd.

Environment design communication. Towards the end of this dissertation, a perceptual study is presented to evaluate the right visual mode for the users to perceive and understand the environment spaces correctly. Traditionally, this has been done via 2D blueprints. However, not all stakeholders (e.g., government officials, end-users, or other partners) are capable of reading floorplans. The presented user study evaluates whether a novice user's perceptual understanding of an environment agrees with established spatial measures (e.g., visibility, accessibility, and organization of space) and whether that agreement depends on the mode of visual exploration. Experimental results indicate that using virtual reality (VR) to explore the environment space results in better agreement between the users' perception of the space and the spatial measures. In most cases, virtual reality is the only mode that shows a significant positive correlation between the two. These results have implications for how the sharing and collaboration of environment design can be done most effectively. It appears that novices may gain a significantly better understanding of potential design space if they are allowed to experience it using VR. Intuitively, this means personal experience with a design is useful in communicating the attributes of the environment.

9.2 Limitations and Future Work

The dynamic workflows and solutions presented in this dissertation to analyze human–building interactions do have some limitations. They are the proofs-of-concept to establish that data-driven computational techniques (e.g., human behavior simulations) can be integrated into standard environment design processes, in both the early stages of the environment design, as well as once the environment models are matured.

In human behavior simulations, homogeneous crowds are used (i.e., agent behaviors are uniformly distributed), and agents are operated at a high level of abstraction where they could not see furniture and other physical items in the environments. In the future, more advanced scenarios will be considered where heterogeneous agents will be confronted with evacuation and other meaningful procedures while accounting for agent groups and psychological factors (e.g., stress and panic). Further studies will also improve the level-of-detail in simulation scenarios to have more informed design iterations.

The presented solutions only consider a limited number of static and dynamic analyses. Future work will involve running more advanced static analyses incorporating a representative description of user activities. More advanced dynamic analyses will involve accounting for additional crowd-related measures (e.g., walking efforts – naturally, humans try to minimize their walking efforts).

The user interface of the simulation service does not allow users to alter the environment designs within client-side web-browsers. It only enables users to author crowd scenarios, run the simulations, and analyze crowd-aware analytics and feedback. Future work will enable the alteration of the environment designs within a user's web-browser interactively on the client-side.

The developed solutions to human—building simulations in this dissertation are the preliminary research prototypes. Certain assumptions have been made in the process, including single-storey buildings and the absence of ramps and staircases in the design space, which are to be addressed in future research.

The joint environment–crowd parameter exploration workflow can have a significant performance overhead depending on the number of tunable parameters in each setting. Future work will explore methods to expedite the computational processes by means of machine learning and graphics acceleration techniques.

9.3 Summary

This dissertation has covered a particular application side of human behavior simulations in areas of the environment design analysis and exploration. The presented work contributed several solutions to analyze human–building interactions. The experiment results and findings from the studies demonstrate the effectiveness of incorporating crowd-aware analytics in the environment design pipelines. I hope that this dissertation will stimulate further research in data-driven human–building interactions.

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Appendices

Appendix A

Human–Building Simulation

In this chapter, I will explain the fundamentals of running human behavior simulations in the environments. I will discuss the crowd simulator and the individual crowd steering techniques which are used for human simulations. I will also discuss how the 3D environment models are represented so that the crowds can interact with the design space of these environments during simulations. The human–building simulation process presented in this chapter will serve as a common framework used in Chapters 4 – 9 to run human behavior simulations in the environments.

A.1 Overview

Three main components are involved in the human-building simulation process. These include: (1) an environment configuration, (2) a crowd configuration, and (3) the simulator. The environment configuration is comprised of design space features which contain architectural elements (e.g., walls, pillars, obstacles, and floors), and other physical elements with semantics (e.g., desks, chairs, and counters). A crowd configuration contains information about the virtual agents, including the initial (or starting) position of the agents in the environment, agent occupancy count (e.g., how many agents will participate in different activities during the simulation), an ordered sequence of activities they will engage in (e.g., egress, gathering in a meeting area and exploring an exhibition from one exhibit point to another), and their behavioral characteristics (e.g., walking speed, social distancing, and walking in groups). Once the environment and the crowds have been configured, and the user has selected a crowd simulation approach, the simulator computes the movement of the agents from their initial positions to their destinations.

A.2 Environment Configuration

There are many different ways and levels of detail to represent an environment, from a simple 2D or 3D geometric layout, to semantically rich BIM models that include every detail. In the current context, the elements of an environment are referred with the term "features". The environment features (F_e) are the combination of architectural and other physical components of the environment. An architectural component or element ($E_a \in F_e$) can be a wall, a pillar, an obstacle, a floor, or a door, and has both a set of geometric attributes (e.g., position in space, angle to the floor or adjacent element, dimensions, and elevation) and a graphical representation (e.g., surface pattern, surface color, and texture graphics). The physical elements ($E_p \in F_e$) are other meaningful objects in the environment space (e.g., a table, a desk, a chair, a mounted information screen, and a shelf). They also have geometric attributes and graphical representations.

Formally, an environment configuration is defined as:

$$E_c = \langle F_e \rangle \tag{A.1}$$

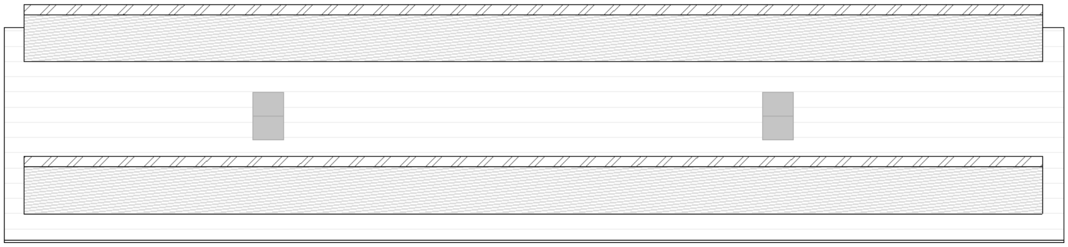

Figure A.1. A simple environment model (BIM) is designed in Autodesk Revit. The environment has a set of two walls forming a hallway and two pillars, one on each side.

Environment configurations are stored and communicated to the simulator in XML representation (Singh, Kapadia, Faloutsos, & Reinman, 2009b). Figure A.1 shows a 3D environment designed in a mainstream modeling tool (e.g., Autodesk Revit). The design layout has a set of walls forming a hallway, and two pillars, one on each side, shown in Listing A.1. The XML tags 'worldBounds', 'obstactle', and 'circleObstacle' relate to environment floor, wall, and pillar elements, respectively, in the simulator.

Listing A.1: The environment configuration of a 3D layout shown in Figure A.1.

```
<worldBounds>
    <xmin>23.61</xmin>
    <xmax>23.81</xmax>
    <ymin>0</ymin>
    <ymax>2</ymax>
    <zmin>5.27</zmin>
    <zmax>5.77</zmax>
    <color><r>231</r><g>231</g><b>231</b></color>
</worldBounds>
<obstacle>
    <xmin>18.52</xmin>
    <xmax>38.52</xmax>
    <ymin>0</ymin>
    <ymax>2</ymax>
    <zmin>6.83</zmin>
    <zmax>7.03</zmax>
    <textureGraphics>brickwork</textureGraphics>
</obstacle>
<obstacle>
    <xmin>18.52</xmin>
    <xmax>38.52</xmax>
    <ymin>0</ymin>
    <ymax>2</ymax>
    <zmin>3.83</zmin>
    <zmax>4.03</zmax>
    <textureGraphics>brickwork</textureGraphics>
</obstacle>
<circleObstacle>
    <radius>0.5</radius>
    <height>2</height>
    <color><r>82</r><g>82</g><b>82</b></color>
    <position>
        <x>5.52</x><y>0</y><z>33.71</z>
    </position>
</circleObstacle>
<circleObstacle>
    <radius>0.5</radius>
    <height>2</height>
    <color><r>82</r><g>82</g><b>82</b></color>
    <position>
        <x>5.52</x><y>0</y><z>23.71</z>
    </position>
</circleObstacle>
```

The processes involved in extracting geometric and graphical information from the environment models may vary from application to application. Once the geometric and graphical information is collected, it can be used to define environment configurations in XML representations.

A.3 Crowd Configuration

A crowd configuration represents the spatial (F_{sp}) and behavioral features (F_b) of virtual agents (A) that participate in different activities (Ac) during the simulation. Spatial features ($F_{sp} \in F_c$) are the properties of agents in the environment. For individual agents, these are the initial locations of the agents at the beginning of the simulation. For group occupancies, these are the region bounds in space within which a user-defined number of agents spawn as a group. The size fo the agents (e.g., shoulder width and height) is also set as part of spatial features. Behavioral features ($F_b \in F_c$), on the other hand, are the steering properties of agents. These include walking in groups in contrast to individual walking, social distance to maintain with other agents, and the walking speed of individuals and agent groups. Lastly, agent activities are the ordered sequence of tasks that agents carry out during the course of a simulation. They are defined by a list of target (or goal) positions in space that agents are supposed to visit, one after the other. With each target position, an additional wait attribute can also be defined to tell the agent to wait at this target for a set number of seconds.

Formally, a crowd configuration is defined as:

$$C_c = \langle A, F_c, Ac \rangle \tag{A.2}$$

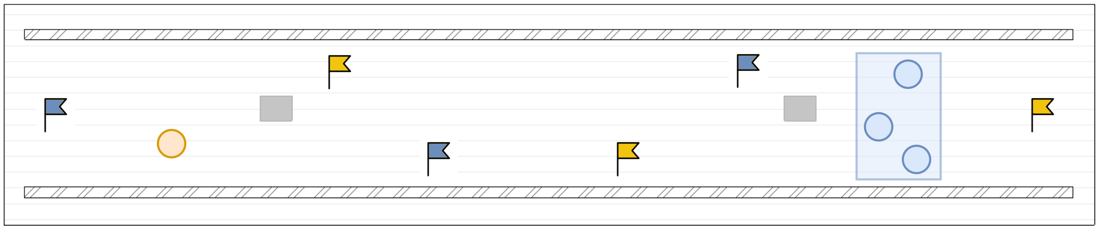

Figure A.2. A simple crowd setup for the environment configuration shown in Section A.2. An individual agent (ORANGE), an agent group (BLUE), and their respective targets (Colored-Flags) are shown.

Crowd configurations are also stored and communicated to the simulator in XML format (Singh et al., 2009b). Figure A.2 shows an agent, an agent group, and their respective targets in an environment layout. The crowd configuration of this setup is shown in Listing A.2. The XML tags ‘initialConditions’ and ‘goalSequence’ relate to an agent’s spatial features and activities (e.g., an ordered sequence of targets), whereas ‘agentRegion’ relates to an occupancy group (e.g., group of agents) in the simulator.

A crowd configuration can be defined via interactive tools by letting users draw/sketch agents, agent groups, and their activities in the environment, and then store it as an XML, or it can directly be set in the XML representation.

Now that I have discussed the environment and crowd configuration processes, in the next section, I will lay down the details about the simulator and the crowd steering algorithms used to run human–behavior simulations.

Listing A.2: The crowd configuration for an environment layout shown in Figure A.2.

```
<agent>
    <name>Bella</name>
    <initialConditions>
        <radius>0.2286</radius>
        <speed>1.3</speed>
        <position> <x>36.00</x> <y>0</y> <z>4.97</z> </position>
    </initialConditions>
    <goalSequence>
        <target>
            <location><x>32.57</x> <y>0</y> <z>6.24</z></location>
            <waitTime>2</waitTime>
        </target>
        <target>
            <location><x>26.77</x> <y>0</y> <z>4.70</z></location>
            <waitTime>2</waitTime>
        </target>
        <target>
            <location><x>19.63</x> <y>0</y> <z>5.53</z></location>
            <waitTime>2</waitTime>
        </target>
    </goalSequence>
</agent>
<agentRegion>
    <name>Friends</name>
    <numAgents>3</numAgents>
    <regionBounds>
        <xmin>21.558</xmin> <xmax>22.69</xmax>
        <ymin>0</ymin> <ymax>0</ymax>
        <zmin>4.41</zmin> <zmax>6.46</zmax>
    </regionBounds>
    <initialConditions>
        <radius>0.2286</radius>
        <speed>1.3</speed>
    </initialConditions>
    <goalSequence>
        <target>
            <location><x>24.95</x> <y>0</y> <z>6.25</z></location>
            <waitTime>2</waitTime>
        </target>
        <target>
            <location><x>29.88</x> <y>0</y> <z>4.66</z></location>
            <waitTime>2</waitTime>
        </target>
        <target>
            <location><x>37.32</x> <y>0</y> <z>5.50</z></location>
            <waitTime>2</waitTime>
        </target>
    </goalSequence>
</agentRegion>
```

A.4 The Simulator

To run multi-agent simulations, an open-source agent animation framework, SteerSuite (Singh et al., 2009a), is used. SteerSuite is a multi-purpose platform that allows to run simulations using different crowd steering techniques, evaluate crowd steering behaviors, optimize parameters of a crowd steering algorithm, analyze simulation statistics, and much more.

Several crowd steering algorithms are supported in SteerSuite. These include the approaches that use social forces like attraction and repulsion to push agents toward their goals and pull them away from collisions (Helbing et al., 2000; Karamouzas et al., 2009), reciprocal forces to avoid collisions (Van den Berg et al., 2008; Van Den Berg et al., 2011), affordance forces to calculate space-time planning for agent navigation (Kapadia et al., 2009) and more. All of these crowd steering techniques have different behavioral characteristics.

The focus of this dissertation is less on human–behavior simulation and more towards the application side. For example, to develop tools and workflows to analyze virtual and built-environments using human–behavior simulations. Therefore, comparing behaviors of different steering algorithms is out of the scope of this dissertation.

Given the environment (C_e) and crowd (C_c) configurations, a simulation scenario (S) is defined, which is then used to render a 3D animation scene and run the simulation. Formally, a simulation scenario is defined as:

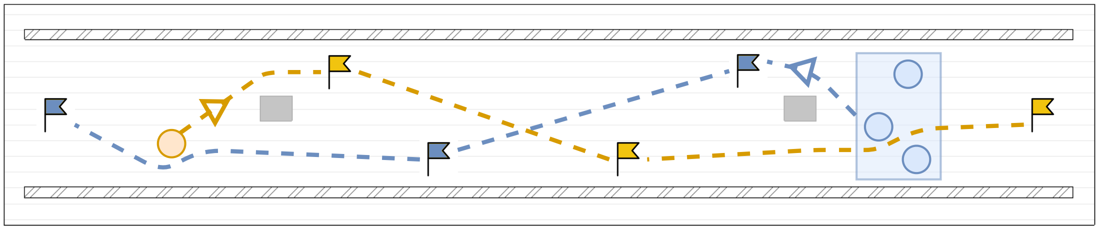

Figure A.3. An abstract overview of agent steering for the crowd configuration shown in Figure A.2. The global path navigation for the individual agent (ORANGE) and agent group (BLUE) is shown as dotted lines.

$$Scenario\,(S) = \langle C_e, C_c \rangle \tag{A.3}$$

Mostly, the static elements in an environment configuration are rendered as polygons in the scene. The circular shapes (e.g., pillars), however, are rendered as cylinders. The agents are also represented as cylinders (*green*) in the simulation where the circumference of circular disks (e.g., shoulder widths) is set to two times the radius as defined in the crowd configuration. Furthermore, the target positions (goals) are shown as flags in the scene. Figure A.3 shows a generalized overview of global path planning by the simulator. Figure A.4 shows a snapshot of agent movements at $t = 110^{th}$ frame during the simulation. During a simulation, agents are aware of the semantics of the environment through implicit means of their assigned targets in the environment.

Note that if a user does not specify any explicit characteristics for the crowd while defining a crowd configuration, the simulator, in this case, uses normative locomotion for agent walking.

Figure A.4. A snapshot of crowd simulation at $t = 110^{th}$ frame for the crowd configuration shown in Figure A.2.

The users can choose to run simulations for a defined number of frames or until all the agents in the scenario complete their assigned activities. During a simulation, the simulator keeps a temporal track of trajectories of all the agents from start to end. These trajectories are then used to perform path analyses and to compute other simulation statistics.

A.5 Summary

Appendix A covers the theoretical details for the understanding of the human–building simulation process. It discusses in detail the different components involved in running multi-agent simulations from environment configurations, crowd configurations, to the simulator.

The results presented in the dissertation from the dynamic analysis are simulated 10 times. The statistics from these simulations are then presented and shown as an average. In each simulation, the crowd density is kept to 1.08 $agents/m^2$ that represents LoS level D in Fruin's Level of Service (Fruin, 1971b) unless specified otherwise by the user. The multi-agent simulation process discussed in this chapter will serve as a common framework for the tools and workflows presented in Chapters 3 – 7 to analyze human–building interactions by running human behavior simulations in virtual and built-environments.

Appendix B

User Surveys

Appendix B contains the questionnaires and the corresponding user ratings for the user surveys included in Chapters 3 and 8.

Domain Knowledge

	Poor	**Below Avg.**	**Avg.**	**Above Avg.**	**Excellent**	**Average scale 1–5**
Ability to interpret architectural or interior designs?	0%	0%	0%	100%	0%	4.36
Prior experience with architecture or interior designs?	0%	0%	0%	100%	0%	4.00
Prior experience in urban planning and design?	0%	0%	13.3%	86.7%	0%	4.36
Prior understanding of spatial Space-Syntax measures?	0%	0%	46.7%	53.3%	0%	3.43

Table B.1: Domain knowledge ratings of user study participants (self-provided).

Opinion of Participants on the Effectiveness of analytics workflows

	Poor	**Below Avg.**	**Avg.**	**Above Avg.**	**Excellent**	**Average scale 1–5**
	Do you consider this tool as a valuable addition to traditional geometric modeling tools?					
B	0%	0%	0%	53.3%	46.7%	4.46 (89.2%)
C	0%	0%	0%	40%	60%	4.60 (92.0%)
	In day-to-day work, do you think these analyses can help you make more informed decisions while designing?					
B	0%	0%	0%	86.7%	13.3%	4.13 (82.6%)
C	0%	0%	0%	93.3%	6.7%	4.06 (81.2%)
	Do you see this approach as helpful for improving architecture designs?					
B	0%	0%	6.7%	93.3%	0%	3.93 (78.6%)
C	0%	0%	6.7%	93.3%	0%	3.93 (78.6%)
	Such visualization tools can be adopted into architectural design workflow pipeline?					
B	0%	0%	6.7%	93.3%	0%	3.93 (78.6%)
C	0%	0%	26.7%	73.3%	0%	3.73 (74.6%)

Table B.2: The opinion of participants on the effectiveness of static and dynamic workflows and their respective visualizations to analyze environment designs in real-world environment modeling processes (self-reported). Identifiers B and C refer to design methods (B) and (C) respectively.

Domain Knowledge

	Poor	**Below Avg.**	**Avg.**	**Above Avg.**	**Excellent**	**Average scale 1–5**
Ability to interpret architectural or interior designs?	0%	0%	7.1%	50%	42.9%	4.36
Prior experience with architecture or interior designs?	0%	7.1%	21.4%	35.7%	35.7%	4.00
Prior experience in urban planning and design?	0%	7.1%	7.1%	28.6%	57.1%	4.36
Prior understanding of spatial Space-Syntax measures?	7.1%	7.1%	21.4%	64.3%	0%	3.43

Table B.3: Domain knowledge ratings of expert participants (self-provided).