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SimService: A Cross-browser Cloud-based Crowd Simulation Platform for Architectural Design Analysis

ABSTRACT
At present, designers mostly use their intuition and experience to predictively account for how the built-environment might support human activity. Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools only provide a static representation of buildings, which ignores the impact that a building produces on its occupants and their movements. To address this issue, computational techniques such as crowd simulation have been developed. With few exceptions, crowd simulation frameworks are often decoupled from building modeling tools used in architectural design. They usually require specific hardware/software infrastructures and expertise to be used, hindering the designers' abilities to seamlessly simulate, analyze, and incorporate human-centric dynamics into their design workflows. To bridge this disconnect, we devise a cross-browser cloud-based simulation analytics platform to analyze architectural designs with respect to human occupancy. The platform allows users to sign-up for simulation services, upload building models (e.g. BIM files), devise targeted scenarios, perform their own experiments, and instantly generate crowd-based analytics for their designs. A cross-domain environment design and analysis case-study is conducted to showcase the practicality and effectiveness of the proposed workflow.

Author Keywords
simulation as a service; crowd simulation; architectural buildings; spatial analytics; BIM

ACM Classification Keywords
I.6.3 SIMULATION AND MODELING : Applications; I.6.5 SIMULATION AND MODELING : Model Development; I.6.8 SIMULATION AND MODELING : Types of Simulation; J.5 ARTS AND HUMANITIES: Architecture; J.6 COMPUTER-AIDED ENGINEERING: .

1 INTRODUCTION
Analyzing how a building design impacts the movement and activities of its prospective inhabitants is a critical aspect of architectural design. While established building performance evaluation methods, such as cost, structure, energy, and lighting mostly rely on static building representations, human behavior analytics accounts for the dynamic movement of people and their spatiotemporal impact on user experience, operational efficiency and space utilization.

Crowd simulation, however, presents high integration costs into architectural design pipelines. Prior solutions demand deep expertise in a particular simulation platform and they require solving sophisticated interoperability challenges to import building geometries, annotate buildings with space semantics, define crowd parameters, generate simulation results, and visualize spatiotemporal data maps of space utilization.

To address these challenges, we adopt a Software-as-a-service paradigm for software distribution and licensing using cloud computing [24]. This gained popularity in recent years and has several advantages both as a business model, but also for its users. In particular, 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, specifically utilizing web-based or cloud services, allows tools to be used as needed on many platforms without re-configuring core processes.

In this paper, we aim to address the complexities related to running crowd simulation to facilitate its adoption in the architectural design community. Specifically, we contribute a cross-browser/cross-platform crowd simulation and analytics service for human-centric architectural design. This service includes a platform for designers to import built-environments as standard BIM infrastructures (i.e. IFC), and author domain-specific crowd scenarios in a domain-agnostic experience. As well, the platform provides exploratory and comparative analysis of these scenarios through informative visualizations in an interactive workspace. We demonstrate the effectiveness of this platform in three different design domains with different requirements. Finally, we show that the platform can effectively and seamlessly be used to inform decision making in the design pipeline.

2 LITERATURE REVIEW
In recent years, crowd simulation has gained popularity in architectural design. It enables architects to evaluate building designs from a human behavior perspective, and it supports advanced visualization of behavior analytics metrics for enhanced communication and decision-making among design stakeholders. In this section, we summarize prior work on crowd simulation and recent developments of the software-as-a-service paradigm that can be used to provide a more seamless integration of crowd analytics into architectural design pipelines.

2.1 Crowd Simulation

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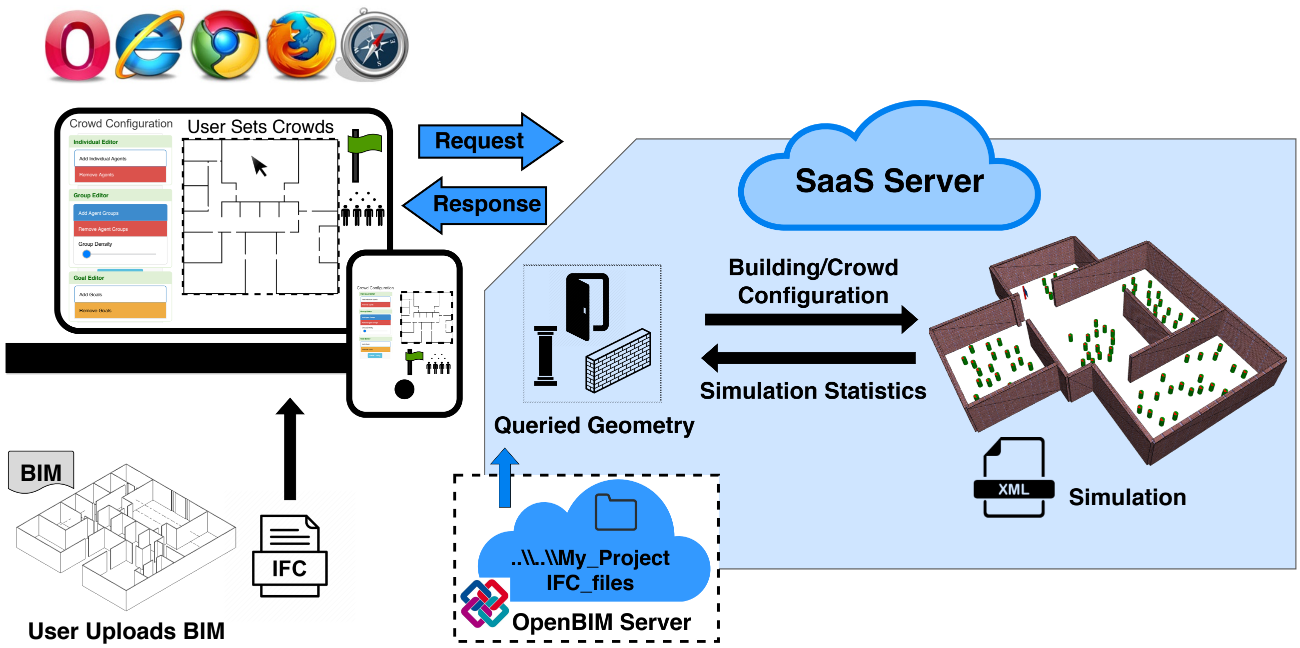


Figure 1: An overview of *SimService* framework. User uploads a BIM file (e.g. IFC) to the system, interactively sets up crowd configuration, runs the simulation and analyzes spatial visual and quantitative feedback for occupants–building interactions.

Crowd simulations provide time-based dynamics of potential human–building interactions in virtual environments. Research in this field has evolved quite rapidly over the last few decades [22, 23]. Several simulation techniques have been proposed to imitate human-like movements [10, 15]. Particle-based simulation approaches revolve around computing local-level interactions for speed, motion and relative position of every individual to deliver large crowd behaviors [17]. Some approaches use social forces like repulsion and attraction to model individual occupant interactions [9, 12]. Hybrid rule-based approaches avoid future collisions in crowd [21]. An egocentric approach using affordances computes space-time plan for individual agents [11]. Reinforcement learning and deep learning have been used to model complex and more realistic crowd behaviors [8, 16].

2.2 Crowd-aware Building Analysis and Design

In recent years, different approaches have focused on using crowd simulations to analyze architectural buildings and environments for making crowd-informed design decisions. Some efforts have been put in optimizing architectural elements to improve occupants' movement flow during evacuations [1, 6, 5]. Computing optimal egress routes for virtual and built-environments using computational techniques affords predictive egress planning [2]. Interactive methods have been developed for rapidly optimizing small-scale virtual built-environments within user-selected parameters [7]. Narrative-based modeling approaches model day-to-day procedures in a hospital environments for informed decision making [18]. Interactive computational tools afford both static and dynamic crowd-aware analytics in built-environments [25]. In the area of parametric building design, a node-based framework was designed for the joint modelling of the built-environment and occupants' characteristics and activities [27]. Following this work, another framework automatically explores, both individually and jointly, the building and crowd behavioral parameters, to design crowd-efficient building layouts [26]. A multi-paradigm general purpose framework for event-based simulations of dynamic crowds combines models in built-environments to account for environmental conditions such as temperature and acoustics [19].

These approaches, however, are often integrated into specific building design platforms and require certain hardware/software infrastructures and expertise to be utilized. In addition, they require users to setup a wide range of parameters such as the semantics of the built environment, the characteristics for the crowds in the given built-environment including the spawning areas (starting positions of virtual occupants), walking speed, behavioral attributes, walking directions, target goals, etc.

2.3 Software as a Service

Software as a Service 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 services on-demand by means of some client-side infrastructure (e.g. Application Program Interface (API), Web Interfaces, etc.) often via the internet [13]. 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 [3]. The work presented in [4] discusses cloud computing and virtualization platforms used for civilian and military modelling and simulation applications. Distributed architectures which use a model-driven engineering technique to extract geometric information of building model from CAD/BIM tools have been 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) [28]. In contrast, our platform 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. [29] 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 [14].

3 SYSTEM OVERVIEW

SimService provides a cross-browser cloud-based simulation service to perform crowd-aware analytics for built environments supporting a seamless integration in architectural design workflows. It allows architects and designers (users) to upload BIM models, author simulation scenarios by setting crowd configurations, run simulations and get crowd-aware analytics for their building designs. Figure 2 shows an overview of the interface for SimService. Further details on individual functions is discussed below.

3.1 Model Visualization

SimService allows users to visualize their uploaded BIM models both in 2D and 3D. The 2D visualization is an orthographic projection of the model (i.e. top–down view). Distance between camera and the model is set such that it covers all the elements of BIM into the scene. By default, user interactivity is disabled for 2D view. The 3D visualization is a perspective projection of model from the top. Like in 2D projection, distance between camera and the model is set such that it covers all the elements of BIM into the scene to give a full view of the model. By default, user interactivity is enabled for 3D view so users can interact with their models by means of rotation around model's origin (in both X and Y directions), and also zooming in and out of models. A "Reset" functionality is also available to reset the camera to default in 3D view.

3.2 Simulation Scenario

We formally define a simulation scenario $S = \langle B, C \rangle$ which contains the specification of a building layout B (e.g. geometric information like positions and attributes of walls, doors, floors, etc.) and the virtual crowd C. A virtual crowd $C = \langle C_I \cup C_G \rangle$ consists of individual occupants and occupancy groups, where $C_I = \langle O, A, P \rangle$ defines a collection of occupants O their desired activities A (e.g. evacuation or day-to-day scenarios) and optional parameters P of the crowd simulator being used, and $C_G = \langle O_G, A, P \rangle$ defines a collection of occupancy groups O_G their desired activities A and optional parameters P of the crowd simulator.

3.3 Building Specification and BIM

SimService allows users to upload their building models as standard BIM representation, Industry Foundation Classes (IFC). For an IFC, system supports both IFC2x3 and $IFC4$ certifications (schema). The system does not limit users to use any particular building design tool for generating an IFC and can be sourced any main stream building design platforms. When a BIM model is uploaded, it is sent to an *OpenBIM* server, internally hosted by our system, and queried for geometric information of the model. BIM server stores the model and sends back building specifications (e.g. walls, doors, floors, etc.) to the system in an XML format. The uploaded model and respective system generated files get saved to user's profile directory and can be accessed at a later time.

3.4 Crowd Configuration and User Interaction

SimService allows users to define crowd configurations for design-specific simulation scenarios to run with their BIM models. The "Scenario Editor" in Figure 2 summarizes a crowd configuration process. On the right is a building layout of an exhibition space (e.g. art gallery). On the Left are the allowable actions a user can perform. These include adding and removing individual occupants as well as occupancy groups, setting crowd-density level (LoS) for number of occupants to spawn within an occupancy group, and adding and removing targets or goals for the occupants to walk to. An occupancy group is added by drawing a rectangle into the scene (*Pink* region) and number of occupants to spawn within that group is calculated by multiplying area of that occupancy group 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 scenario. A user can then select one or more targets from the list. On Bottom-Right is an example of crowd configuration set for an emergency evacuation. Once a crowd configuration is created, user can then save it by selecting a "Save Config" action.

3.5 Crowd Simulation

The system uses SteerSuite [20], an open platform to run and optimize crowd simulations. Occupants are simulated using a social forces model for crowd steering behaviors [9]. The system itself is not limited to use only social forces technique. Other crowd steering methods can also be adopted. When a user selects a "Simulation" action, the system passes current simulation scenario S with both building specification B and crowd configuration C to SteerSuite in an XML representation. If a crowd configuration is not defined, the system will generate a default crowd setup for the given BIM model and use it. Once the simulation is completed, occupants' trajectories and other simulation statistics are send back to the system as feedback.

3.6 Simulation Feedback

After a simulation is completed, the "Analyze" action gets enabled. It allows a user to visualize spatial quantitative and qualitative feedback from the simulation. Figure 3 shows occupants' trajectories (path analysis – Top) and density contours (bottleneck analysis – Bottom) respectively. The traces are shown in *Blue*, from starting position to the target, for all the occupants. To make the simulation experience intuitive for users, *SimService* allows to animate the traces with

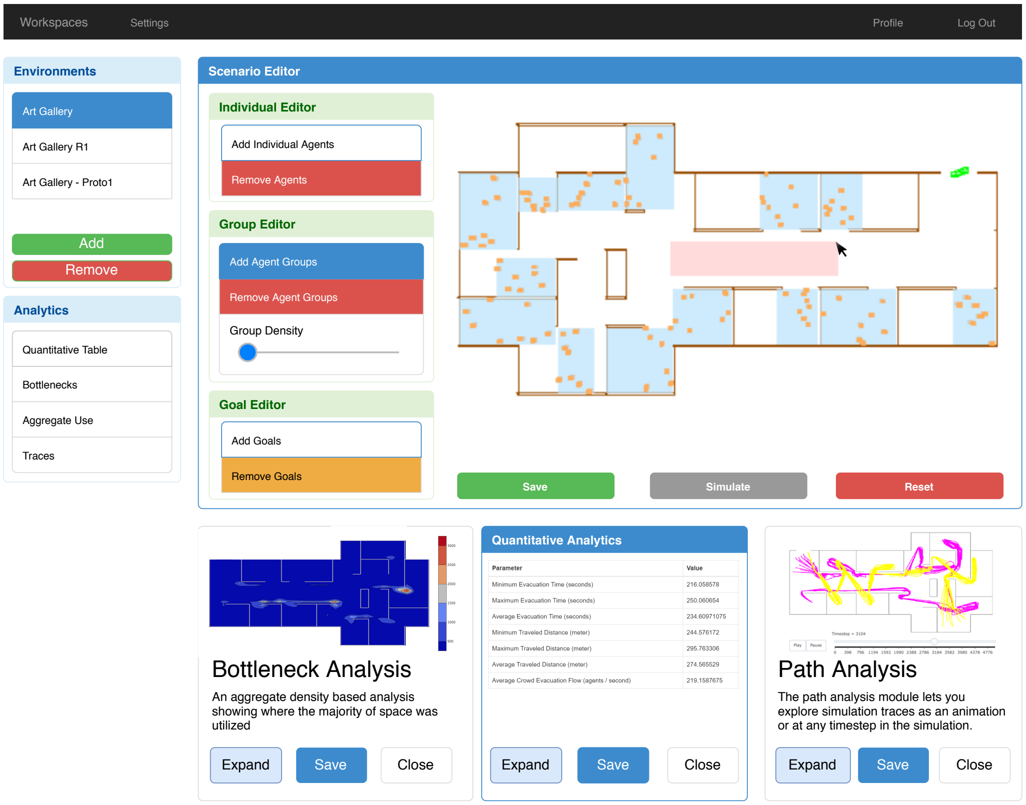


Figure 2: An overview of *SimService* workspace interface. The interface allows the user to layout, store, and retrieve workspaces for projects. Within the workspace, users can design scenarios, run simulations, and create analytics portfolios.

a ‘play’ button and go back-and-forth with a help of a slider. The heatmap is a color-coded representation of an average occupant density per square meter, calculated for whole design space of a building and for all the occupants, over the course of simulation. *Red* regions show areas of high density (e.g. potential bottlenecks), whereas *Blue* shows less dense areas.

Figure 4 shows simulation statistics as quantitative numbers. Simulation statistics include minimum, maximum and average evacuation times and traveled distances over the course of simulation, as well as an average *Exit Flow* of occupants. The exit flow is calculated by dividing average evacuation time with total number of occupants completed the simulation.

4 CASE STUDY

This section presents a case study to demonstrate the effectiveness of the proposed platform in three different design domains, showing how the SaaS approach can be effectively and seamlessly used to inform decision making in the architecture design pipeline. Each design environment (BIM model) is created in a different architecture design tool to showcase the usefulness of *SimService* as a singular service-based crowd analytics solution.

4.1 Eatery Design

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

In this use case, we demonstrate how *SimService* can be used to analyze crowd dynamics of potential human–building interactions for two completely different simulation scenarios. A real-world restaurant style environment is created using Autodesk Revit. It is then exported in a standard BIM format (e.g. IFC2x3). This IFC is then imported directly into *SimService* from the dashboard.

Figure 5 shows analytics for a restaurant environment for an emergent egress evacuation and a group dine-in scenario. For egress evacuation (top row), using *SimService* controls, we interactively added virtual customers in different spaces of restaurant with an objective (e.g. target) to move towards nearest exit. Crowd trajectories are shown in Blue, highlighting the paths virtual customers followed while moving towards exits. The color-coded heatmap 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), we added two different groups of virtual customers, 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 dinning 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

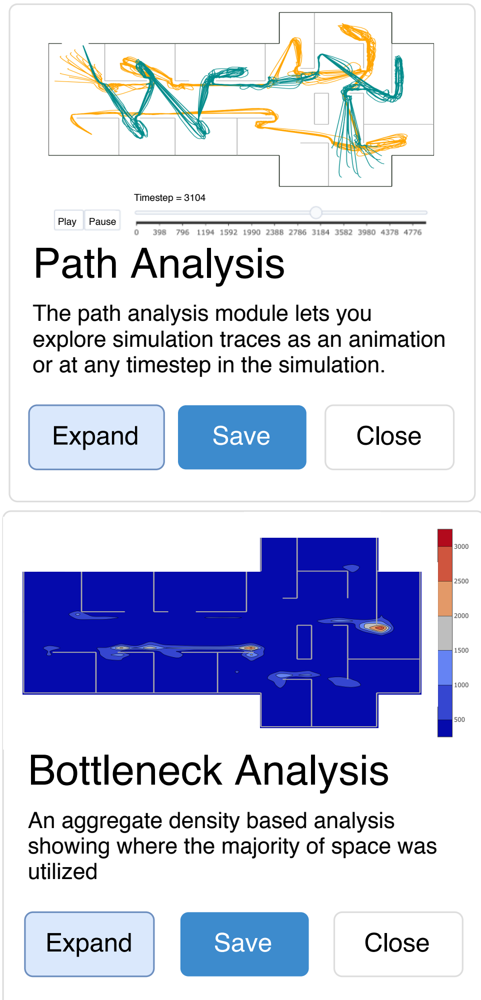


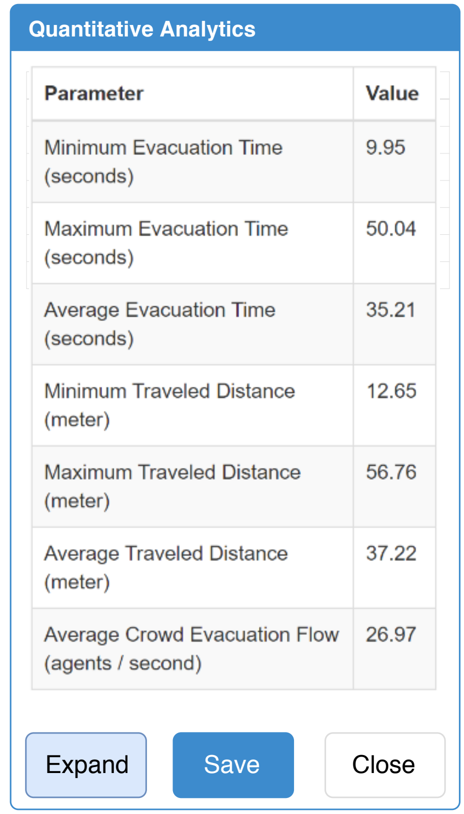
Figure 3: Qualitative tools afford quick exploration of simulation results and problems areas. Our bottleneck analysis thresholds aggregate occupancy maps to bring focus to various types of flow bottlenecks in designs.

paths they followed along 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.

4.2 Exhibition Design

A real-world exhibition style environment (e.g. an art gallery) is created using Rhinoceros. It is then exported using the IFC format and imported directly into *SimService* from the dashboard.

Figure 6 shows the analytics for an egress evacuation and a group-based exhibition exploration scenario. For egress evacuation (top row), we interactively added virtual visitors at different exhibit points in the art gallery with an objective to move towards nearest exit. Path analysis reveals that the obstacle in the middle hallway towards left-side, helped in forming multi-lane in the left-side of the gallery. The heatmap shows bottleneck in the middle hallway towards right-side of the gallery near the exit. These analyses showcased that a designer might want to consider adding an obstacle in the hallway towards right-side of the gallery as well, to help formation of lanes for egress, or make other design improvements accordingly. For group-based exhibition exploration (bottom row), we added two different groups to explore the gallery from one exhibit point to another, making stops, and then moving to the next. Analytics for both path and bottleneck analysis is presented in the figure.



Parameter	Value
Minimum Evacuation Time (seconds)	9.95
Maximum Evacuation Time (seconds)	50.04
Average Evacuation Time (seconds)	35.21
Minimum Traveled Distance (meter)	12.65
Maximum Traveled Distance (meter)	56.76
Average Traveled Distance (meter)	37.22
Average Crowd Evacuation Flow (agents / second)	26.97

Figure 4: Quantitative feedback from crowd simulation.

4.3 Workplace Design

A workplace environment (e.g. an office) is created using SketchUp. It is then exported in a an IFC format and imported directly into *SimService* from the dashboard.

Figure 7 shows analytics for an egress and a daily work-routine scenario of two different teams. In egress scenario (top row), virtual employees are added in different spaces in office with an objective to move towards nearest exit. Path and bottleneck analyses are presented in the figure. The heatmap reveals multiple bottlenecks in the hallways near meeting rooms and cafeteria. For a daily routine scenario, we added two different teams in different spaces in the office and showed their work-routine activities including attending meetings, going to cafeteria, visiting colleagues, etc. Employees trajectories and density-contour map are shown. Several bottleneck areas in space are revealed in the heatmap.

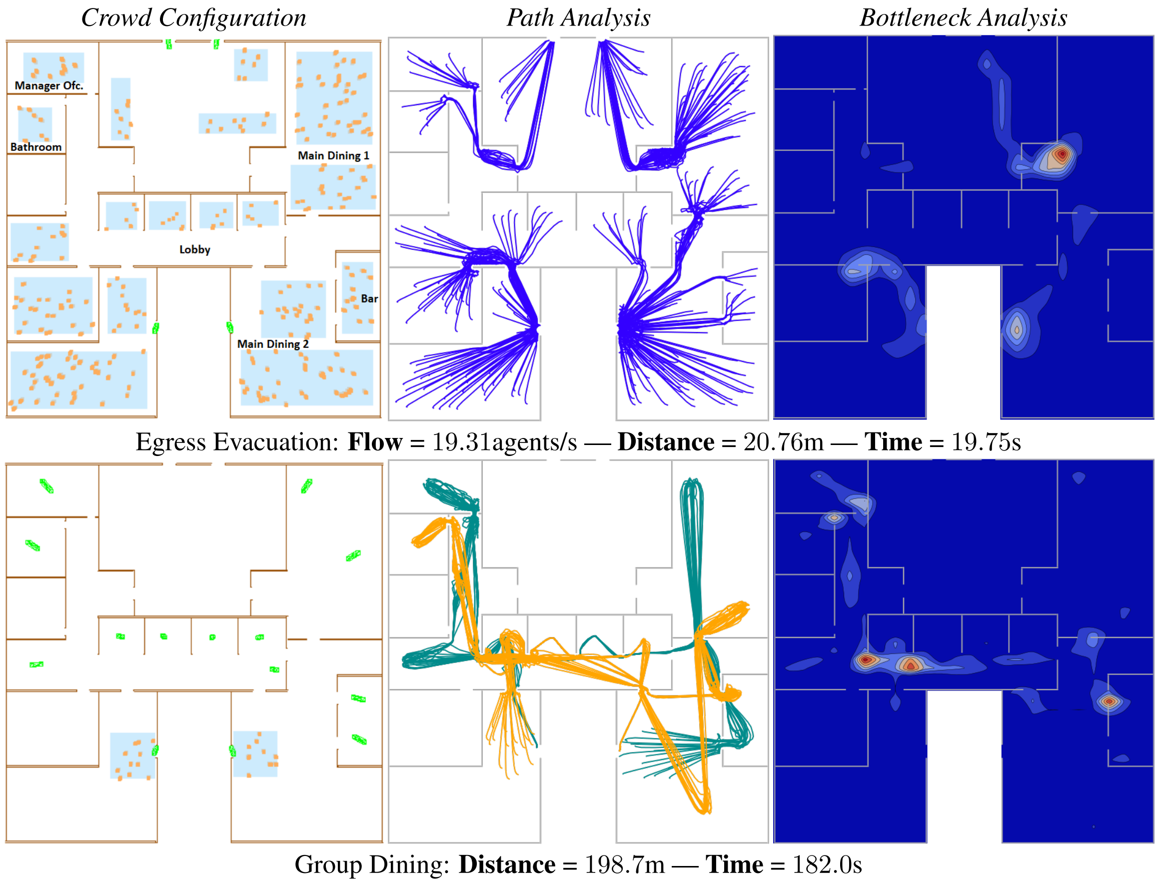


Figure 5: Crowd analytics for an eatery environment (e.g. a restaurant). Two different scenarios are presented: Top – an egress evacuation where customers from different spaces in the restaurant moving towards nearest exit, and Bottom – a group dining where two different group people come to the restaurant, wait in the lobby, go to the bar, dine-in, go to the washroom and leave. Crowd trajectories are shown in *Blue* for egress and multi-colored for group dining scenario. Crowd-density analysis is shown as color-coded heatmap (Red–Blue) where denser crowd areas (bottlenecks) are highlighted in dark red. Crowd exit flow for egress evacuation, and average evacuation time (**T**) and traveled distance (**D**) for both evacuation and group dining scenarios are also reported. *Green* cylinders are the stopping points (e.g. targets) for agents, whereas *Orange* represent group agents.

5 CONCLUSION

This paper presented a cross-browser cloud-based crowd analytics framework for architects and designers to develop human-aware architectural environments. Eliminating all the hardware/software infrastructure dependencies, a single solution is proposed to bring the building models from different architecture design tools (e.g. Autodesk Revit, Rhinoceros, or SketchUp) into an interactive crowd authoring workspace to set up design-specific crowd scenarios, remotely run the simulations for the authored crowd scenarios, and analyze visual feedback in terms of path and bottleneck analysis, as well as crowd trajectory animations. A case study is presented to showcase the effectiveness of this approach by analyzing architectural environments for different domains with respect to human-occupancy. The current system does not allow users to alter their environment designs within the system but users can author crowd scenarios however they like. Future work will include a user study with novices and experts from the architecture community to test and validate the usefulness of this approach, and adding support to alter the buildings within the system.

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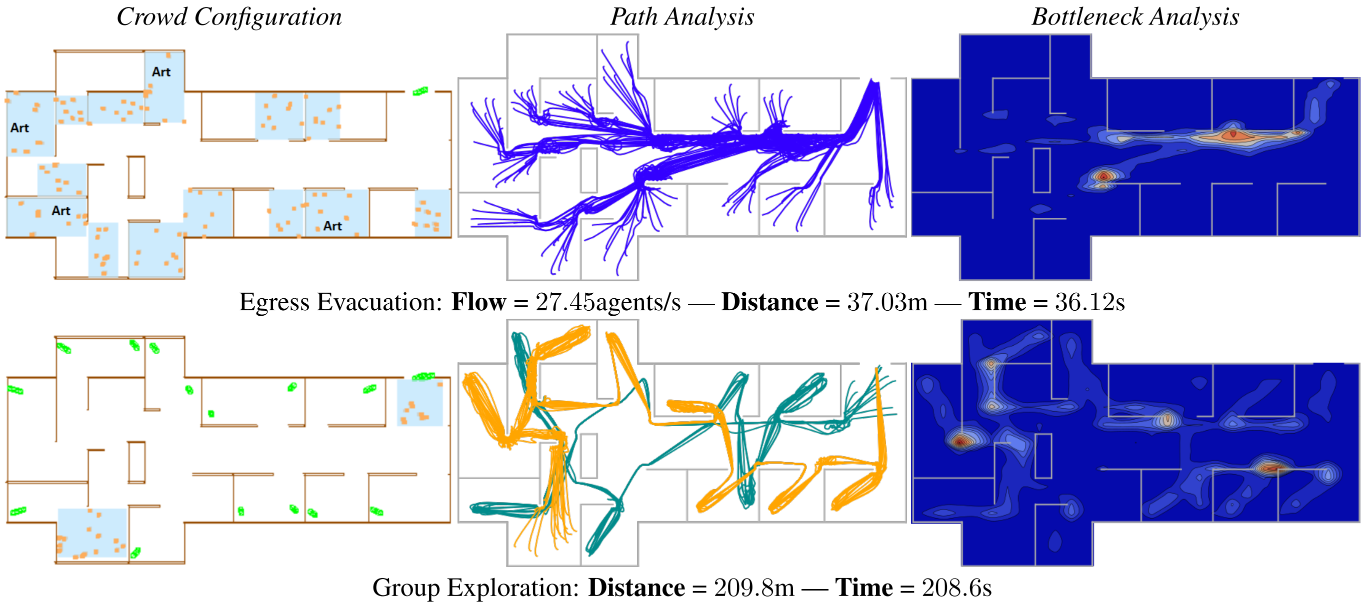

Figure 6: Crowd analytics for an exhibition environment (e.g. an art gallery). Two different scenarios are presented: Top – an egress evacuation where visitors from different spaces in the gallery moving towards nearest exit, and Bottom – a group exploration where two different group people exploring 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 heatmap (Red–Blue) where denser crowd areas (bottlenecks) are highlighted in dark red. Crowd exit flow for egress evacuation, and average evacuation time (**T**) and traveled distance (**D**) for both evacuation and group dining scenarios are also reported. *Green* cylinders are the stopping points (e.g. targets) for agents, whereas *Orange* represent group agents.

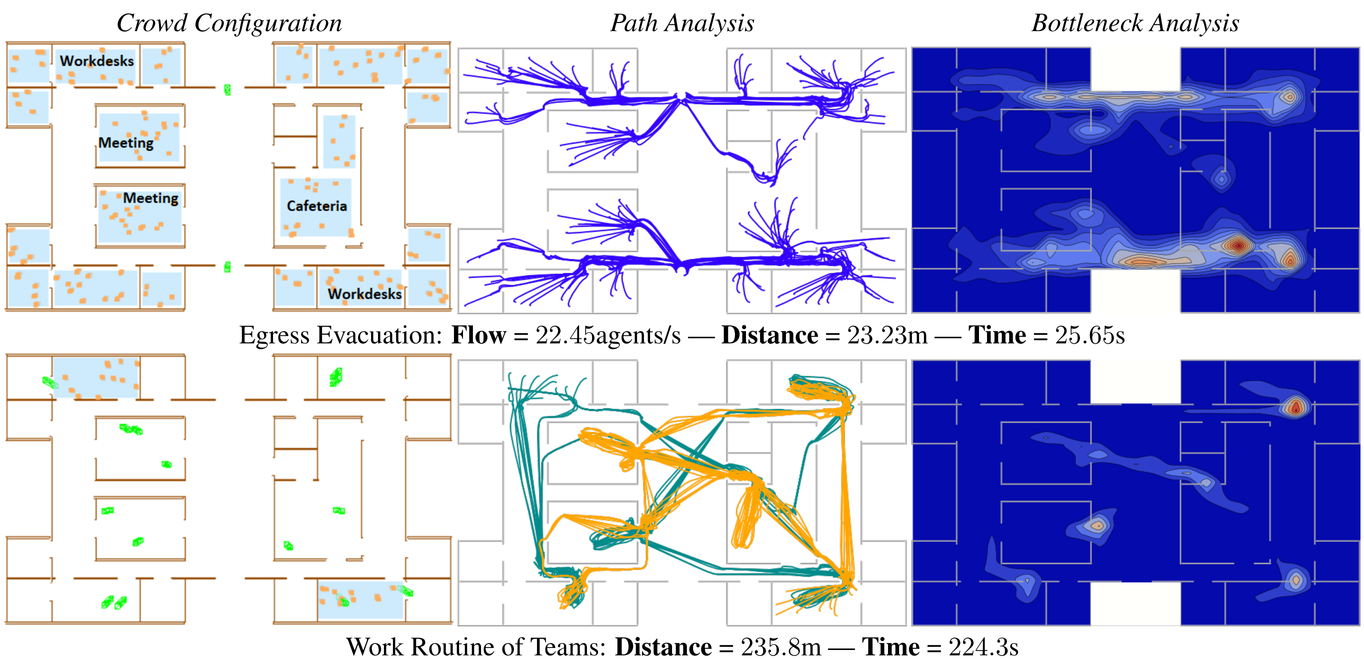

Figure 7: Crowd analytics for a corporate work environment (e.g. an office). Two different scenarios are presented: Top – an egress evacuation where employers from different spaces in the office moving towards nearest exits, and Bottom – a daily work routine of two different teams attending meetings, going to cafeteria and visiting colleagues.

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