Joint Parametric Modeling of Buildings and Crowds for Human-Centric Simulation and Analysis

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Abstract. Simulating groups of virtual humans (crowd simulation) affords the analysis and data-driven design of interactions between buildings and their occupants. For this to be useful in practice however, crowd simulators must be well coupled with modeling tools in a way that allows users to iteratively use simulation feedback to adjust their designs. This is a non-trivial research and engineering task as designers often use parametric exploration tools early in their design pipelines. To address this issue, we propose a platform that provides a joint parametric representation of (a) a building and the bounds of its permissible alterations, (b) a crowd that populates the environment, and (c) the activities that the crowd engages in. Based on this input, users can systematically run simulations and analyze the results in the form of data-maps, spatialized representations of human-centric analyses. The platform combines Dynamo with SteerSuite, two established tools for parametric design and crowd simulations, to create a familiar node-based workflow. We systematically evaluate the approach by tuning spatial, social, and behavioral parameters to generate human-centric analyses for the design of a generic exhibition space.

Keywords: Human-centric analytics · Crowd simulation · Parametric modeling · Building occupancy · Multi-agent systems

1 Introduction

Architectural design involves the systematic exploration of design options to identify solutions for a given social, physical, and environmental context [16,31]. This is an iterative process that involves the progressive refinement of design solutions to achieve a target performance [27]. Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools have been developed in the last decades to assist architects in such a process. These tools help architects

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evaluate design solutions mostly in terms of energy performance, cost, lighting, and structure. However, predicting the impact that a building produces on its occupants is often left to intuition. Poor assessments at the design stage can lead to under-performing buildings and diminished user satisfaction or productivity.

Simulation methods have been developed to represent human behavior in day-to-day and emergency scenarios [17,28]. Some of these approaches have been used to evaluate how a building design affects the behavior of the building occupants [14,15]. However, with few exceptions [35], these simulation frameworks are often decoupled from digital building modeling tools used by architects (e.g. CAD or BIM tools), hampering the designer's abilities to seamlessly simulate, analyze, and incorporate human-centric dynamics in practice.

In this work, we introduce a joint parametric representation of buildings and crowds for modeling design options, simulating human behavior, producing human-centric analyses, and incorporating the results. In conventional approaches designers modify a building model to generate a unique design solution. *Parametric modeling* explicitly encodes the relationship between building components. In this way, a designer can explore the large space of possibilities by simply modifying component parameters [36]. Our framework directly embeds, within a parametric design framework, not only traditional building modeling features, but also the modeling of crowds and the activities they engage in. Designers can leverage the node-based visual data-flow of parametric design tools to model the relationships and constraints between building design elements, crowd properties and activities in order to perform iterative human-centric analyses aimed at informing decision-making in architectural design. The proposed platform couples Dynamo – a BIM-based parametric modeling tool embedded into Revit – with SteerSuite – an established crowd simulator [33]. With newly modeled Dynamo nodes and pre-existing SteerSuite capabilities, our platform provides an integrated framework for simulation-based human-centric analyses in the domain of architectural design.

The first step of the framework involves generating a parameterized representation of (a) a *building*, which includes bounds of permissible alterations and additional data to support human behavior simulation (e.g. building semantics, spawning regions, movement targets); (b) the *crowd* that populates the buildings (e.g. number, types, distributions); and (c) the *activities* people are engaged in (e.g. day-to-day or emergency evacuation activities). The designer can then simulate a broad range of parametric behaviours and activities and then quantitatively analyze the results. The framework provides several human-centric analyses such as crowd measures, e.g. evacuation times, or spatiotemporal data-maps, e.g. aggregated density, speed, and movement maps [24].

We illustrate the capabilities of the proposed approach using a case study where we systematically tune spatial, social, and behavioral parameters to simulate and analyze dynamic situations in the design space of a gallery. We argue that the proposed approach holds promise to augment the iterative design process with human-related factors.

2 Crowd Simulation in Architectural Design

Several approaches have been proposed to address the gulf between static representation of buildings and the impact of design choices on the intended building occupants and the activities they engage in.

Static Human Behavior Analyses. Static analyses of building layouts, such as Space-Syntax, calculate spatial features such as visibility, connectivity, accessibility, and organization of a space using an abstract representation of a building geometry and topology [2,12,34]. Other approaches extend building models with information pertaining to occupant activities [20] and spatial cognition abilities [5,13]. These approaches, however, do not consider dynamic features of human behavior such as occupant movement and activities.

Dynamic Human Behavior Simulations. In contrast, dynamic analyses of human behavior provide a time-based representation of a building in-use by their prospective occupants. Beyond a building model, these methods explicitly model individual occupants or crowd entities who will populate the space (specifying occupant types, density, desired velocity, and grouping), and the activities they will engage in (e.g. moving to a target location, gathering with other agents, etc.). The problem is commonly addressed by coupling BIM with a video game engine to generate dynamic visualizations of a building in use from a first-person perspective [37]. This approach, however, requires the manual operation of a human-controlled avatar, limiting a designer's ability to analyze how a building affects the behavior of multiple people at the same time. Multi-agent systems (MAS), instead, use autonomous virtual agents to simulate the mutual interactions between people and their surrounding environment [17]. Particle-based approaches model crowd behaviors while accounting for local-level interactions between homogeneous entities by simplifying crowd agents to particle dynamics [26]. A common approach is to derive movement updates from physically modelled social forces [11,19]. Hybrid frameworks combine rules, prediction, and planning methods to avoid future collisions in a crowd [33]. Event-driven approaches coordinate the behavior of large groups of agents to perform collaborative behaviors [18,29]. Data-driven methods adopt learning techniques to capture realistic crowd behaviors [22,23].

Human Behavior Simulation in Architectural Design. MAS techniques have been applied to represent pedestrian movements [38] in emergency evacuation activities [8,25] and day-to-day behavior in different workplaces, such as offices [9], universities [30], and hospitals [28]. Preliminary studies have shown that human behavior analyses can support the iterative refinement of design solutions in terms of day-to-day and emergency behaviors [14,15]. Human behavior simulation methods, however, are often decoupled from a building modeling environment, possibly hampering their use to evaluate design solutions iteratively. To address this issue, static and human behavior analyses have been incorporated in a BIM framework where designers can generate a design and then run static and dynamic analyses to evaluate their design [35]. However, in this approach, the designer needs to manually specify building, crowd, and activity parameters in a disconnected fashion, since they are not integrated in a shared environment where the relationships and constraints between different parameters can be explicitly modeled.

Our Approach. In this work, we provide a shared modeling environment where designers can jointly model buildings, occupants, activities and the connections among them. Specifically, we leverage the workflow proposed by node-based parametric design, where buildings are modeled not as monolithic objects but as relationships between building components. In this way, a designer can manually specify the constraints between buildings, occupants, and activities as well as the bounds for admissible conditions (e.g. the maximum number of agents that can be spawned in a specific space region). Additionally, the designer can run dynamic analysis of human behavior activities and manually tune visualization and analysis parameters to gather insights that may inform successive design iterations or behavior simulations.

3 Parametric Modeling of Buildings and Crowds for Human Behavior Simulation and Analysis

3.1 Overview

We propose a platform that couples parametric design of buildings and crowds to support analyses of human spatial behavior in not-yet-built environments. Specifically, a user can model a parametric building design, crowds and their activities in a combined framework, where relationships between components can be explicitly modeled. After designing a parametric simulation configuration, the user can simulate crowd behavior over time and observe dynamic crowd-based analytics in the form of aggregate data-maps, spatialized representations of human-centric objectives over time [24]. Based on the simulation results, a user can iteratively fine-tune building, crowd, and activity parameters to simulate additional activities and gather insights that can inform decision-making in architectural design. Figure 1 shows an overview of the framework.

3.2 Main Components

The platform couples Dynamo, an established tool for parametric modeling, with SteerSuite, an established crowd simulator.

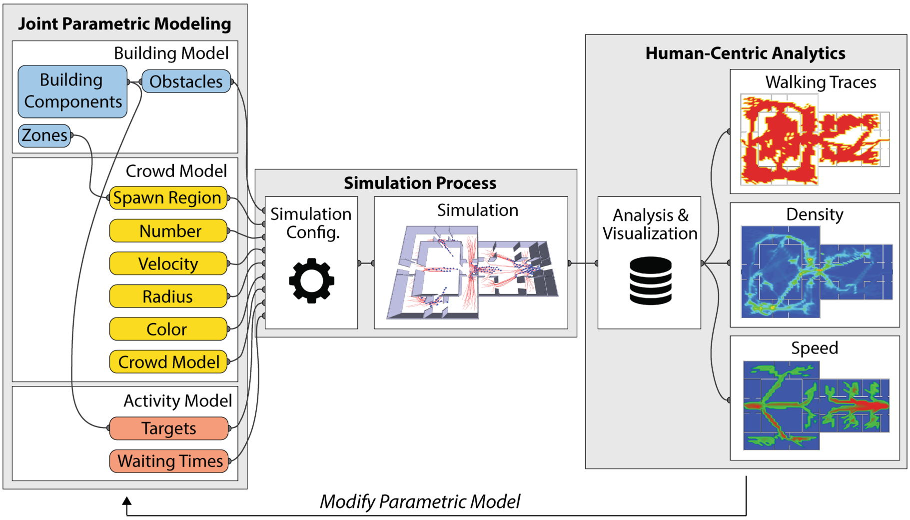

Fig. 1. Framework for parametric modeling and analysis of crowd behaviors in built environments.

Dynamo. An Autodesk Revit ® plugin that enables visual programming of building components and the relations between them [1]. Each visual component is represented as a node in a workflow. Each node encodes a script that can create a geometry in Revit, read-write data from a file, perform some operations on BIM data, or communicate data with another program. Multiple nodes can be connected so that the output of a node can be used as input for a different node. Different from other parametric modeling approaches, such as Grasshopper, Dynamo is coupled directly with Revit. BIM models – beyond geometric data – store meta-data that can be used to perform static and dynamic human-centric analyses [35].

SteerSuite. An open framework for developing and evaluating steering algorithms, simulating crowd behavior using established simulation approaches, and sharing the results with other researchers [32]. Several industry standard simulation approaches are currently incorporated in Steersuite including: (a) *Social Forces* – a method to compute attraction and repulsion forces among agents and with obstacles [10], (b) *RVO* – a widely used approach that uses reciprocal velocity obstacles for collision avoidance [3], (c) *PPR* – a rule-based approach which combines reactions, predictions, and planning [33], and (d) *FootSteps* – a biomechanical approach that simulates agent foot steps to support realistic movement and interactions [4]. In this work, SteerSuite is used for dynamic crowd simulations with parameterized crowd and space inputs. Custom Python nodes facilitate the integration of SteerSuite and Dynamo.

3.3 Joint Parametric Modeling of Buildings and Crowds

In a joint parametric modeling environment, the components required to simulate human behavior in a building are the *building's* layout, the *crowd* that populates the building, and the *activities* that the virtual people engage in, as well as the relationships among these different components. These relationships and parameters are outlined in the following subsections.

Building Modeling. A building layout is composed of architectural components (e.g. walls, doors, floors, and equipment) as well as *zones* – discrete portions of space that host different kinds of activities [7]. Both types of entities, which can be modeled using traditional CAD and BIM approaches, are defined as sets of adjustable parameters and can be used as input to define additional crowd parameters. For instance, the building 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 behaviours. Figure 2 shows a parametric building model of an art gallery designed and visualized in Dynamo with different possible layouts generated by tuning building parameters.

Crowd Modeling. A crowd is composed of a user-defined number of agents that move in a space. Additional parameters include the speed at which agents will move, one or more target goals, a color with which an agent is rendered, the radius of the disk which represents geometrically a virtual agent in the simulation, and a steering model. A user can select between the available steering models, such as social forces, RVO, and PPR, as described in Sect. 3.2. The joint parametric modeling proposed in this work enables using space parameters as input for crowd parameters. For instance, zone models can be used as spawning regions were agents are created at the beginning of the simulation, or may be associated with agent behaviours. Figure 3 shows a parametric crowd model in Dynamo.

Activity Modeling. A crowd can be engaged in different activities, such as a day-to-day use of space or an emergency evacuation. Such activities can be modeled by specifying agent movement targets, or behaviours, and the duration of their performance at each destination. A straightforward example may be specifying as movement target at emergency exists, thus modelling a simplified evacuation scenario. More complex scenarios can be modelled by identifying series of movement targets in a space (e.g. the location of the art works), or behaviours (like behaviour trees, and/or zone dependent behaviours) where agents move in space from one location to another. The proposed joint parametric representation enables using input from the building model to define input for the activity model. For example, the location of the art works specified in the building model can be used to define movement targets in the activity model. Figure 4 shows the activity model visualized in Dynamo.

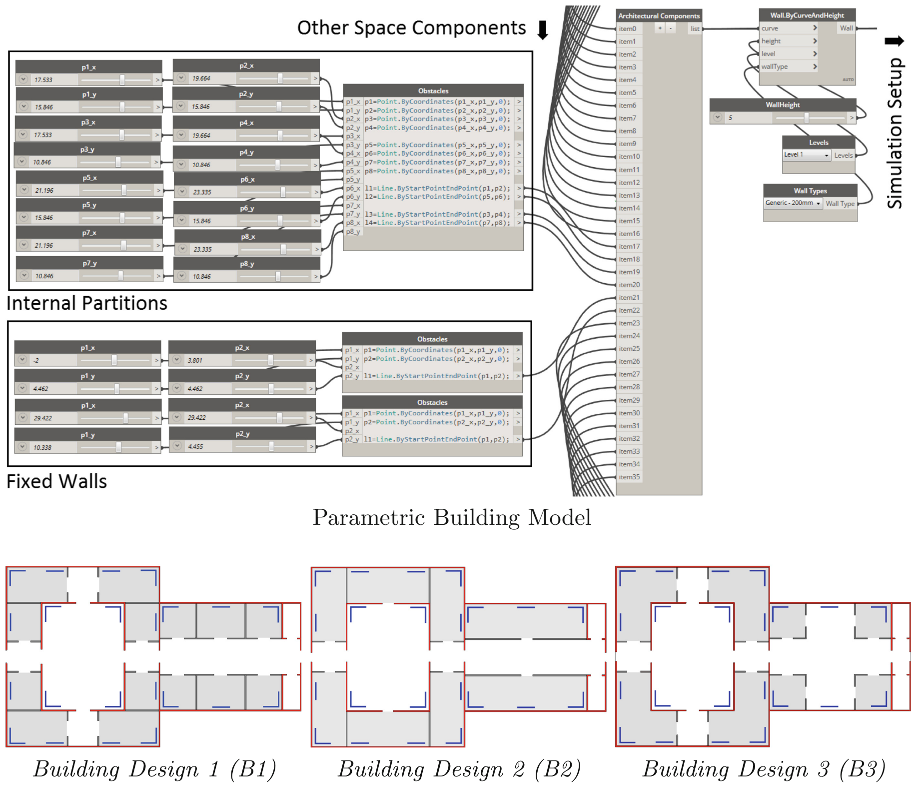

Fig. 2. *Top*: parametric building modeling of an art galley visualized in Dynamo. The model is composed of a set of fixed and movable partitions, which parameters can be tuned to generate different building layouts. *Bottom*: three variants of the art gallery created by tuning the parameters of the 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; blue lines represent the art works (i.e. potential targets for the crowd). (Color figure online)

3.4 Crowd Simulation

The building, crowd, and activity models are used as input for a simulation phase, which computes the movement and behavior of the crowd over time. The Dynamo node workflow is designed to aggregate the different input data and generate a scenario, effectively defining the simulation to execute in SteerSuite.

A user can visualize the simulation in real-time, live update simulations in the background as parameters change without visualizing the 3D graphics. As a simulation is completed, the data, the set of spatio-temporal trajectories, are communicated back to Dynamo for the analysis phase. This process closes the loop of data-driven design without breaking the workflow of the designer. Figure 5

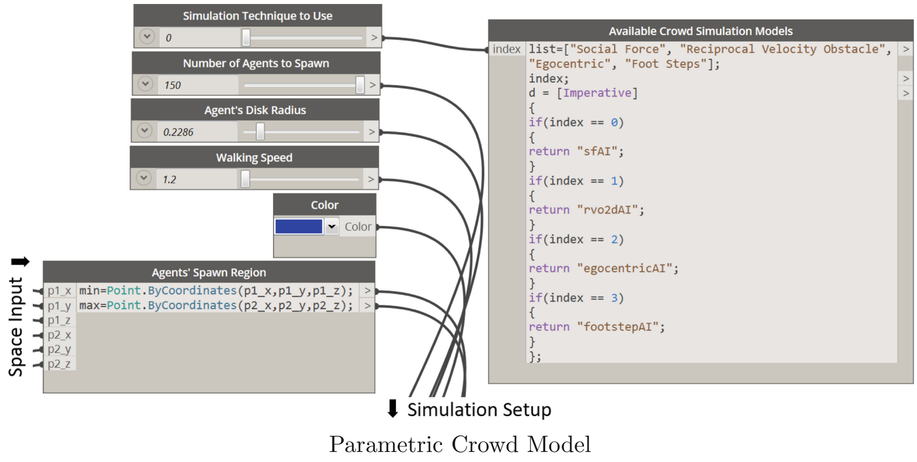

Fig. 3. A parametric crowd model that allows a user to tune different crowd parameters. Input data for the spawning regions originates from the parametric building model.

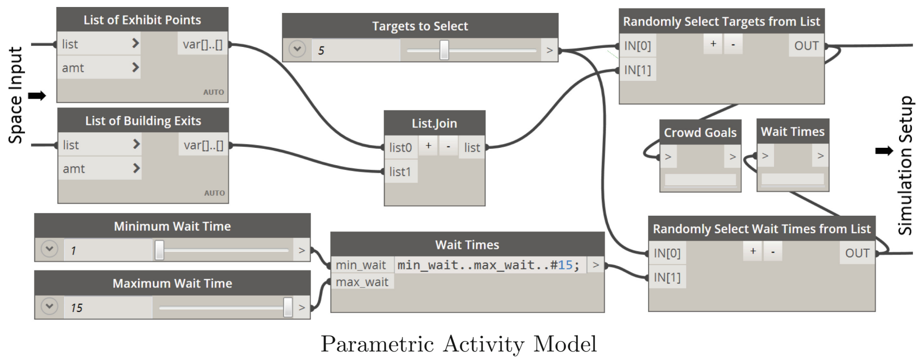

Fig. 4. The crowd activity model visualized in Dynamo. The parameters can be tuned to generate different activities, such as evacuation or day-to-day scenarios in an art gallery.

shows the simulation nodes visualized in Dynamo as well as a snapshot from a running simulation.

3.5 Crowd Behavior Analysis

The simulation output can be analyzed with respect to different analysis methods including (but not limited to) density, trajectory, and speed data maps. *Density*: defined as the number of agents per square meter. We calculate the average density per square meter for the building space over the course of a simulation. *Trajectory*: the path that an agent in motion follows over the course of the simulation. *Speed*: defined as the distance traveled over time. We calcu-

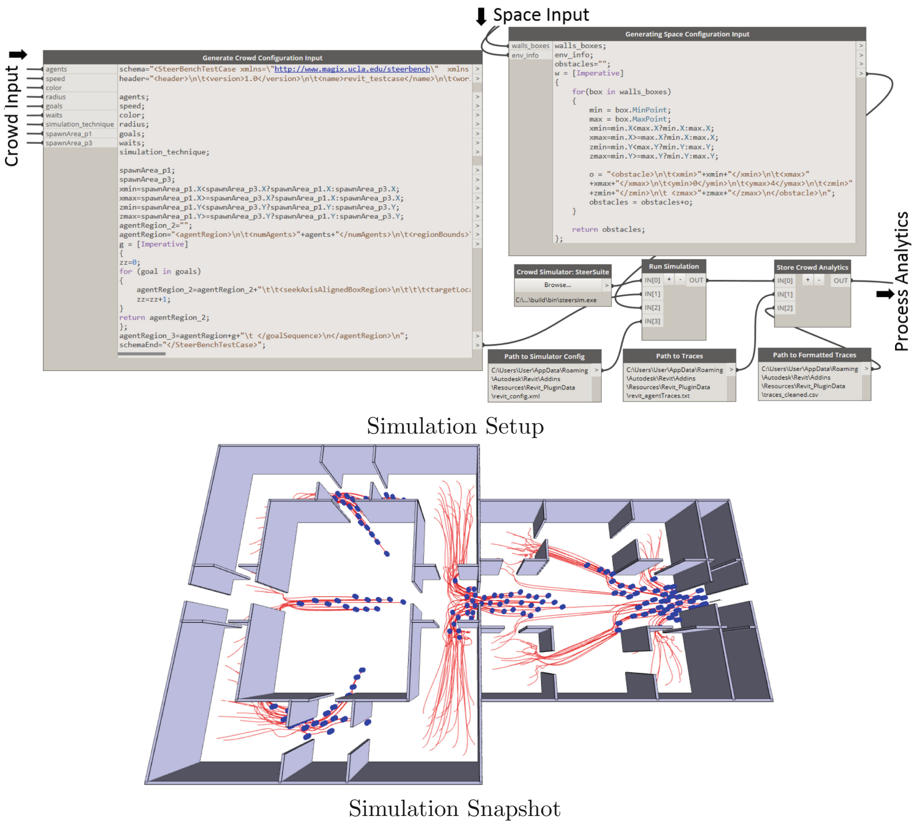

Fig. 5. *Top*: crowd simulation setup visualized in Dynamo. *Bottom*: screenshot of a simulation for an evacuation activity run through SteerSuite. The blue circles represent the occupants. The red lines represent occupants' movement traces. (Color figure online)

late the average speed over all agents for each sample point during the course of simulation. Figure 6 shows the crowd behavior analyses, parameterized and visualized in Dynamo, as well as the output of the analyses, visualized in Revit. Architects and designers can use these results to systematically examine the interaction between a building and its occupants.

4 Case Study

In this section we preset a few demonstrative examples to illustrate the potential of the proposed platform and how it may be used.

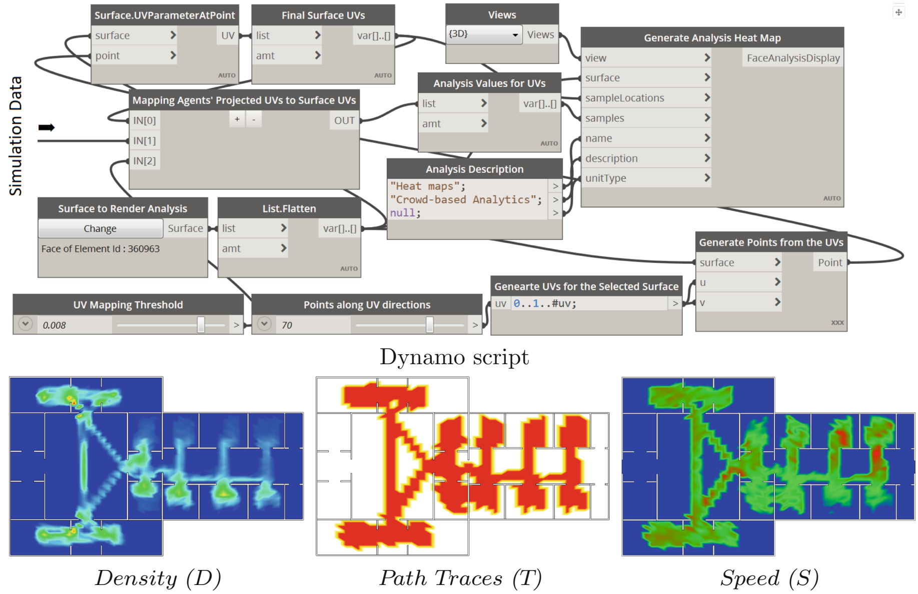

Fig. 6. Top: modeling of crowd behavior analysis visualized in Dynamo. Bottom: examples of human-centric analysis for an exhibition activity. Left–Right: Density (red regions are the most congested areas compared to blue ones), Trajectory (red regions are the areas traveled by virtual agents during the course of simulation) and Speed (red regions are the areas where agents traveled with high speeds compared to blue ones) heat maps are shown. (Color figure online)

4.1 Simulation Setup

Building Parameters. Three variations of a floorpan are created by tuning the parameters of the adjustable partitions of an art gallery (Fig. 2: Bottom). In the remainder of this section, these variants are named *B1*, *B2* and *B3*.

Crowd Parameters. A total of 150 autonomous agents are randomly distributed and initialized in 14 different spawn regions for building (B1), 8 different regions for building (B2) and 8 different regions for building (B3), as shown in Fig. 2 (Bottom). We parameterize the crowd movement into two categories in terms of walking speed. *Adults (C1):* represents the adult walking. A speed of 1.2 m/s is considered an average walking speed of an adult with normative gait and without to use of mobility aids [6,21]. *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 as *C1*, and *C2*, respectively.

Activity Parameters. We consider two different simulation activities. *Day-to-day (A1):* represents a day-to-day situation 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 s with each exhibit before moving to the next. *Evacuation (A2):* represents an emergency situation (e.g. fire egress) where all the occupants vacate the building through their nearest exits.

Human-Centric Analyses. In this study we consider three types of analyses, namely density, walking traces, and average speed, as previously described in Sect. 3.5.

4.2 Results

Figure 7 shows data maps of density, trajectory, and average speed analyses, for all three building spaces with both day-to-day and evacuation activities.

In building (*B1*) and for 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, during the evacuation activity (*A2*), this congestion is mostly found near the building exits due to bottlenecks near egress points. For the trajectory map (*T*) during a day-to-day activity (*A1*), we see complex trajectories because the crowd moved from one exhibit point to the other in order to explore the exhibition, whereas in the evacuation activity (*A2*), we see symmetric trajectories as the agents tried to vacate the building from their nearest exits. For the average speed map (*S*) during exhibition activity (*A1*), the higher walking speed is recorded in the corridors and hallways, whereas in evacuation activity (*A2*), the highest speed is recorded near the building exits.

In building (*B2*) and for 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, whereas during the evacuation activity (*A2*), the congestion is found near the 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*), we see comparatively more complex trajectories and for evacuation activity (*A2*), the symmetric trajectories are found as the agents vacated the building from their nearest exits. However, for both activities, the trajectories show that virtual crowds traveled more areas compared to areas traveled in building (*B1*). For the average speed map (*S*) during exhibition activity (*A1*), the higher walking speed is recorded not just in the corridors but also at the exhibit areas, whereas in evacuation activity (*A2*), high walking speed is only recorded near the egress points.

In building (*B3*) and for 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*)

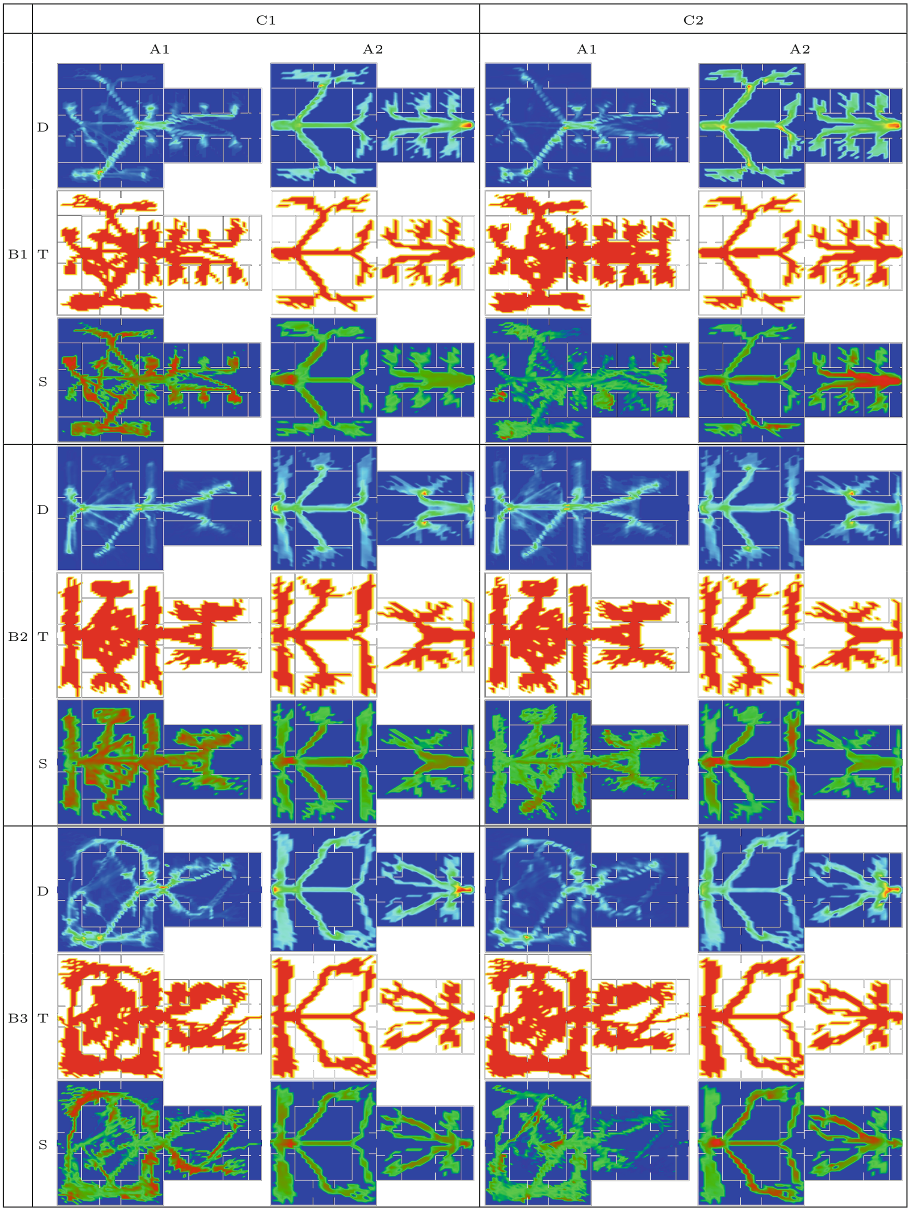

Fig. 7. Selected results for different iterations of human-centric analyses. Specifically, we considered three building layouts (B1, B2, B3), two crowd configurations – "Adults" (C1), and "Mix-Adults" (C2), two activities – "Day-to-day" (A1), and "Evacuation" (A2), and three analyses – "Density" (D), "Path Traces" (T) and "Speed" (S).

during exhibition activity (*A1*), we see complex trajectory structures at the middle corridor as well as at the exhibit points with multi-route trajectories, and for evacuation activity (*A2*), the symmetric trajectories are found as agents moved to the nearest building exit. For the average 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 building exits.

The speed analysis also reveals interesting patterns. In the case of evacuation (*A2*) the mix-adult crowd (*C2*) shows more variation and asymmetry in speed than (*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 proof for concept. In a realistic setting a user would use multiple levels of analysis to identify and analyse further areas of interest or use 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.

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

5 Conclusions and Discussion

In this work, we presented a joint parametric design workflow where users can 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). The proposed platform couples Dynamo – an established tool for parametric modeling, with SteerSuite – an established crowd simulator to support analyses of human spatial behavior in not-yet-built environments.

A case study is conducted to analyze the effectiveness of the proposed framework. Three variants of an exhibition space are created by parameterizing the partitioning walls of an art gallery. Two diverse crowd behaviors are selected in terms of walking speed namely “Adults”, and “Mix-Adults”. Finally, two sets of crowd activities are performed namely “Day-to-day” – a normal day-to-day scenario and “Evacuation” – an emergency evacuation scenario. The framework allows users to systematically run simulations with the defined input parameters and analyze the results in the form of data-maps – spatialized representations of human-centric analyses to gather insights that can inform the design process.

While in this study we analyzed a selected number of building, crowd, and activity configurations, our platform can simulate infinite variations of these parameters in a systematic fashion.

Future work will involve: (a) extending the activity and crowd models to account for additional parameters; (b) incorporating additional human-centric analyses, such as crowd flow, evacuation times, and exit usage; (c) representing the simulation results by means of a dashboard that supports the storing and exploration of the different design solutions; (d) embedding into the platform an optimization process that systematically tunes selected building, crowd and activity parameters to improve a building design and operation; and (e) conducting a user study to determine how the platform can be used by architects to simulate and evaluate design options.

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