Joint Exploration and Analysis of High-Dimensional Design–Occupancy Templates

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Figure 1: *Experiment 1* explores diverse environment configurations using a default parameterized crowd, *Experiment 2* explores a default parameterized environment against a diverse set of crowds, *Experiment 3* explores the selected design from *Experiment 1* using diverse crowds, *Experiment 4* explores diverse environment configurations using the selected crowd from *Experiment 2*, and *Experiment 5* jointly explores diverse environment and crowd configurations.

ABSTRACT

Crowd simulations provide a practical approach to evaluate building design alternatives with respect to human-centric criteria, such

as evacuation times and flow in case of emergency scenarios. Coupled with Building Information Modeling (BIM) tools, they support architects' iterative exploration of design alternatives. However, methods based on manually configuring a design and a corresponding simulation are not practical for exploring the potentially very large number of design solutions that satisfy human-centric design goals and requirements. Often, for practical reasons, designers may consider standard crowd configurations which do not capture the behavior of diverse occupants that may exhibit different locomotion abilities, movement patterns, and social behaviors. We posit that a joint exploration of high-dimensional building design and occupancy features is necessary to more accurately capture the mutual relations between buildings and the behavior of their occupants.

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To test this hypothesis, we conducted a series of experiments to automatically explore joint high dimensional design–occupancy patterns using an unsupervised pattern recognition technique (i.e. K-MEANS). We demonstrate that joint design–occupancy explorations provide more accurate results compared with sequential exploration processes that consider default design or crowd features, despite the longer computational times to simulate a large number of solutions. The findings of this case study have practical applications to the design of next-generation design exploration tools that support human-centric analyses in architectural design.

CCS CONCEPTS

• **Human-centered computing** → **Visual analytics**; • **Computing methodologies** → **Visual analytics**; *Classification and regression trees*; *Modeling and simulation*; • **Applied computing** → **Computer-aided design**; *Architecture (buildings)*.

KEYWORDS

Human-centric analytics, crowd simulation, parametric modeling, building occupancy, multi-agent systems.

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1 INTRODUCTION

One of the major challenges in architectural design is the exploration of a wide range of design alternatives and the identification of those that best satisfy design goals while adhering to constraints [Kalay 2004]. Even though Building Information Modeling (BIM) tools support the analysis of physical aspects of buildings, such as structure, cost, lighting and energy consumption, at present, they cannot predict the impact that a building’s design will produce on crowd movement. Synthetic crowd simulation is a cost-effective means of exploring this space. However, crowd simulation approaches are mostly developed in the computer graphics community to represent the movement and dynamic interactions between virtual agents (e.g. Kapadia et al. [2015]). These approaches do not always account for the systematic impact that different building designs produce on occupant movement and activities. To capture the mutual relations between environment design and occupant behavior, it is necessary to study them jointly, in a shared modeling environment that enables the exploration of how environment features affect crowd behavior, and vice versa.

Prior work demonstrated a parametric modeling framework that jointly represents (a) a building and the bounds of its permissible layout alterations, (b) a crowd that populates the environment, and (c) the activities that the crowd engages in using a visual-node workflow commonly used in established parametric design approaches (e.g. Grasshopper [gra [n. d.]]) [Usman et al. 2019]. Users, such as architects or engineers, can manually adjust the building and crowd configurations, run crowd simulations, and analyze the results in the form of spatialized representations of human-centric analyses. This process, however, requires the manual

exploration of a vast numbers of solutions in a high dimensional design space that uniquely combines space and crowd features.

In this paper, we conduct a series of experiments that use high value thresholding and an unsupervised pattern recognition technique to automatically explore the vast number of space-crowd parameter configurations. We posit that a joint exploration of high-dimensional building design and occupancy features is necessary to comprehensively capture the mutual relations between buildings and the behavior of their occupants. To test this hypothesis, we systematically explore how design configurations and crowd features impact the flow of people in an evacuation scenario.

2 RELATED WORK

There is an established body of work exploring how crowd simulations can be incorporated in to architectural design processes to inform the design of human-centered environments.

2.1 Crowd Simulations in Built Environments

There is a rich literature on crowd simulation techniques to represent the movement of people in virtual environments [Kapadia et al. 2015; Pelechano et al. 2016]. Particle-based approaches compute local-level interactions among individuals for motion, speed and relative positions [Reynolds 1987]. Physical force models use repulsion and attraction to model individual crowd interactions [Helbing and Molnar 1995; Karamouzas et al. 2009].

2.2 Simulating Human-Building Interactions

Researchers have used crowd simulation techniques to simulate the movement of people in built environments to approximate building–occupant behaviors. Some approaches focus on day-to-day behavior of people in offices [Goldstein et al. 2010], hospitals [Schaumann et al. 2017], and universities [Shen et al. 2012]).

In these simulations, both crowd as well as building design factors affect the behavior of building occupants [Hong and Lee 2018; Hong et al. 2016]. Prior work has manually explored how different crowd configurations can affect the movement of people in environments [Chu et al. 2015]. Other studies have manually compared generated building design options to identify which design solutions better satisfy a set of key performance indicators [Schaumann et al. 2019]. Usman et al. [2018] presented an interactive architectural analysis tool to inform human-focused building designs. Interactive tools have been developed to study and evaluate the effects of pillar placements on crowd movement flows during evacuations [Haworth et al. 2017].

2.3 Joint Exploration of Building Designs and Human-Behavior

Recent work has focused on automatic user-in-the-loop generation of optimal building design solutions using dynamic crowd simulations [Feng et al. 2016; Haworth et al. 2017; Michalek and Papalambros 2002; Pottmann et al. 2015; Shi and Yang 2013; Turrin et al. 2011]. However, these methods are tailored to solve specific design problems, and are not integrated within established architectural design pipelines that include parametric building modeling. To address this, a system was recently proposed as a more comprehensive framework that jointly models (a) a building and the bounds

Figure 2: Design space of the environment used in case study 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.

of its permissible alterations, (b) the occupants that populate the building, and (c) the activities that people do on a day-to-day basis or in case of emergency scenarios Usman et al. [2019]. Designers can thus manually explore high-dimensional building-occupancy configurations and visualize the results in the form of spatialized data maps.

The aforementioned approaches, however, do not jointly model the parameter space of environment and crowd configurations, either treating them independently, or simplifying them. The focus of this study is to challenge this simplification, thereby showcasing that an automatic joint exploration of a vast number of solutions combining environment and crowd parameters is necessary to capture accurate building-occupancy relations and improve designs.

3 EXPERIMENTAL SETUP

We conduct a series of experiments to explore a large set of environment and crowd parameter configurations in “isolation” (i.e. environment/crowd only) as well as “jointly” to analyze crowd behaviors in a built environment for the said two workflows. Often, the design space exploration is based on environment parameters alone or at times using some constant crowd features (which may not exhibit different locomotion abilities and social behaviors) to account for human-behaviors for potential environment–occupant interactions. By doing so, designers may fail to identify a vast number of design solutions that satisfy human-centric environment design goals and requirements and may lead to ill posed designs that are unable to accurately capture the high dimensional design space.

The dimensionality of crowd and environment features is, taken individually, high and when considered jointly, multiplicatively

large. As the feature dimensionality of either space grows the solution space grows rapidly and makes exhaustive exploration of solutions intractable—especially with continuous feature spaces. To address the exploration of such an enormous solution space, we adopt a method for finding patterns in high value designs of the exhaustive solution space. First, we discretize all solutions spaces regularly (in the system the granularity may be set by the user). Second, we threshold the highest value designs with respect to some given metric (in this paper we use crowds’ exit flow) using only the 95th percentile of solutions (in the system the threshold value can be set by the user). Finally, we perform unsupervised pattern recognition to identify salient patterns in the remaining high value designs—we refer to these as templates. The templates are captured by clustering similar parameters (features) for environment and/or crowd configurations using an unsupervised pattern recognition technique, k-means++ with the squared Euclidean distance metric [Arthur and Vassilvitskii 2007; Hartigan and Wong 1979]. 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. *Exit 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 a parametric design framework [Usman et al. 2019].

Exit Flow is used as a metric to evacuate simulations. It has been defined in several different ways [Helbing et al. 2007; Johansson et al. 2008]. Here, we define it as the rate at which the agents reach their goal or target position.

Table 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. Using the environment templates found in *E1*, *E3* explores the crowd features. Using the crowd templates found in *E2*, *E4* explores the environment features. This experimental approach gives us the best of environment and crowd parameter templates from *E4* & *E3* respectively. Finally, we explore the joint parameterization by testing all of the environment configurations using all of the crowd configurations (*E5*).

Figure 2 shows the default and alternate configurations of a real-world office space currently under construction. Table 2 and Table 3 show the environment and crowd parameters, and their values respectively.

4 “SEQUENTIAL” VS “JOINT” PARAMETER EXPLORATION

We simulate the best performing environment templates (*Experiment 4*) against the best performing crowd templates (*Experiment 3*) from the sequential parameter exploration process. Figure 3 (LEFT) shows the respective aggregate density maps from the sequential exploration process. *Exit Flow* value for the simulation is also reported. Environment template # 1, simulated against crowd template # 2,

Table 1: An overview of the experimental setup. Further details on these experiments can be found in Section 3. For experiments E1,E4 and E5, top 5% of the flow-based sorted configurations (i.e. only the 95th percentile of solutions) are selected. Gray colored cells highlight the best performing of environment and crowd templates from sequential and joint parameter exploration respectively.

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 2: Environment parameters and their permissible values. A default (D) environment configuration has design space parameters such that doors are placed in the middle, hallway width is 3.5m and exits are on both (LEFT/RIGHT) sides of the environment.

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

yield the highest exit flow of 5.398 agents/second. Simulations from “sequential” exploration yield an exit flow of 4.80 agents/second on average. Also, the door placements are made such that they are opposite to each other expect for room 2 and 6, causing more congestion in the hallway, hence, slowing down the movements.

We also simulate the environment and crowd templates which were found from the joint parameter exploration process (*Experiment 5*). Figure 3 (RIGHT) shows the respective aggregate density maps from the joint exploration process. *Exit Flow* value for the simulation is also reported. Jointly discovered environment–crowd template # 1 yield the highest exit flow of 6.488 agents/second. Simulations from joint exploration yield an exit flow of 5.762 agents/second on average. Parameterization from joint exploration produced 34.7% and 27.6% increased in exit flow compared to sequential best and

Table 3: 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.

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) 33% agents (1.3) (D) 33% agents (1.6)	66% (1.0) 17% (1.3) 17% (1.6)	17% (1.0) 17% (1.3) 66% (1.6)

average simulation results respectively. Overall, joint exploration process produced better environment–crowd parameters which yield higher values for both highest and average exit flows. 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.

Figure 3: Density maps from sequential (LEFT) and joint (RIGHT) exploration of environment–crowd parameters during evacuations. Exit Flow values are also reported.

5 CONCLUSION

The presented work motivates the study of an automatic joint modeling of high-dimensional environment–crowd parameterization. The comparison indicates that joint exploration of environment–crowd features (E5) yields higher value design solutions compared to sequential parameter explorations. 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, E3–E4), which resulted in smooth crowd movements and higher exit flows. However, in order for this to be a practical consideration, there is a significant computation overhead. Hence, future work is needed to expedite the computation process by means of machine learning and graphics acceleration techniques. Future work will also investigate individual parameters within environment and crowd configurations which have strong positive or negative impact with respect to design performance and the importance of generalized design features.

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