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2017

The final publication is available at:

https://doi.org/10.1145/3136457.3136463

Crowd Sourced Co-design of Floor Plans using Simulation Guided Games

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ABSTRACT

Crowd-aware environment design is a complex combinatorial decision process, where small changes in a design may affect crowd flow patterns in unexpected and potentially unintuitive ways. Existing solutions rely on expert intuition, best practices, or automation. To address the dimensionality and complexity of the design process, we propose leveraging automation and human creativity at a large scale akin to crowd sourcing, within a gamified collaborative design framework. Using our system, “players" (novice users or experts) can rapidly iterate on their designs while soliciting feedback from computer simulations of crowd movement and the designs of other players. Our approach affords a new way of thinking of the solution space in that it inherently supports competitive collaboration, co-design, and crowd sourced solutions. We evaluate our framework through a preliminary user study.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in collaborative and social computing**; • **Applied computing → Computer-aided design**; • **Software and its engineering → Interactive games**;

KEYWORDS

Architectural Design, Gamification, Co-Design

ACM Reference format:
Nilay Chakraborty, Brandon Haworth, Muhammad Usman, Glen Berseth, Petros Faloutsos, and Mubbasir Kapadia. 2017. Crowd Sourced Co-design of Floor Plans using Simulation Guided Games. In *Proceedings of MiG '17, Barcelona, Spain, November 8–10, 2017,* 5 pages.
https://doi.org/10.1145/3136457.3136463

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MiG '17, November 8–10, 2017, Barcelona, Spain

ACM ISBN 978-1-4503-5541-4/17/11…$15.00
https://doi.org/10.1145/3136457.3136463

1 INTRODUCTION

Designing an architectural or urban environment plan is a complex problem for which good solutions balance aesthetics, functionality, utilization, and structural safety. This makes the problem inherently multiobjective and the solution space combinatorial. Incorporating the dynamics of large groups of people, or crowds, further complicates the solution space and is prohibitively expensive to do with real people. Thus environment layout designs are commonly tested using synthetic crowds that try to model realistic behaviours under varying conditions. In particular, a layout's performance is most critical during dangerous situations such as evacuations, so these scenarios are used to stress test environments.

Industry architectural design tools do not natively account for evacuation planning or crowd-aware stress testing. While there are tools used to analyze designs with simulated crowds, they do not have an integrated environment for evaluation, optimization, and collaborative design. Together these tools are complex and require years of training, architectural, and safety knowledge to use appropriately. Fully automated computational solutions for crowd-aware architectural design may miss solutions which are technically sound, crowd-aware, and aesthetically pleasing. These are highly dependant on the quality of the objective functions for each of these requirements. Recent work in this field has sought for user-in-the-loop optimization processes which make up for these shortcomings and provide the user (designer) more control over solution directions.

Our solution is to gamify the process of layout design for crowd-aware environments. This game provides the players with feedback in terms of crowd simulation, path traces, and heatmaps of evacuation dynamics, while affording them editing power within the constraints imposed by the architect or designer. We focus on evacuation success and fitness as a metrics for success in the game - making crowd motion and dynamics core to play. As well, the players are given then means to parametrize the crowds to tune microscopic and macroscopic motions and explore designs under different conditions.

The approach of gamifying complicated problems affords many benefits to both the process and the solution. The most immediate is that the game provides a fun and interactive collaborative platform for architectural and urban planning. By providing a means to implement the design process as gamified levels with built-in

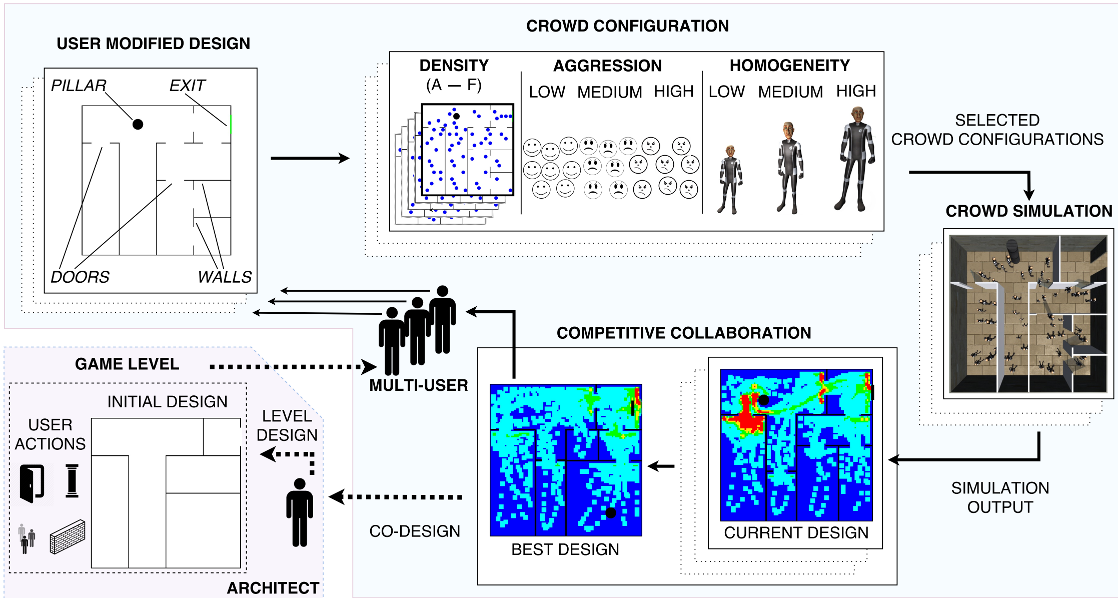


Figure 1: Framework Overview

architectural constraints, a planner, environment designer, or architect can convert a design problem into a playable game. This approach affords several uses for the system. First, by providing the game via the internet, or large scale network of collaborators, design solutions may be crowd sourced. As well, the designer may access and leverage the processes, platforms, and people in the gaming world, which can produce radically new ways of working, collaborating, or learning in this domain. Providing the analysis and designs of other players as well as the fitness of their designs affords competitive collaboration. Leveraging the collective knowledge of the players within an iterative process of co-design with stakeholders can lead to optimal, creative, and unintuitive design solutions while facilitating the exchange of ideas. The interface ensures that a user with any level of knowledge in a related field can produce an design plan. Thus, this system can also be used as an engaging learning platform in the field of architectural education.

2 RELATED WORK

There is an established and growing interest in computer-aided architectural methods to explore design spaces and provide optimal solutions with respect to problem criteria [Pottmann et al. 2014]. While there are popular manual solutions, such as Autodesk Revit and Rhino3D, these tools do not account for crowd behaviour and optimization. Crowd simulation is a dynamic solution for objectively analysing and understanding design choices from a human-centric perspective [Haworth et al. 2017; Michalek and Papalambros 2002; Shi and Yang 2013; Turrin et al. 2011]. Of particular interest is the optimization of high density egress scenarios, such as evacuations [Berseth et al. 2015; Jiang et al. 2014; Johansson and Helbing 2007]. As well, layout optimization approaches have been used in digital games, though the objectives have only tangentially related to crowd simulation [Barriga et al. 2014; Bauer and Popović 2012; Berseth et al. 2014a].

The maturity of research in simulating crowd dynamics has resulted in a wide variety of approaches [Kapadia et al. 2008; Thalmann and Musse 2013]. In particular, agent based methods have proven useful in architectural navigation and analysis, such as social forces [Helbing et al. 2000], predictive models [Singh et al. 2011; van den Berg et al. 2011], data-based methods [Guy et al. 2012; Pettré et al. 2009], and meta approaches such as parameter optimization [Berseth et al. 2014b; Wolinski et al. 2014].

There is a plethora of research on the usefulness of games, play, and gamification for educational purposes [Connolly et al. 2012]. There is evidence that play is a strong mediator in learning and, furthermore, simulation can be used as a key ingredient to interactive learning environments [Rieber 1996]. Recent work shows success in using games to guide collaboration in crowd-sourced design [Debkowski et al. 2016; Li et al. 2012; Müller et al. 2015]. Closest to our approach are serious games utilizing crowd simulations in training, planning, and evaluating emergency evacuation plans [Ribeiro et al. 2013].

3 FRAMEWORK OVERVIEW

Our system affords co-design between architects and players, collaboration amongst players, and the crowd sourcing of designs through an online game. The system reimagines environment designers as game designers, design collaborators as gamers, and gamers as design collaborators. This approach affords two distinct cycles: a high frequency cycle of gamified collaboration, and a lower frequency cycle of co-design, as seen in Figure 1. We leverage the wealth of research in crowd simulation to present a gamified design tool for environments that uses parametrized crowd evacuation simulation as criteria for architectural analysis.

Our game gives players the tools to construct, modify, and analyze environment designs. A player can add elements to the provided environment, such as doorways, walls, and pillars. The player's goal, and the game's success criterion, is to create an efficient design that affords the evacuation of all agents in the shortest possible time. The player can make use of crowd evacuation simulations, total evacuation time, and aggregate crowd density via heat maps to identify regions for improvement.

The following sections provide an overview of the modules in the game framework.

Initial Layout - Co-Design. An architect or designer provides the initial layout and parametrization of the environment for players to work with, akin to designing a level in a game.

Player Modified Layout. Players drive an optimization process through the gamification of the design process. There are several elements which may be added or modified such as walls, pillars, and doorways, subject to the constraints defined by the architect or designer.

Crowd Behaviour Configuration. The player may configure a set of characteristics of the crowd to model a range of behaviours and dynamics for which the environment's fitness is evaluated. While in depth details are provided in the Crowd Configuration and Simulation Section, the parameters are: (a) *Level of Service (LoS)* - the crowd density; (b) *Level of Aggression (LoA)* - the distribution of agent speed and acceleration; (c) *Level of Homogeneity (LoH)* - the distribution of agent widths and heights.

Crowd Simulation. After a player has finalized an environment configuration, they may run a variety of crowd simulations. A simulation ends once all crowd agents have successfully evacuated the environment.

Evaluation. After the simulation has ended, the game displays the players' ranking in order of lower total evacuation time. In this phase, the players can visualize and analyze their results using heat maps of crowd dynamics.

Collaboration. Players may view the designs and performance of the other players. They may use this feedback to improve their own designs or even adopt another player's design for the next round.

4 ENABLING CO-DESIGN

Architectural, or environment, layouts are primarily composed of walls, pillars, corridors, and doorways. Our game provides tools to the player to modify and create these elements in a layout. However, the game also provides the tools to create gamified levels with different forms of challenges, an example of an architect provided and player altered design can be seen in Figure 1. The architect or designer imposes their own constraints on the designs as limits on what can be added, or modified in the level. Ultimately, they set desired constraints and degrees of freedom for architectural elements. This includes fixed elements (such as outer or structural walls), required elements for design completion (such as number of doorways or pillars), pair-wise constraints between elements (such as angle or position), group constraints (such as in-line configurations), and even available crowd types (such as aggressive versus passive evacuations). As well, architects may formulate game levels in terms of separate portions of a larger environment, changing the complexity or the scope of subsequent iterations (levels). This means that a player may work from the micro to macroscopic portions of a larger design task.

Gamifying architectural design opens the design process to players with any level of architectural knowledge. To meet these ends, the game framework provides a means of specifying the aforementioned constraints in the layout design phase such that even casual players can follow architectural standards. As well, the game allows the architect to step in to the design process and incorporate changes players have introduced while fixing or modifying constraints on the environment. This is core to enabling co-design and affords a balance between the necessary aesthetics (such as symmetry, alignment, and pose), functionality (like location of a load bearing pillar), and performance (evacuation dynamics).

The gamification framework and level specification affords a number of options for guiding the player towards producing high values designs. This includes messaging, invalid action highlighting (those which break constraints), and general design guides provided to help casual players learn about architectural standards or constraints. Thus, the game can be used as an educational tool for novice designers or casual players.

5 COMPETITIVE COLLABORATIVE DESIGN OF ENVIRONMENTS

The game framework supports optimal environment design through an iterative approach. Players can improve their design to reach optimality by iterating on subtle design modifications and running simulations. The framework also supports collaboration and competition by exposing players to other's designs and performance analyses.

A user is afforded the ability to reinforce their design by learning from the best player's moves. This is achieved by revealing the best player's analyses and design. A player can use this knowledge and attempt to incrementally improve their design. By allowing players to iteratively replay and view other players designs and analyses, the game fosters collaboration which can guide the players towards a more optimal architectural design. In a way, this stage brings together the power of combinatorial optimization, human creativity, and crowd sourcing to collaboratively tackle complex design tasks.

6 CROWD CONFIGURATION AND SIMULATION

Our system utilizes Unity's® crowd simulator system, which uses Reciprocal Velocity Obstacles (RVO) [van den Berg et al. 2011] for local steering and navigation meshes for the walkable area representation with A* search for global path planning [Hart et al. 1968]. Crowd members are distributed based on the parameters set by the player. The architect or designer may modify the destinations and distributions for locations of crowd members. For accurate navigation, the navigation mesh of the environment and path plans for each member are recomputed after every environment change and before simulation. Finally, Unity's® Mecanim system handles character animation of a humanoid character model.

To afford rigorous and complete analysis across dynamics and behaviours, the crowds are parametrized for aggression, homogeneity, and density. These parametrization and crowd definition are

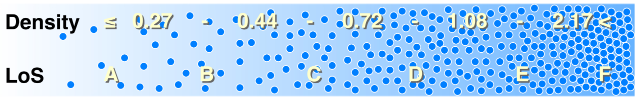
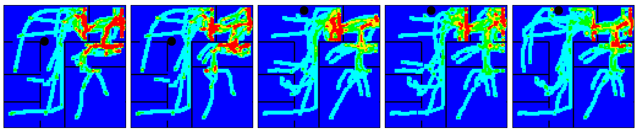


Figure 2: LoS value and crowd density mapping, where density is measured in people per square meter.



T=16.61s T=12.73s T=10.69s T=9.32s T=9.17s

Figure 3: Images from four design iterations in the single player mode are shown in a sequence for crowd configuration LoS A, LoA Low, LoH Low. Each iteration decreases the total evacuation time T. The player explores a combination of door and pillar placements to break up the crowd and direct flow.

provided in the rest of this section - an example of a parametrization can be seen in Figure 1.

Level of Aggression (LoA). Three degrees of aggression are provided; low, medium and high. The aggression degree determines the distribution of speed and acceleration of members in the crowd.

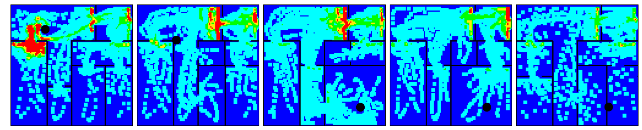
Level of Homogeneity (LoH). Three classes of homogeneity are available to the player: low, medium, and high. Changing this configuration changes the distribution of the radii, heights and masses of the crowd members accounting for varying body shapes and masses in the crowd.

Level of Service (LoS). There are six Levels of Service available to the player. LoS is used by traffic engineers to measure the quality of traffic flow both for automotive and pedestrian applications. LoS classes are typically given a grade level (from A-F), which are summarized in Figure 2. We employ this qualitative approach to constructing crowds of particular densities in order to reduce the complexity of evaluation design for potentially novice users who may not understand crowd density.

We formally denote a crowd $C = \langle G, K, L \rangle$ where G, K, L denote LoS, LoA, LoH respectively. $G = \{g_{min}, g_{max}\}$ where g_{min} and g_{max} represents the crowd density range values for each level of LoS. $K = \{S_{high}, S_{low}, F_{high}, F_{low}\}$ where S_{high}, S_{low} represents the high and low speed bounds and F_{high}, F_{low} acceleration bounds. $L = \{M_{high}, M_{low}, H_{high}, H_{low}, R_{high}, R_{low}\}$ where M_{high}, M_{low}, H_{high}, H_{low},R_{high}, R_{low} represents the high and low LoH factors for mass, height and radius of the crowd respectively. We distribute the crowd configuration parameters amongst the crowd members with fixed probabilities based on the selected intensity, or amplitude, for each parameter. This results in a total of 54 unique crowd behaviors.

7 CROWD-AWARE ENVIRONMENT ANALYSIS

A suite of analysis tools are made available to a player in order to visually validate their simulation results. In addition to fully animated heterogeneous crowd simulation, we visualize crowd dynamics using heatmaps so that the user can improve their design by identifying regions which are not performing well. The heatmap is an orthographic view of the design overlaid with a statistical histogram of some crowd dynamic. We provide two types of map utilized in crowd analytics, the aggregate static density map, and the space utilization map [Still 2000]. The space utilization map highlights all crowd agent paths. The aggregate static density map reveals the level of crowd density of a region in the layout. Figure 3 is an example of an aggregate static density map, an orthographic view of walls, doorways, and pillars in the layout with aggregate crowds density displayed as heat traces. If a region is not performing well, such as with congestion, crowd density will rise and the region will become more red.



T=16.41s T=13.69s T=11.17s T=9.66s T=8.15s

Figure 4: Iterative decrease of total evacuation time in the competitive collaborative mode, where each iteration decreases the total evacuation time T for LoS C.

8 EVALUATION

A preliminary user study is conducted to evaluate the gamification of architectural design using our system when player designs are crowd sourced via the online version of the game. Participants are asked to solve a common but complex problem in architectural design - emergency evacuation under varying crowd conditions. We hypothesize that gamification of such a complex combinatorial problem in architectural design provides a player an innovative means to improve their design and gradually approach optimality in terms of shorter total evacuation time. As well, we hypothesize that competitive collaborative design is an effective solution to this problem.

For the experiments, participants are provided with a pre-designed layout. Participants may add and adjust (size, position, rotation) walls, doorways, and pillars. There are several constraints associated with each element in the layout, in addition to the static layout provided when the game starts. Participants may not remove or move the fixed elements in the given layout, particularly the bounding and structural walls, see "Initial Design" in Figure 1. There are a fixed number of walls (2), pillars (1), and doorways (6) that must be placed by the participant. Walls may be placed only if they form an enclosed space - for this experiment, partial dividers are considered invalid. A wall may not be made to pass through an outside, or bounding, wall. Finally, all agents in the crowd simulation must be able to evacuate the environment.

Preliminary results from the user study show iterative improvement in the single player case, Figure 3, as well as the multiplayer case, Figure 4. Aggregate crowds dynamics are displayed as heat traces. These highlight the fact that participant is decreasing the evacuation time as progressing with the design iterations.

9 CONCLUSION

This paper describes an online mutliplayer, collaborative, co-design ready game system for architectural design. In particular, the system focuses on the architect as game designer, and the player as collaborator in the gamification of crowd-aware design of environments for evacuations. The system utilizes parametrized crowds to assess environment designs under varying conditions. User studies show that single player and multiplayer modes produce high value environment designs. In particular, with respect to total evacuation time, single player designs exceed default performance, and in turn, multiplayer designs exceed single player designs.

Limitations in the system include a non-standard interface for architectural design. As well, the crowd simulation may not perfectly reflect human behaviour. Moving beyond evacuations and basic parameters would be beneficial in an industry setting. Limitations in our studies include the open and unconstrained nature of the system. Players can choose how they parametrize and evaluate the environments using crowd simulation. Of the 54 possible crowd configurations, many were not utilized, constraining our analyses to the few populated with data. In our studies, the player generated designs are not verified or ranked by an architect, although the do fall within their bounds. This is a part of a more extensive future study.

ACKNOWLEDGMENTS

This research was partially funded by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery and Create programs.

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