DESIGNING CROWD SAFETY

Agent-Based Pedestrian Simulations in the Early, Collaborative Design Stages

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Abstract. Contemporary agent-based pedestrian simulations offer great potential to evaluate architectural and urban design proposals in terms of medical risks, crowd safety, and visitor comfort. Nevertheless, due to their relative computational heaviness and complicated input-parameters, pedestrian simulations are not employed during the design process commonly. Simulation results significantly impact planning decisions, especially when they are already available in the early design phases. This paper analyzes the requirements of pedestrian simulations for early planning stages, such as seamless integration into iterative and collaborative design processes, interactivity, and appropriate visualization of results. For this purpose, we combine two existing projects: a high-accuracy pedestrian simulation and the CDP//Collaborative Design Platform. To adapt the simulation method to the requirements of early planning stages, we investigate interactions that blend intuitively with the design process and enable multiple users to interact simultaneously. We simplify simulations' input parameters to match the level of detail of the early design phases. The simulation model is adapted to facilitate continuous and spontaneous interactions. Furthermore, we develop visualization techniques to support initial design negotiations and present strategies for compensating computation time and giving constant feedback to a dynamic design process.

Keywords. Pedestrian Simulation; Agent-Based Simulation; Early Design Stages; Collaborative Design; Human Computer Interaction.

1. The Potential of Pedestrian Simulations in the Early Design Stages

During the medical crisis of 2020, the relevance of pedestrian flows for the management of public spaces and buildings have become evident. The need to adapt various existing areas and buildings to uncertain and dynamically changing conditions has drawn additional interest to computer simulations that predict crowd dynamics and congestion (accu:rate, 2020a). In a short time, public spaces, event spaces, and working environments have to be changed to fit new safety

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regulations. Moreover, in other planning contexts, the prognosis of pedestrian movement is essential to guarantee comfort (Asriana et al. 2016), security (Kretz 2007), and health (Aschwanden 2012).

Simulations reveal the most meaningful impact on the design in the early planning stages (Roetzel, 2014). Embedding knowledge from simulations in the planning process could enable designers to foster pedestrian comfort in conformity with other economic, ecological, and aesthetic goals. Furthermore, simulations anticipate problems, which can be solved with less effort in the early design stages than in later phases of planning and construction (Serginson et al. 2013). However, the early design stages imply a high level of uncertainty, which is reinforced by the involvement of various actors, like laypeople, planners, and professionals, and the relevance of heterogeneous design parameters (Wurzer et al. 2012). Complex planning problems have no single ‘good’ solution but can only be resolved by informed negotiation (Rittel and Webber 1973). Designers collaboratively iterate countless alternatives to evolve an acceptable solution. Since these negotiations are highly contingent, dynamic, and complex, the supply of relevant information can be crucial for a productive debate (Kunze et al. 2012).

Advanced behavioral agent-based pedestrian simulations are seldom used in the early design stages (Asriana and Indraprastha 2016). Commonly they work as stand-alone desktop applications with user input and output unfit to meet the described dynamic conditions. While only a relatively small amount of research concerning agent-based simulations in early planning phases exists (e.g., Aschwanden 2012, Asriana and Indraprastha 2016), this topic is well explored in the context of energy and climate simulations. The research covers the availability of input parameters (Roetzel 2014), integration of tools into design interactions (Attia et al. 2012), and the presentation of relevant results (Petersen and Sendsen 2010). For this reason, these tools can serve as a reference for the development of interactions and visualization techniques regarding pedestrian simulations.

2. Project Setup

In this research project, we embed highly accurate agent-based pedestrian simulations in the early design stages. To achieve this goal, we link the existing simulation tool *crowd:it* (accurate 2020a) with the project CDP/Collaborative Design Platform which was developed during the last 10 years at the Technical University of Munich (Schubert 2020).

2.1. CROWD:IT SIMULATION METHOD

The assessed simulation tool *crowd:it* was developed as a spinoff in the research context. On the one hand, this method builds upon the theoretical work of Angelika Kneidl on pedestrian locomotion and navigation (Kneidl 2013). On the other hand, it is based on the *Optimal Steps Model* model by Michael Seitz and Prof. Gerda Köster (Seitz 2016) (accu:rate 2020b). In combination, these approaches enable indiscrete, microscopic movement, including behavioral and biomechanical aspects (Seitz and Köster 2012) as well as advanced wayfinding (Kneidl al. 2012). Thus, they give insight into local crowd dynamics such as cueing or stop-and-go-waves (Kneidl 2013). On the downside, this high resolution of results is computation-intensive and requires a relatively high literacy for preparing and evaluating the simulation. At this point *crowd:it* is mainly employed as a pc application for high-fidelity prognoses of pedestrian behavior in late planning phases.

2.2. CDP / COLLABORATIVE DESIGN PLATFORM

Conventional simulation interfaces (mouse, keyboard, screen) do not match the prerequisites of cooperative design situations (Kunze et al. 2012). Therefore, the project builds upon a seamlessly connected hard- and software solution (Schubert 2014). We suggest a hybrid physical-digital interface to incorporate the simulation in a haptic design model (see figure 1). This interface consists of a horizontal touch-sensitive screen serving also as a table. Planning contexts are imported from OpenStreetMap (Petzold et al. 2015). Physical objects (e.g., styrofoam blocks) can be placed on the table and serve as haptic input. A 3D-scanner recognizes these elements and places them in the virtual planning context. Users interact with the table by cutting, deforming, and moving these physical objects as well as via simple touch gestures (Schubert 2014).

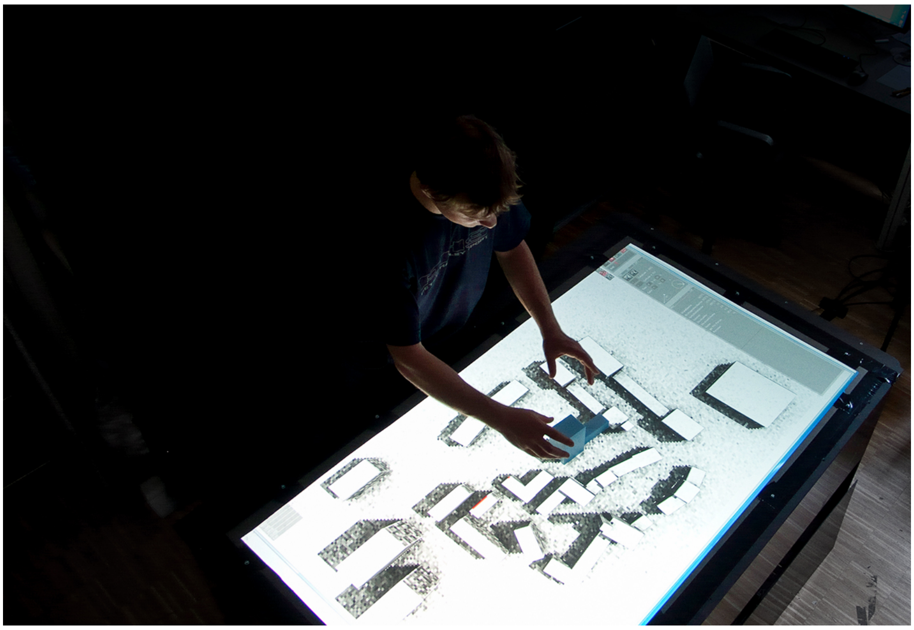

Figure 1. CDP//Collaborative Design Platform - a hybrid digital-physical interface.

3. Prototype development

Early design stages involve the iteration of various design alternatives. Multiple qualitative and quantitative criteria are juxtaposed in open-ended discussions.

Users interact frequently and simultaneously with the design to understand the impact of adaptations on relevant planning parameters. Therefore, design tools have to provide meaningful and immediate feedback. Our prototype aims to support this erratic and dynamic process without disrupting the design flow. Contrasting to conventional PC simulations, we recognize the following criteria:

- **Integration:** The tool must integrate seamlessly into the planning process. It ought to facilitate intuitive geometric modifications. Furthermore, simulation results have to be relatable to the current design. By this, simulation output becomes relevant in the discussion.
- **Interactivity:** The prototype must foster a simultaneous and non-hierarchical interaction and presentation of results. Interfaces must be accessible for all collaborators to support an open and productive discussion. Furthermore, tools must facilitate continuous interaction instead of interrupting the design process with passive calculation phases.
- **Intuivity:** User interactions and the presented results must be comprehensible for non-experts. User-input ought to be effortless and no obstacle in the design flow. The shown information and visualization methods must be chosen carefully to match the conditions of early design discussions.
- **Synchronicity:** To inform dynamic interactions, the simulation has to react directly to user input. A significantly delayed presentation of results disrupts the discussion. Thus, initial feedback must be provided responsively.

3.1. USER INTERACTION

To achieve these goals, we adapt simulation inputs to the described table setup. Collaborators gather around the table and have equal access to the input model. Instead of importing the contextual geometry from a .dxf file, the context is loaded from OpenStreetMap and can be modified during the negotiation process. The interaction with the simulation must be easily understandable, effortless, and synchronous with the design process. To achieve this goal, we elaborate on simplified, intuitive, and continuous interactions.

3.1.1. Reduction to Benchmark-Scenarios

The parameters for sophisticated simulation settings are unavailable in the early design stages or are highly insecure. Thus, replacing the intricate contextual setup of a simulation with predefined ‘benchmark-scenarios’ is a strategy derived from energy evaluation tools in the early design phases (Roetzel 2014, Attia et al. 2012). Hence, we assure that the input does not exceed the level of detail of the early planning stages. Instead of delivering absolute numbers (like evacuation time), the simulation should evaluate crowd-dynamics qualitatively regarding key scenarios. Therefore, the extensive settings are reduced to three cases: *Entrance, Exit, and Stay.* Through these scenarios, the simulation addresses different aspects like efficiency, pedestrian comfort, and safe evacuation. Simulation settings like the setup of agents’ checkpoints and targets are defined by presets depending on the scenarios. Thus, we bypass a time-intensive setup.

3.1.2. Intuitive Interaction with Simulation Objects

Physical objects on the table serve as a haptic interface. They represent simulation objects such as agent-sources, obstacles, and targets. By modifying these elements, users interact with the design and the simulation simultaneously. Each element's color defines its meaning in the design context (see figure 4): Red objects represent entrances and exits. Yellow blocks stand for minor attractions like food stands, blue ones for major attractions such as a festival stage. Simple obstacles are embodied by grey blocks or can be drawn as polylines on the table using hand gestures. An element's size defines its relative importance - the number of spawning or attracted agents. The simulation interprets these objects depending on the selected scenario. During an (emergency) *Exit,* all agents spawn in attractions, from which they move towards the entrance objects. During a *Stay* scenario, entrances serve as both the agents' sources and their final targets, whilst attractions signify intermediary checkpoints.

3.1.3. Continuous Interaction

Classical pedestrian simulations do not facilitate user interactions during the simulation process. Even on a highly performant PC, this simulation process endures from several minutes to hours for large-scale simulations. However, in a dynamic design discussion, the calculations are likely to be interrupted by frequent and unanticipated interactions. An adaptation in the scenario's geometry requires a restart of the simulation: agents are removed and reset to their origin. Therefore, we propose two measures to compensate for this break in the user interaction: continuous simulation and seamless blending.

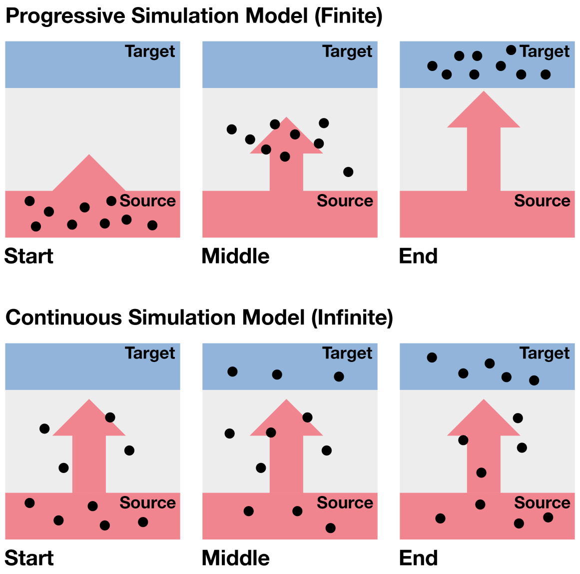

Figure 2. Progressive vs. continuous model.

Continuous Simulation: Classical agent-based simulations spawn a limited amount of agents and terminate when the last agent has reached its ultimate destination (see figure 2). Therefore, the simulation time and the total amount of agents are finite. Thus, users have to wait until agents spread over the simulated area to estimate crowd dynamics far from the agents' sources. Until the impact of a design adaptation becomes visible, agents have to reach this part of the simulation area. To reduce this delay, we propose a continuous simulation model. Agents are spawning and exiting the simulated area infinitely. After a restart, agents are partly generated on the way to their targets. By this, we achieve an instantaneous and constant distribution of agents.

Seamless Blending: The disappearing and respawning of all agents at the start of a simulation represents a problematic break. Therefore, we suggest 'blending' the new simulation seamlessly into the old one by preserving the agents' positions and current targets if possible. Only significant modifications (e.g., removing an entrance) require updating the concerned agents' status. By this, agents generally persist after interactions and even keep moving in the same direction. The initial calculation time of started simulations can be compensated by blending them visually with the terminated one. This method may compromise simulation results initially since the new simulation parameters would not have led to this exact constellation of agents. However, due to the continuous simulation model, this inaccuracy is leveled out while the simulation is proceeding further.

3.2. VISUALIZATION

For a meaningful integration of simulations in planning discussions, results must be intuitively relatable to the design. Being displayed on the table, the simulation augments the design model with an additional information layer. Thereby, the information is well visible for all attendees. To inform tentative design actions, we elaborate on the ad hoc display of adequate simulation results.

3.2.1. Heat Cloud

Differentiated heatmaps and statistical graphs represent simulation results accurately but are hard to interpret for laypersons and are often inappropriate to the level of detail of the early design stages (Attia et al. 2012). Instead of precise numbers (like absolute evacuation time), early and contingent design iterations benefit from 'ballpark figures' to evaluate initial alternatives (Roetzel 2014). Relevant information with respect to our key scenarios *Entrance, Exit, and Stay* is displayed: Problematic densifications have to be highlighted to indicate bottlenecks and overcrowded facilities. Pedestrian comfort and personal distance are also relevant in non-emergency scenarios. Furthermore, the realistic simulation of local crowd dynamics is an advantage of accurate agent-based simulation tools. This simulation output should be presented since it can provide valuable hints about congestion development.

Typical representations for pedestrian simulations are the animation of agents, agents' paths, and heatmaps (see figure 3). The animation of agents directly renders the agents' movements in the simulated environment. This method illustrates dynamic crowd movements clearly. However, it does not display pedestrian densities comprehensibly. Agents‘ paths reveal patterns of crowd movement. Nevertheless, this method does not show if densified paths signify congestions or a consecutive passage. Heatmaps offer great potential for evaluating designs since they highlight problematic areas and differentiate congestion levels. Several types of information can be depicted in heatmaps, such as occupancy, significant congestion, or ’frustration‘ (Kretz 2007). The proposed display methods cover relevant aspects of pedestrian simulations. Nevertheless, switching and meticulously comparing these representations in discussions is effortful and confusing. Therefore, we aim to combine these techniques’ advantages in a single visualization method - an indiscrete *Heat Cloud*.

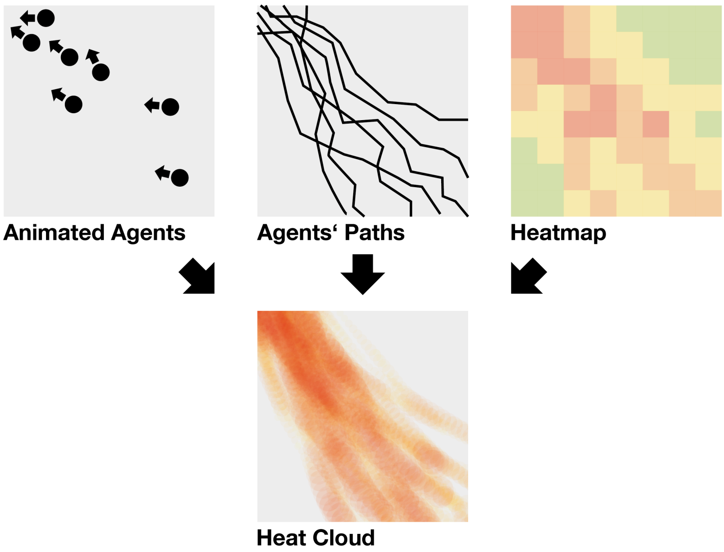

Figure 3. Synthesis of different visualization methods.

As an indicator, we revisit the principle *Level of Service*, derived originally from traffic planning (Oeding 1963, Fruin 1970). This concept distinguishes five *Levels of Service* defined by the available area per agent in relation to their speed - from a free flow of pedestrians to densification to problematic congestion (Bitzer 2010). This principle correlates pedestrian density, comfort, and velocity in ’fundamental diagrams’ (Holl 2016). The agents’ *Level of Service* is evaluated in each simulation step by calculating the average distance to its closest three agents. If the resulting value signifies a problematic density, the agent’s location is added to the *Heat Cloud*. Thus, this map stores one point for every congestion event. The points’ size and hue represent the specific *Level of Service.* By this, it is possible to differentiate between casual and grave congestions. Tracking agents’ congestion levels during several simulation steps also reveals their movement patterns, and the dynamics of congested spots become distinguishable (see figure

4). Since the *Heat Cloud* points are linked to specific agents and localized in the simulation space, it is possible to detect all points affected by a design interaction. By removing and updating parts of the cloud selectively, most of it can stay intact after user interactions.

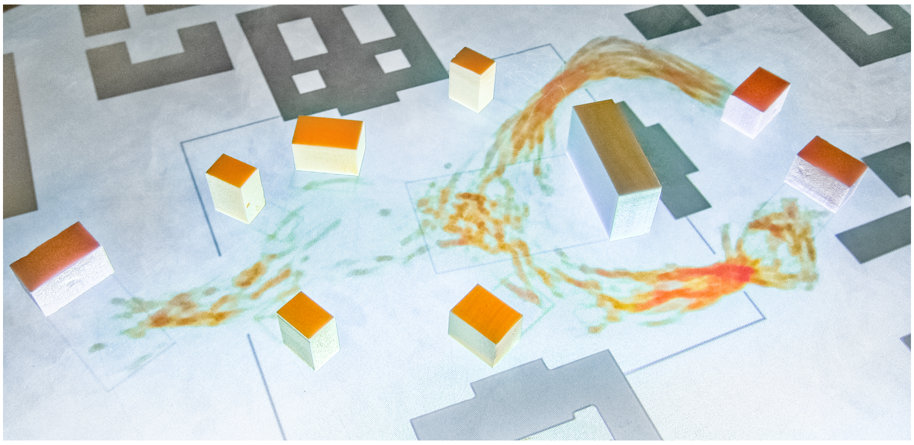

Figure 4. Blocks of different colors and sizes as input, and Heat Cloud visualization.

3.2.2. Responsive, Preliminary Results

Design interactions in the early design stages can be experimental and erratic. Instantaneous feedback is essential to inform design modifications. Thus, results can serve as hints, which support iterative problem solving (Petersen and Svendsen 2010). Since large scale agent-based simulations are computation-intensive, final results are not available instantly. Intermediary simulation output (the agents' movement steps) can be displayed immediately. The *Heat Cloud* grows while the calculation proceeds. Nevertheless, this is not sufficient to give dynamic feedback to design discussions. Therefore, we introduce two types of provisory results (see figure 5). The agents' targets are available at the beginning of the simulation. Afterward, a static navigation field is calculated before the first step of the agents' movement. Based on this data, rough navigation graphs are generated for an initial prognosis of the agents' movement. From these hypothetical trajectories, preliminary points in the *Heat Cloud* are added. The first approximation based on the agents' targets is replaced as soon as navigation fields are available. Afterward, this preview is updated with the final results as soon as they become available. Thus, the simulation immediately responds to interactions with a first preview and approximates final results subsequently.

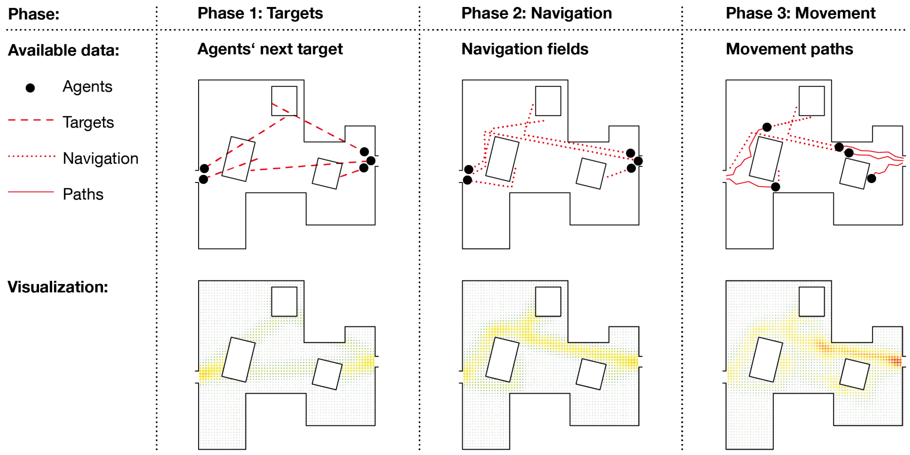

Figure 5. Responsive visualization employing preliminary results.

4. Conclusion

We have presented an approach to introduce advanced pedestrian simulations in the early design stages. By this, designers can optimize pedestrian flows mutually with other relevant planning parameters. Compared to contracting an external enterprise for a comfort and safety analysis, this integrated method is extremely time-efficient. Since the creation and exchange of data-models, the simulation, the preparation of results, and the subsequent evaluation take up to several days, our method represents a significant optimization.

To achieve this integrated solution, we have shown how to embed pedestrian simulation in a collaborative, interactive environment. Also, we have elaborated on user input suitable to the conditions of the early design stages. A haptic, non-hierarchical user interface enables dynamic and simultaneous interactions. The simplification of input-parameters adjusts the simulation to the level of detail of early-stage negotiations. Furthermore, the simulation is adapted to allow the continuous adaptation of the input model. Thus, we embed the user-input seamlessly in the negotiation process. We have presented visualization methods that effectively support the design process by highlighting problematic congestions and displaying crowd dynamics. We achieve responsive feedback by amortizing computation time with the usage of preliminary results. The impact of design adaptations is instantly presented and influences the discussion reciprocally.

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