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Towards Democratizing Human–Building Simulation and Analytics

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Abstract. This work presents a concise summary of the workflows we have developed over time to simulate human-movements and dynamics of human-building interactions. We talk about the applications of human-behaviour simulation in the analysis of building environments. We then discuss the approaches which use dynamic human-aware simulations in improving environment designs. We highlight the challenges in existing simulation workflows, which are usually decoupled from environment modeling tools or often tightly coupled with any specialized modeling platform. Such workflows require significant infrastructure and domain expertise, hindering the users' abilities to seamlessly simulate, analyze, and incorporate dynamics of human-building interactions into their preferred design workflows. We introduce a democratized approach using an on-demand service-based workflow for human-behaviour simulation and analysis of human-building interactions.

Keywords: Crowd simulation · Multi-agent system · Human-building interaction · Computer-aided design · Virtual environment · Built environment · Simulation-as-a-service

1 Introduction

Due to the advent of sophisticated sensing solutions and smart and connected environments, it is now possible for buildings and environments to passively monitor, and actively interact with their human inhabitants. In order for buildings to be resilient in this digital age of smart environments [50], it is imperative to consider how AI techniques and predictive analytics can be used to fundamentally inform the design and management of these spaces while accounting for and leveraging these innovations.

Estimating how an environment design impacts the movement and activities of its prospective inhabitants is a critical aspect in architecture design. It is

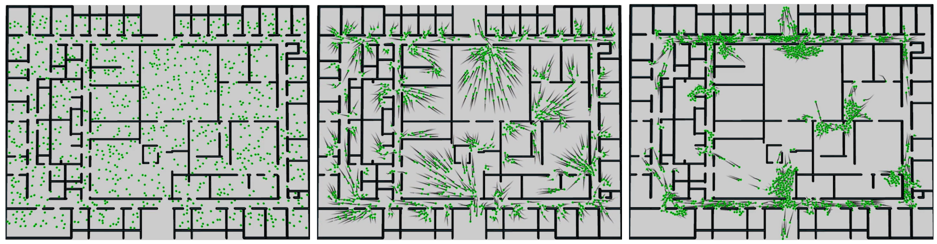

Fig. 1: Egress evacuation of an office environment. Three snapshots are presented in raster order of a real-time simulation of multi-agent navigation with a planning-based steering approach which uses an egocentric field for planning paths, optimized to reduce time-to-destination (e.g., twice as fast as its default configuration and exhibits a less turbulent pattern).

essential to account for human occupancy and behavior in the design and management of buildings and environment spaces. While many established building performance evaluation methods in Computer-Aided Design (CAD) and Building Information Modeling (BIM) tools, such as energy, structure, and lighting, mostly rely on static environment representations. How an environment design will perform for the dynamic movement of people, its spatiotemporal impact on user experience, operational efficiency and space utilization, is mostly left to designers and architects' experience and self-intuition. Predicting and accounting for Human-Building Interaction (HBI) is very challenging if not impossible to do unassisted in built environments.

To this end, we advocate an approach for simulating HBI in semantically meaningful environments. We make use of crowd simulation techniques [23, 32, 43] in mimicking human-like movements in building environments. The simulation of human dynamics, from person-to-person interactions to global-scale transportation networks, affords a plethora of revolutionary predictive and analytical powers across several fields.

In research and industry, crowd simulation has afforded the power to predict and optimize the spaces and processes which drive the modern world. However, crowd simulation techniques present high integration costs into environment modeling pipelines. The early solutions developed required expertise in a particular simulation platform and present sophisticated technical and workflow challenges, such as loading building geometries, annotating buildings with space semantics, configuring crowd parameters, generating simulation results, and visualizing spatiotemporal data maps of space utilization.

In this work, we focus on the applications of human-behaviour simulation in the analysis of HBI, and how these predictive and analytical powers have and can be democratized. The use of democratization in the context of technology has and does largely refer to the increase in access to sophisticated technologies. In general, this means the expansion of a technology's user base and its associated information production. That is, the ability for a wide range of users, primarily non-experts to participate in the modification, use, and extension of specialized knowledge, techniques, and tools which transform or produce information or material. In this work, we focus on the use of a broad set of techniques, algorithms, and systems centred around human-movement and behaviour simulation. We then introduce an on-demand service-based platform and approach for removing or abbreviating the underlying barriers associated with big data production and analysis in the dynamic context of human movement simulation and its myriad uses, not limited to: virtual environment analysis, predictive architectural design, predictive urban design & planning, accessible design & accessibility analysis, safety critical analysis, and forensic analysis of disasters. The proposed platform provides exploratory and comparative analysis of HBI in semantically meaningful environments through informative visualizations in an interactive work-space.

The remaining sections of this chapter talk about our work in human-movement and behaviour simulations, HBI, the use of behaviour simulations to analyze and improve environment designs, and lastly the proposed democratized workflow for the analysis of HBI, in more detail.

2 Human–Movement & Behaviour Simulation

Human movement and behaviour simulation have a long and rich history in the literature [23, 32, 43, 1, 31]. The area is split among a few approaches. First, methods are largely either agent-based or cellular-automata. In this work, we focus on high fidelity agent-based models as they promise to capture high-fidelity phenomena at the microscopic and mesoscopic scales. Next, agent-based models are largely broken into several areas: physical force-based methods; geometric optimization-based methods; field-based methods; data-driven methods; planning methods; and machine learning methods. However, no list is exhaustive as the area of research is very active. In this section, we will touch on two particular areas which move away from expertly defined or ad hoc rules and toward high fidelity representation of humans–planning and machine learning methods. These methods either seek to solve for agent actions within target constraints or to learn policies from simulations and data.

Evidence for Fidelity and Diversity Recent work has shown that single-particle methods, of which much of the human movement and behaviour simulation literature is composed of have many drawbacks. In particular, the biomechanical modelling is extremely important, as stepping used in bipedal locomotion of humans is neither linear or consistent across scenarios [39]. Most recently, it has been shown that modelling heterogeneous walkers at the footstep level impacts crowd behaviour and quantitative outcomes [18]. That is, diversity in mobility has a significant impact on simulation results. These results provide significant motivation toward the planning and machine learning approaches to human behaviour simulation.

Planning-based Methods Planning-based methods typically take into account additional information to produce high fidelity short-term plans which resolve steering and collision avoidance behaviours. Often this information is biologically inspired. For example, an egocentric field of attenuating resolution can be used as the basis for planning paths, similar to how vision can be used in biological navigation [24]. Additionally, assuming not all situations require the same type of steering decisions, methods can be composed of several steering possibilities which are then integrated as a singular plan [40]. Very high fidelity movement behaviours can be generated by moving beyond the single-particle linear time-step movements of prior models. By representing movement as the inverted pendulum of human bipedal walking, space-time plans of several steps can be found which solve the steering behaviour problem[41, 5]. That is, instead of making instantaneous movement decisions as the simulation updates, the model can plan any number of steps ahead, more akin to how humans navigate. These methods can be extended to model people with interesting, or non-normative gaits, such as patients post-stroke [18].

Learning-based Methods More recently, machine learning methods have been proposed to alleviate the need for expert or ad hoc rules and control paradigms used to produce movement and behaviour simulation previously. Vector Quantization has been used to model multi-agent pedestrian navigation [27]. Similarly, preliminary work has shown to successfully simulate small groups of navigating agents [7, 8]. A set of models have shown that this problem is both tractable and scalable [30, 28]. However, this approach requires scenario-specific training to converge on expected emergent behaviours. Reinforcement learning (RL) has been shown to map particularly well to the agent movement simulation problem both conceptually and in practice [29, 44]. Models have learned continuous actions using a curriculum training approach, like prior expertly defined models [26]. However, these methods must overcome several hurdles related specifically to the Multi-Agent RL (MARL) problem, most serious of which is the non-stationary problem–the issue of learning updates among agents invalidating prior observations between those agents. More recently, the MARL problem, rules definition, and simplified underlying model representation have been address through multi-agent hierarchical reinforcement learning (MAHRL). This approach separates low-level skills related to locomotion form high-level skills like navigation and uses a biomechanically inspired action representation (footstep plans) to communicate between levels [3]. Figure 1 shows a simulation of multi-agent navigation for a planning-based approach which uses egocentric fields to plan navigation paths.

3 Modeling Human-Building Interactions

The maturity in modeling human movements and behaviours (Section 2) facilitates the investigation of how the design of semantically meaningful environments impacts the movement and occupancy of its inhabitants, and is a precursor

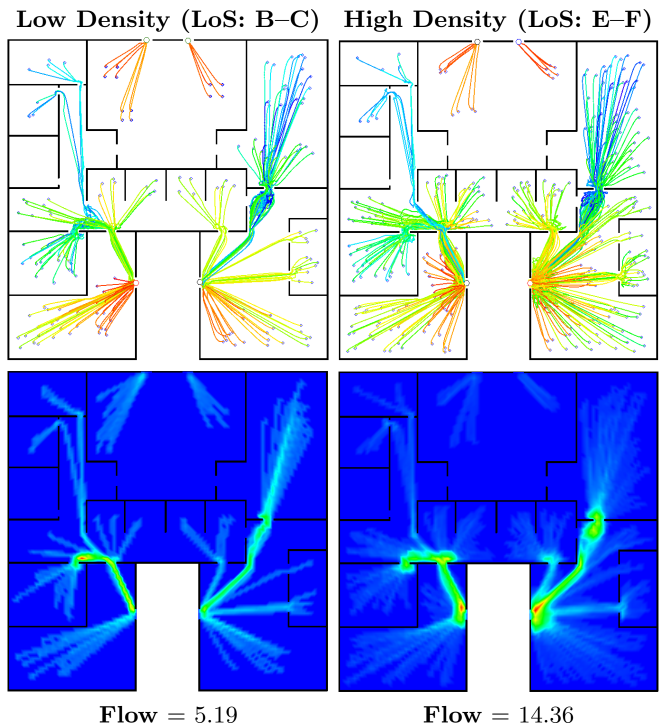

Fig. 2: Showing crowd-aware analytics for different crowd occupancy levels. Each column maps a different crowd occupancy level (e.g., Level of Service). Top row shows the color-coded crowd trajectories based on evacuation times (**T**) and traveled distances (**D**). The trajectories in *Red* show shorter traveled distances and evacuation times. Trajectories in *Blue* show longer distances and evacuation times. Average crowd flow values (**F**) for egress (i.e. occupants/second) are also shown. Bottom row shows crowd density heatmaps with high density in red (problematic areas – e.g., bottlenecks) and low density in blue.

to informing the design of buildings with respect to human-centric performance criteria [36].

3.1 Wayfinding in Complex Environments

One of the most important functions of a building is its ability to inform how people can find their way in the building and is one of its prominent performance indicators. There are many aspects of the design of a building which contribute to human wayfinding such as its architectural complexity, the design and placement of signage etc. Our research examines building models to investigate these aspects. We have conducted a study to investigate the effects of cues in the immediate environment and from other people on decision-making of human subjects during navigation through a virtual airport terminal. We observed that environment layouts with no visual cues led to shorter decision times and higher navigation accuracy compared to layouts with visual cues [54]. We have developed a biologically inspired computational model of human-signage interaction based on information theory. Our model allows for greater flexibility to modeling agent-signage interaction by adding different types of noise with respect to the environment (e.g., layout complexity, crowds, and other distractions), signage (e.g., multiple information clusters, visual salience), and agents (e.g., attention, reasoning, memory) [13]. We have developed a computational framework to automatically identify indoor landmarks for building models based on a navigator's pattern of locomotion. We formalized our landmark identification process as a hierarchical multi-criteria decision-making problem grounded in human information theoretics. We validated our framework with a controlled virtual reality (VR) experiment to compare the most salient landmarks obtained from eye-tracking data and our framework [12]. Using the frameworks in [12, 13], we have developed an automated approach to extract wayfinding decision points from a 3D building model to serve as the basis for estimating the wayfinding complexity of the environment layout. We then used agent-based simulations to interactively optimize the placement of signage within environment design to improve wayfinding [11]. We have developed a framework to procedurally generate arrival and destination locations and times for virtual agents in large complex facilities (e.g., train station, airport, etc.). Our framework is expressive enough to generate the wide variety of crowds seen in real urban environments while maintaining the realism required for the complex, real-world simulations of a transit facility [34].

3.2 Integrated Modeling of Individuals, Crowds, and Building Semantics

In order to account for human-building interactions, one of key components is to be able to generate plausible "narratives" of human crowd behaviours that integrates individual motivations, desired behaviours of human movements and interactions, and semantics of the environment space. To this end, we have developed a natural language style interface to author collaborative and context-dependent virtual crowd behaviours in a given building environment to get insights on the mutual interactions between the people and the environment they inhabit [51]. We have also developed workflows (Figure 3) to author complex multi-agent behaviour narratives to satisfy time-varying building occupancy specifications and agent-level behaviour distributions using a prioritized resource allocation system to improve decision-making in designing a building layout. Such approaches can be used generate progressively more complex and plausible narratives that satisfy spatial, behavioral, and social constraints to modeling more realistic human-building interactions. We also presented a case study to highlight the effectiveness of this approach to seamlessly author behaviour narratives that can be used for visualizing, analyzing and communicating how buildings may be used by their future inhabitants [53, 52].

3.3 Joint Modeling of Human-Building Interactions

It is important to consider the phenomenon like change in temperature with the presence of humans and propagation of sound cause by their movements, in an effort to jointly model the interaction between a building and the resulting behaviour of its inhabitants. To this end, we have developed a multi-paradigm approach to model event-based simulations of dynamic human-behaviours in a building environment, which accounts for ecological conditions such as temperature changes, acoustics, sound propagation, human occupancy, and other en-

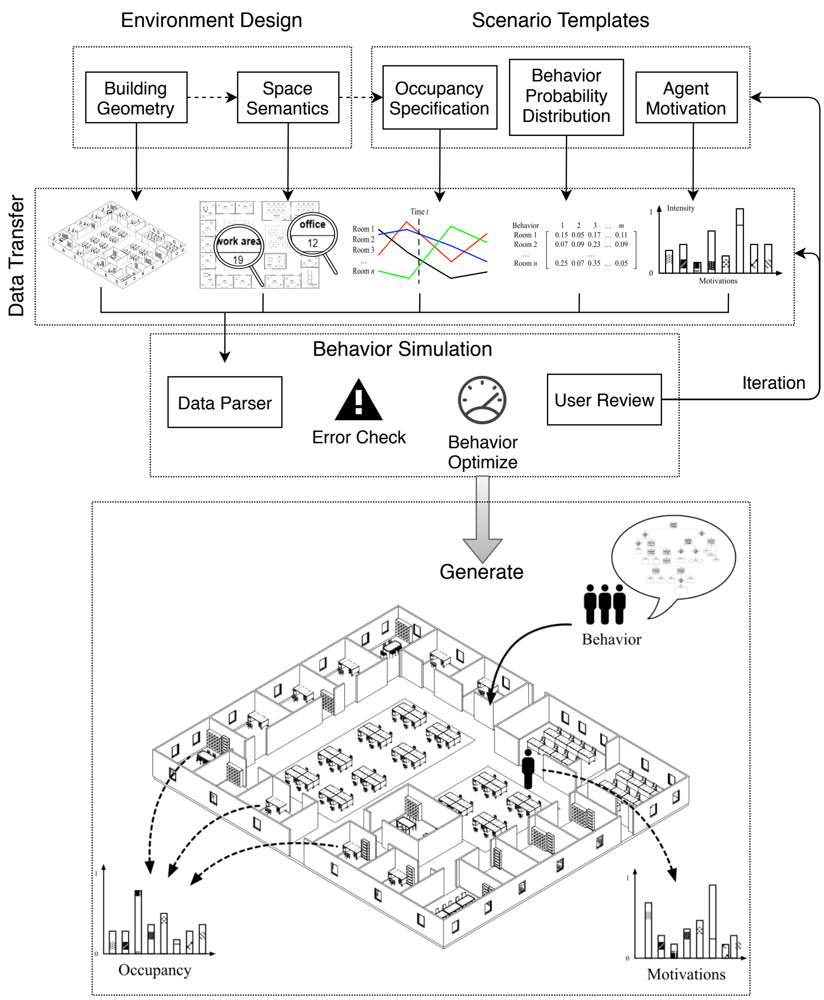

Fig. 3: A multi-constrained authoring of occupant behaviour narratives that accounts for building-level occupancy specifications, zone-level behavior distributions, and occupant-level motivations.

vironmental and occupancy phenomena that unfold at different time scales [37, 38]. We have developed a node-based representation to jointly parameterize different spatial and human behavioural parameters to model human activities and interactions in a building design [49].

3.4 Machine Learning for Human-Building Interaction

The use of advance machine learning techniques allows to learn data-driven models to predict hard-to-interpret and complex factors governing human behaviour such as the amount of time it would take a crowd to evacuate a building, without needing to run prohibitively expensive crowd-based simulations. We have developed a general imitation model to imitate the movement of expert agents in highly dense crowds. We trained our model using different learning techniques (e.g., Behavior Cloning and Generative Adversarial Imitation Learning) on a set of domain scenarios with diverse characteristics. The empirical results revealed that the simpler behavior cloning method is overall better than the more complex reinforcement learning method. In addition, the results also indicated that training samples with diverse agent-agent and agent-obstacle interactions are beneficial for reducing collisions when the trained models are applied to new scenarios [33]. We have developed an optimization framework to learn and understand relationship between environment layout and crowd movements. Our framework automatically determines the optimal environment configuration for a new layout without rerunning expensive crowd simulations [21]. The workflow we have developed in [42] present an instant prediction approach to predict the movement flow of crowds in large-scale realistic building environments without running new crowd simulations. We also presented a case study to evaluate the prediction results of our method with respect to ground truth.

4 Analysis and Optimization of Environment Designs using Human-Behaviour Simulations

During an environment design process, architects and game-level designers have to examine a vast set of solutions to identify efficient parameters which would increase the design performance by following given set of constraints [22]. Examining each solution iteratively, however, is time consuming, and perhaps less efficient [35]. To help designers with these challenges, we have developed computer-aided design (CAD) tools which allow a predictive analysis and evaluation of built-designs' performance [52].

The majority of early CAD methods were limited to performing static computations of quantitative metrics for evaluating environment-design performances. Modern techniques can now also produce optimal and efficient environments due to the advancements in optimization methodologies and computing powers. We categorized them into static and dynamic workflows (e.g., as discussed in [46]). Some of these advanced approaches utilize spatial configurations of built-designs (e.g., Space-Syntax), which relates to a constructive relation between society

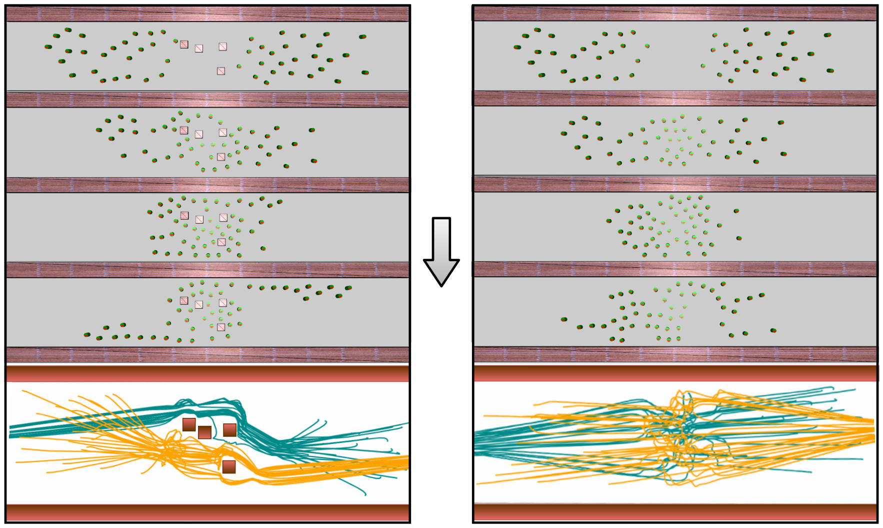

Fig. 4: Snapshots in raster order of two-way crossing scenario where two groups of agents move in opposite directions. The placement of pillars (left) at optimal locations improves the movement flow for both groups compared to the case without pillars (right).

and a built-design. Measures like visibility, accessibility and organization of a built-space from such configurations are static in nature and tend to correlate with human spatial behaviors [2, 20, 45]. Other approaches are more dynamic and utilize crowd simulations [23, 32], to account for how humans would act and interact with built-designs. Measures like pedestrian flow, evacuation time, and travel distance from such approaches directly relate to HBI.

4.1 Integrated Computer-Aided Design Tools

We have developed several tool for environment analysis and optimization. We showed that optimization processes could produce the placement of architectural elements (e.g., doors and pillars) using human behavior simulations to improve pedestrian flow for not-yet-built environments [16, 15, 6, 14] (Figure 4). We developed a user-in-the-loop approach to maximize the movement flow of occupants by optimizing the position of architectural obstacles in an Adaptive Mesh Refinement Approach [17]. We developed an environment optimization framework to automatically find optimal egress routes in a not-yet-built environment using human behavior simulations for safety-critical analysis and optimization [9]. Using another approach, we developed an analysis tool which allow architects and designers to analyze their designs with measures from Space-Syntax, as well as using dynamic human behaviour simulations [47]. Expanding on this approach we developed a human-centred AI approach that uses interactive optimization to analyze designs with measures from Space-Syntax, and yield a diverse set of design recommendations for the users to choose from [4] (Figure 5). Most recently, we have developed approaches [19, 10] which closes the loop between designers, stakeholders, and community by crowd-sourcing environment floorplans from community by re-imagining the design process in a multiplayer game setting, Figure 6.

4.2 Parametric Workflows

We have developed node-based frameworks using mainstream architecture modeling tools to parameterize environment and human-behavioral parameters for modeling human activities in not-yet-built environments. We showed occupants' trajectories and density heat maps for human-building interactions as analytics for designers and architects [49] (Figure 2). Using the work in [49], we presented a case study to investigate joint parameter exploration and sequential parameter exploration workflows to identify optimal set of environment and human-behavioral parameters in a not-yet-built environment space [48].

5 A Single Platform to Human-Behaviour Simulation and Analysis for Virtual Environments

Running a human-behaviour simulation (e.g., using crowd simulation) in a real-scale complex environment setting, however, presents high integration costs into environment design pipelines. Prior solutions require expertise in a particular human simulation platform and present sophisticated technical and work-flow

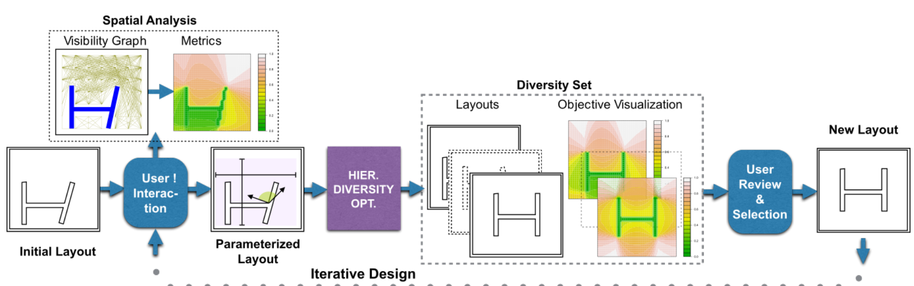

Fig. 5: With an initial environment design, the user specifies permissible alterations to the layout as bounds on the degree to which different environment elements can transform. The user then specifies one or more focal regions in the environment for which different spatial measures are computed, to quantify visibility, accessibility, and organization of the space. A multi-objective hierarchical diversity optimization produces a set of diverse near-optimal solutions concerning user-defined optimality criteria, from which the user may select one and repeat the process as desired.

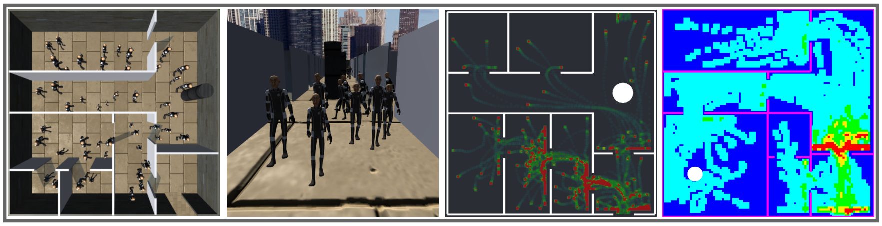

Fig. 6: Crowd-sourcing the environment floorplan from community by re-imagining the design process as a gamification approach, allowing game users to rapidly iterate on their designs while soliciting feedback from computer simulations of crowd movement and the designs of other players.

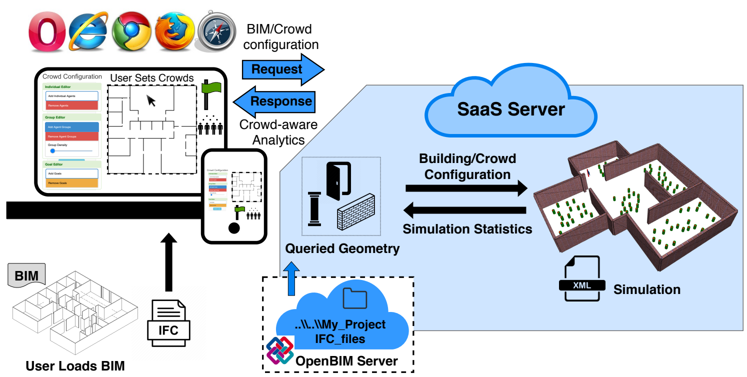

Fig. 7: A service-based cross-platform framework to simulate the dynamics of human-building interactions. It allows users to upload their environment models, set up human-behaviour parameters, runs the simulation and analyzes spatial visual and quantitative feedback for their environment designs.

challenges, such as loading building geometries, annotating environments with space semantics, configuring human-behaviour parameters, generating simulation results, and visualizing spatiotemporal data maps of space utilization. In addition, previous approaches have mostly been developed either as standalone systems or integrated in some particular environment design platform, limiting users' abilities to human-aware design of environments.

The goal is to democratize human-behaviour simulation and analysis of environments and have a single, integrated platform for researchers and industry experts from across disciplines to share environment models, analyze environments for human-behaviour simulations, crowd-source collaborative human-aware environment designs, and share simulation-driven analytics for environments with other users.

In this regard, we propose to use a cross-platform design-domain agnostic integration of dynamic human-behaviour simulation and analysis into environment design pipeline. To address the aforementioned challenges, we propose to adopt a Software-as-a-Service (SaaS) 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 [25]. It has several advantages both as a business model, but also for its users. 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 processes (Figure 7).

We posit that such a platform would foster communication among design stakeholders across different disciplines. It would minimize the required expertise and hardware/software infrastructure dependencies for human-behaviour simulation analyses thus enabling the design of environments that are cognizant of the behaviour of the inhabitants in real-world conditions to ensure safety, productivity and satisfaction of the inhabitants.

6 Conclusion

We have developed an end-to-end workflow the use of human-behaviour simulations in the analysis of virtual environments. We discuss the use of a broad set of techniques around human-movements and behaviour simulations to produce effective predictive and analytical tools. We then highlight the limitations for such tools in terms of limited user base as they require special expertise and certain hardware/software infrastructure to be used. Finally, we introduce a service-based cross-platform approach for removing the underlying barriers associated with traditional human-building interaction approaches, empowering it to be used in the dynamic context of human movement simulations and its myriad uses, not limited to: virtual environment analysis, predictive architectural design, predictive urban design and planning, accessible design and accessibility analysis, safety critical analysis, and forensic analysis of disasters.

Acknowledgements

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