JOIN: An Integrated Platform for Joint Simulation of Occupant-Building Interactions

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Several approaches exist for simulating building properties (e.g. temperature, noise) and human occupancy (e.g. movement, actions) in an isolated fashion, providing limited ability to represent how environmental features affect human behaviour and vice versa. To systematically model building-occupant interactions, several requirements must be met, including the modelling of (a) interdependent multi-domain phenomena ranging from temperature and sound changes to human movement, (b) high-level occupant planning and low-level steering behaviours, (c) environmental and occupancy phenomena that unfold at different time scales, and (d) multiple strategies to represent occupancy using established models. In this work, we propose an integrated platform that satisfies the aforementioned requirements thus enabling the joint simulation of building-occupant interactions. To this end, we combine the benefits of a model-independent, discrete-event, general-purpose framework with an established crowd simulator. Our platform provides insights on a building's performance while accounting for alternative design features and modelling strategies.

Keywords: multi-agent system; multi-timescale representation; crowd simulation; general-purpose simulator; discrete-event paradigm; environmental phenomena; building occupancy.

1. Introduction

A multitude of simulation tools has been developed to model specific building performance criteria. Examples include Radiance (Ward, 1994) for lighting, MassMotion (Morrow 2010; Morrow et al. 2014) for occupant movement, and EnergyPlus (Crawley et al. 2001), DOE-2 (Curtis et al. 1984), or ESP-r (Aasem et al. 1994) for whole building energy simulation. However, although many factors influencing buildings are interdependent, they are typically analysed in isolation mainly due to the development cost associated with integrating different solvers (Goldstein & Khan 2017). Energy simulators, for example, provide a high-level representation of occupants' presence and actions without representing occupant movement. Crowd simulators, instead, represent low-level occupant movement while ignoring how high-level actions may affect energy consumption.

This research aims to make integration efforts more systematic and commonplace so that building-occupant interactions can be analysed in a more scalable and practical way by architects, engineers, and building scientists. To this end, we present JOIN, an integrated platform which combines some benefits that distinguish it from existing approaches, such as the modelling of (a) coupled, multi-domain environmental phenomena such as temperature changes, sound propagation, and occupancy, (b) occupant decision-making including high-level planning and low-level steering behaviour to avoid static and dynamic obstacles, (c) environmental and occupancy phenomena that unfold at different time scales, and (d) different strategies to represent occupant behaviour using established models. Towards this goal, we leverage and build upon established solutions in these disciplines, including a model-independent general-purpose framework and established steering simulator.

This framework significantly extends prior work on a preliminary prototype for a multi-level and multi-paradigm occupant simulation platform that combines a model-independent general-purpose framework and established steering simulator (Schaumann et al. 2019). Specifically, we fundamentally broaden the scope of the approach by extending the platform capabilities to support diverse models of human movement using attraction and repulsive forces (Helbing and Molnar 1995) and a more complex biomechanically-based model of footstep selection (Singh et al. 2011b). Additionally, to demonstrate the interdependence between occupant behaviour and environmental phenomena, we integrate an acoustic simulator that is coupled with the biomechanical model of footstep selection so that the noise generated by occupant footsteps can be calculated and visualized. Finally, we discuss various insights enabled by different platform applications to test the impact of building design features on noise propagation and occupants' experiences and the effects that different movement simulators produce on the simulation results.

We argue that a more systematic and commonplace integration among different simulation approaches could potentially enable in-depth analyses of occupant-behaviour interactions that span across research domains and hold promise to lead to better solvers as well as more efficient, sustainable and human-centred environments.

2. Related work

Systemic efforts to integrate simulation models fall into two main categories: co-simulation, and the use of model-independent simulators. Both of these approaches strive to keep the various simulation models largely separated from one another even though they exchange information during a simulation run.

Co-simulation provides a tractable way to couple multiple existing simulators, which can run in parallel and exchange information. It can be implemented by enabling one simulator to control the others (Janak 1997) or by developing a new program to control all the simulators. Wetter (2011) introduced the Building Controls Virtual Test Bed (BCVTB), a co-simulation environment linking an assortment of building simulation tools, including EnergyPlus, Radiance, Modelica, and others. Hong et al. (2016) developed a modelling tool which enables co-simulation with building energy modelling software using an occupant behaviour functional mock-up unit (obFMU) and a functional mock-up interface (FMI). While co-simulation appears to be the most popular approach for integrating building simulation approaches, it often requires the modification of existing simulators to send and receive information and to be controlled by another program.

A general-purpose, *model-independent simulator* is a program that initiates the different simulation phases and advances simulated time without explicitly referencing any code representing a real-world process (Goldstein et al. 2013). It thus enables the implementation of models using a common interface, allowing them to be combined and coordinated by a single generic simulator (Vangheluwe et al. 2002). Examples include Ptolemy II, Modelica, and the TRNSYS kernel. The main advantage of these approaches is that they alleviate some of the difficulties involved in coupling different models. However, they require developers to embrace a common set of modelling conventions, which can be perceived as restrictive or overly complex. Modelica, for example, emphasizes the use of equation-based modelling, which is unfamiliar to many programmers and may not be suitable for all types of models. The TRNSYS kernel is limited in that it does not support variable time steps, complicating the integration of behaviour patterns that unfold over different time scales or feature irregular intervals of simulated time.

To address this issue, Goldstein et al. (2018) introduced Symmetric DEVS, a set of conventions that can be used as a basis for a model-independent simulator. Symmetric DEVS builds upon building performance simulation (BPS) modellers' familiarity with certain programming techniques, namely conventional procedural programming, which uses familiar "if-then-else" statements, and dataflow visual programming, a popular technique supporting parametric design (Woodbury 2010). Symmetric DEVS incorporates procedural and dataflow programming into the Discrete Event System Specification (DEVS) formalism, known for its generality, relatively minimalistic set of conventions, and ability to represent any time-varying system (Zeigler et al. 2000).

Previous work demonstrated the ability of a DEVS-based simulation approach to capture the two-way interaction between human behaviour and building thermodynamics (Goldstein et al. 2014) using newly developed models within the DEVS framework. To represent a wider range of multi-modal building-human interactions spanning from human movement and thermodynamics, Schaumann et al. (2019) integrated a multi-model crowd simulation framework within a general-purpose framework implementing Symmetric DEVS. The prototyped platform supports a multi-level and multi-paradigm representation of occupancy phenomena that unfold at different levels of abstraction and at multiple time scales.

In this work, we leverage and extend upon the previously developed prototype to demonstrate how different human movement and environmental models exhibiting different behavioural patterns can be inserted or substituted into an evolving composition of interacting solvers.

Among the wide range of occupancy behaviour models currently developed, which are widely covered by Yan et al. (2015) and Gaetani et al. (2016), we specifically focus on *planning* behaviours, which capture high-level decisions governing which spaces occupants inhabit and what actions they perform, and *steering* behaviours, which represent low-level movement decisions. Both types of models are often represented using different time scales.

Planning behaviours are often modelled with a discrete-event approach, where time advances only when changes happen. In these models, each occupant can be treated asynchronously with respect to simulated time, so it remains in its current state until the next event occurs, where a decision-making process is initiated (Goldstein et al. 2011; Zimmermann 2010).

Steering behaviours are most naturally modelled using a discrete-time approach, where time advances at fixed, continuous steps. Some of these approaches capture human movement at a very fine level of abstraction; an example is the work of Kapadia et al. (2015), which accounts for individual footsteps. Other works employ coarser approximations of the human form and strive to support large crowds (Hesham and Wainer 2016).

Our interest lies in the pursuit of a general-purpose platform where complex, yet scalable occupant models can combine the above-mentioned features to capture a variety of multi-level and multi-timescale occupant behaviours and building features in a tightly coupled fashion. An adaptive time-scale approach would enable coupling discrete-event multi-agent models used for high-level planning decisions with discrete-time crowd simulation models used for low-level steering. Additionally, it could enable the coupling of detailed movement simulations with both slow-paced thermal simulations and high-paced acoustic simulations to provide an integrated representation of multi-domain phenomena at multiple timescales.

3. A platform for joint simulation of occupant-building interactions

3.1 Overview

We prototype JOIN, an extensible and multi-purpose platform that supports joint modelling and simulation of the mutual interactions between building phenomena and occupant behaviour. The platform supports the following features:

- *Joint modelling* of multi-domain phenomena ranging from temperature changes, noise propagation, human movement and behaviour that are tightly coupled, since one affects the other. Thermal and acoustic discomfort, for example, may cause an occupant to change their location or operate a building system, which, in turn, may affect the environmental conditions in a given space.

- *Multi-level* decision-making that considers both high-level planning decisions as well as low-level steering behaviour. Our approach combines both methods to capture a full range of occupancy scenarios that influence (and are influenced by) environmental conditions, such as temperature and noise.
- *Multi-timescale* modelling where time advances at discrete-time intervals or discrete events. The first method is convenient to approximate the behaviour of continuous variables, such as the temperature of a building or the movement of the occupants. The second method is useful to model occupant actions (e.g. activating a building system or identifying a destination to visit) and building phenomena (e.g. the sound produced by an occupant's footsteps) that take place at irregular time-steps. The benefits of adopting a multi-timescale representation include preventing (a) loss of time precision, since event times may not align with the prescribed time step; (b) redundant calculations, since decisions may end up being re-evaluated at every time step rather than when necessary, and (c) difficult integration of multiple models and simulation approaches, since no one time step is optimal for all solvers (Haldi and Robinson 2009; Parys et al. 2011).
- *Multi-model* representation of occupant movement and behaviour that capture building-human interactions at different levels of detail which may be appropriate for the simulation purposes. Different simulation models may be more or less appropriate to represent occupant behaviour in specific contexts (Kapadia et al. 2011; Gaetani et al. 2016).

Our work leverages and builds upon an existing general-purpose simulation framework called SyDEVS and an established steering simulator, named SteerSuite.

3.2 SyDEVS: A general-purpose modelling framework

SyDEVS is an open-source modelling framework that employs a node-based workflow to simulate domain-agnostic processes (https://autodesk.github.io/sydevs/). The framework is based on the Symmetric DEVS variant of the Discrete Event System Specification (DEVS) formalism, which provides a set of conventions for representing essentially any discrete event system (Zeigler et al. 2000). The rationale for using DEVS is to support a modular and hierarchical approach to model development while ensuring both discrete-event and discrete-time advancement patterns are accommodated.

The nodes used in SyDEVS can be of two types: *function* nodes or *simulation* nodes (Figure 1). *Function* nodes model a single function that reads a set of input values and calculates a set of output values, which in turn can be used as input for a different node. *Simulation* nodes represent a process that unfolds over simulated time. They handle (a) *Initialization Events* invoked once at the beginning of the simulation; (b) *Unplanned Events* invoked every time a message is received from other nodes at irregular times; (c) *Planned Events* scheduled by the node; (d) and *Finalization Events* invoked once at the end of the simulation process. Simulation nodes can be organized in hierarchical compositions forming *Collection* nodes that contain any number of instances of an atomic node or *Composite* nodes that contain networks of other nodes, thus forming a hierarchy.

Different types of simulators can be encapsulated within SyDEVS nodes to create modular, hierarchical and extensible data workflows which operate at multiple time scales (Goldstein et al. 2017). Thanks to this feature, models requiring dramatically different levels of time precision (e.g. seconds, days, femtoseconds) can be linked together and allowed to interact, thus supporting an integrated environment for conducting joint simulations of multi-domain phenomena.

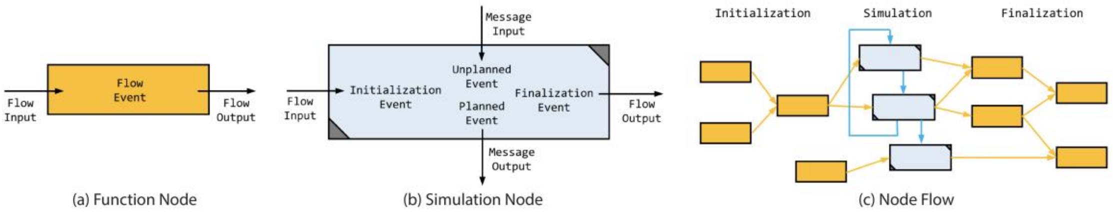


Figure 1: SyDEVS Nodes

3.3 SteerSuite: A framework for modelling occupant movement

SteerSuite is an open-source framework for simulating multi-agent navigation and steering in built environments (http://steersuite.eecs.yorku.ca/). It includes the infrastructure required to run multi-model steering algorithms, namely a simulation engine, planning functionalities and classes to read and write simulation recordings, a visualization system for real-time or pre-recorded simulations in 3D environments, and a built-in module to analyse the simulation results with respect to a set of customary or user-defined benchmarks (Singh et al. 2011a). It both facilitates the development of new steering algorithms or the use of existing ones, including the Social Force model, which computes attractive and repulsive forces for resolving collisions between interacting agents in dense crowds (Helbing and Molnar 1995), and Footsteps, a biomechanically-based approach that models an occupant's centre of mass and footsteps (Singh et al. 2011b).

3.4 Integrated platform for joint modelling of occupant-building interactions

The proposed platform couples the functionality of SyDEVS and SteerSuite to define an integrated framework for modelling multi-domain building-occupant interactions. Specifically, we have used SyDEVS to create a node composition that simulates the interaction between building temperature and occupant behaviour at different levels: a high-level decision-making node determines the occupant response to thermal conditions, while a low-level occupant movement node coordinates occupant steering as it moves through the built environment while avoiding static and dynamic obstacles (e.g. other occupants). In this example, the building features and high-level occupant decisions are modelled using SyDEVS. Instead, low-level occupant behaviour is modelled using SteerSuite, which has been encapsulated within a SyDEVS node. Different from a co-simulation approach, SyDEVS provides a common interface allowing different simulators to be combined and coordinated by a single model-independent framework.

Figure 2 shows an overview of the platform using the SyDEVS notation, which adopts visual layout conventions similar to those developed by Maleki et al. (2015). A SyDEVS composite node contains the following data workflow. In an initialization phase, a series of function nodes specify building and occupant parameters including a building's geometry, external weather conditions, occupants' initial movement targets, speed, direction, and a temperature threshold which, if passed, triggers a high-level occupant decision about where to move next.

These parameters are used as input for a *simulation* phase, where a combination of atomic nodes (connected through an event messaging system) represent joint building-occupant interactions. In this prototype, a "weather" node calculates the outdoor temperature and communicates it to a "thermodynamics" node, which calculates the indoor temperature, while accounting for the occupants' latent heat, modelled in a "heat source" node. The indoor temperature is then perceived by the occupants thanks to a "comfort" node.

The temperature perceived as well as a temperature threshold defined for each occupant inform a high-level “occupant planning” node, which compares the perceived temperature with an occupant tolerance threshold. If the threshold is passed, the agent is assigned a movement target randomly selected from a user-defined target list. In this node, a discrete-event approach is used, since occupants’ decision-making is triggered at irregular times, only when thresholds are passed. While this node could be modelled as a collection of individual decision-making nodes (one for each occupant), in this prototype we implemented a centralized decision-making node that facilitates the coordination between multiple occupants, as demonstrated in other multi-agent approaches (Schaumann et al. 2017).

The selected occupant’s movement target is then communicated to an “occupant steering” node, which coordinates occupants’ movement using SteerSuite core functionality. While discrete events are used to initiate occupants’ movement as a result of a sporadic decision-making process, in this node, a discrete-time approach is appropriate to continuously re-evaluate the state of the world and adapt the movement of occupants to prevent collisions with static objects as well as other occupants.

The updated occupants’ positions are fed back to the previous nodes, which can thus update the indoor temperature and comfort levels, and check whether each occupant’s temperature threshold is passed.

A “building viz” node collects input from the “thermodynamics” and “occupant steering” nodes to visualize occupant movement and the building temperature over time using SteerSuite functionality. In a *finalization* phase, simulation data is analysed to represent aggregated movement data in the form of traces, and temperature data in the form of heat maps.

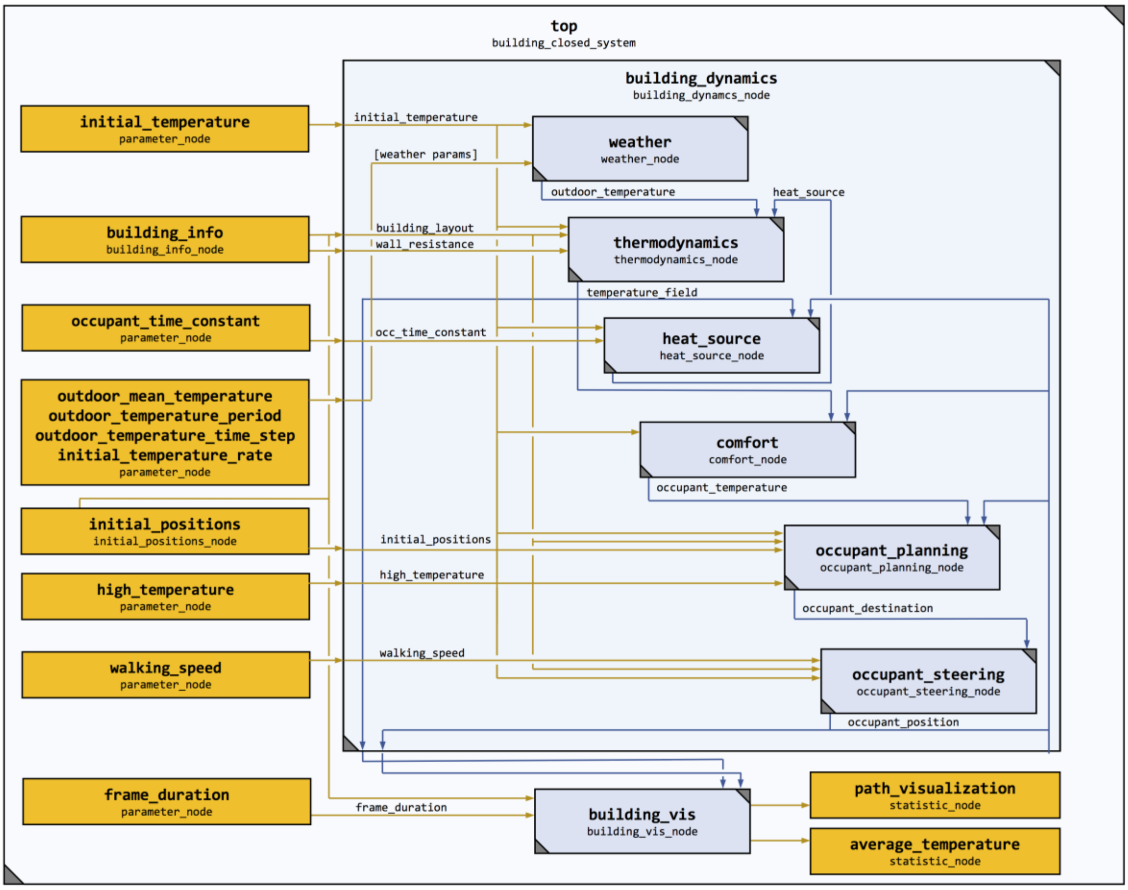


Figure 2: Platform overview represented through SyDEVS nodes that enable a joint representation of building features and occupant behaviour

4. Demonstration of the platform features

We detail a series of studies that demonstrate the platform features previously outlined in Section 3.1. As a testbed, we have used an abstracted floor plan of the Autodesk offices in Toronto. Even though the building is equipped with sensors that measure environmental features, in this work we demonstrate the capabilities of the platform, independent of data collected in this specific site. We leave context-dependent calibration efforts for future work.

4.1 Joint Multi-Level and Multi-Timescale Simulation of Environmental Temperature and Human Occupancy

We simulate the behaviour of 60 occupants in an office space. Each occupant is associated with a specific desk and can either work at the desk or participate in a group meeting held in a conference room. Jointly, we calculate the environmental temperature, which is affected by the external weather conditions as well as occupants' latent heat. If an occupant's temperature exceeds a specified threshold of tolerance, the occupant will trigger a high-level discrete-event decision that will determine a new target location. In this study, we use a low-level discrete-time Social Force model to calculate agents' steering, although other approaches are supported as well. In this example, we do not account for occupants' abilities to operate other building systems (e.g. HVAC or windows). However, the proposed framework supports the prototyping of additional nodes that could handle such operations.

Figure 3 shows different simulation snapshots. The environmental temperature is represented in the form of a heat map. In Figure 3a, the occupants are moving towards their desk or the meeting rooms. In Figure 3b, a temperature heat map reveals increased indoor temperature in the meeting rooms. In Figure 3c, some of the occupants leave the room since the current indoor temperature is higher than their threshold of tolerance. Upon leaving the room, they are directed either to a randomly selected target such as their desks, the restroom, or social space. In Figure 3d, more occupants leave the meeting room causing increased temperature in the newly occupied spaces.

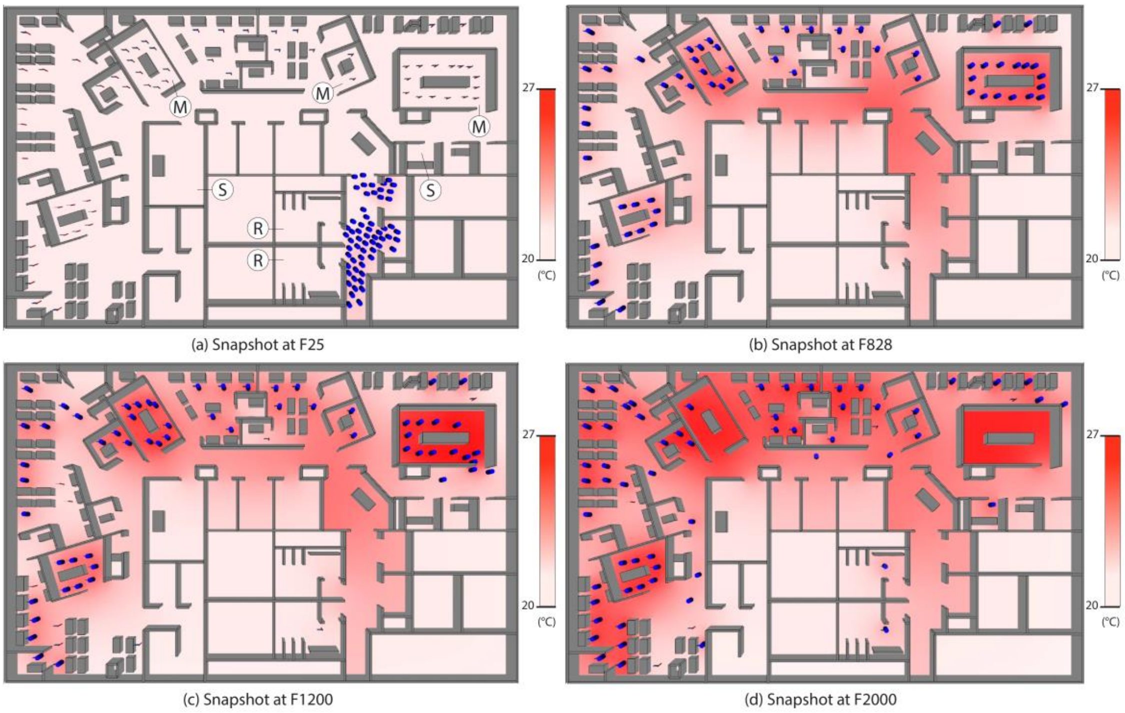


Figure 3: Joint simulation of environmental temperature and human occupancy (M=Meeting room, S=Social area, R=Restrooms)

4.2 Multi-Model Representation of Human Movement

Different models have been developed to calculate occupants' paths while avoiding static and dynamic obstacles. The Social Force model is an established method to simulate the movement of densely populated crowds (Helbing and Molnar 1995). It computes a series of forces that may attract occupants towards a specific destination or repel agents to prevent collisions with static obstacles or other agents. The resulting speed and direction of the agent are produced by the sum of the forces acting upon an agent at a given time (Figure 4a).

Other models capture occupant movement at a finer level of resolution. The Footsteps model, for instance, consists of a biomechanically-inspired method that simulates biped movement using an inverse pendulum approach which accounts for an occupant's feet placement (Singh et al. 2011b). Different from the previous model, agents do not simply react to the presence of static and moving obstacles: they predict the future position of moving obstacles to anticipate collisions and thus produce more natural steering behaviours (Figure 4b).

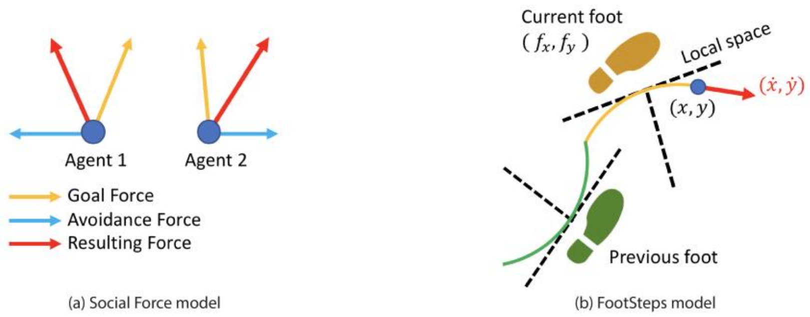


Figure 4: Two established occupant movement simulation models. The Social Force model computes agents' speed and direction as the sum of attractive and repulsive forces. The Footsteps model simulates biped movement using a biomechanically-inspired approach.

In this study, we compare the simulation results produced by these two different occupant movement models. This is achieved by replacing the "occupant steering" node illustrated in Figure 2 with a similar one that contains the Footsteps model rather than the Social Force model. Figure 5a and 5b compare the walking paths produced by only 5 occupants moving to assigned targets. Figure 5c and 5d compare the aggregated walking paths for 60 agents over 2000 simulation frames, using the same simulation scenario detailed in Section 4.1. In both cases, the produced paths exhibit some differences: the Social Force model produces walking paths that distance agents from the building walls, mainly due to the repulsive force produced by static obstacles. The Footsteps model, instead, produces paths that tend to occupy most of the available space. The occupants, in fact, are aware of their surrounding space and can predict future collisions and steer to prevent them. As a result of these differences, the walking distances, velocities, and overall occupancy patterns differ between the models, affecting the overall simulation results, as further discussed in Section 5.1.

Figure 5: Paths analysis using different occupant movement models

4.3 Joint Multi-Domain Simulation of Environmental Acoustics and Occupant Movement

To demonstrate the platform ability to scale and progressively simulate multi-modal features, we incorporated an acoustic simulator that calculates the sound produced by occupant footsteps. This analysis is made possible by the high level of detail of the Footsteps model, which represents occupants' feet placement. Figure 6 shows the extended simulation platform. The modular and extensible nature of our joint approach is highlighted by the fact that only 3 simulation nodes have been added to the previous composition, leaving the other nodes mostly unchanged.

Inspired by the SPREAD model (Huang et al. 2013), the "acoustics" node uses the Transmission Line Matrix (TLM) method to propagate sound outward from point sources. In the case presented here, those point sources happen to be triggered by individual occupant footsteps, though the node itself is unaware of how the sound is produced. As with the thermodynamics node, the environment is represented as a 2D grid of cells. But rather than associate each cell with a temperature value, the TLM method requires each cell to have a separate, possibly negative value for each of the four directions to the adjacent cells. These four values propagate according to a set of rules that give rise to pressure waves emanating from each source and reflecting off walls.

The attenuation of sound waves is controlled by three absorption coefficients: one for the walls, one for the floors, and one for the ceilings. To account, in a very approximate fashion, for the fact that the 3D geometry of the space is reduced to a 2D simulation model, the floor and ceiling coefficients are scaled by the width of each cell divided by twice the height of the ceiling. A more sophisticated acoustics model would allow different wall, floor, and ceiling surfaces to have different coefficients, and would allow the ceiling height to vary from one location to another. The simple model implemented for this study, however, is adequate to demonstrate the coupling of noise propagation with other modelled phenomena.

Each time an agent takes a step, the “occupant steering” node notifies a “sound source” node using discrete-event signals. In turn, the “sound source” node exchanges information with the “acoustics” node to calculate aggregated sound levels. In this simple example, the sound does not affect occupant planning, although we plan to add this feature in future extensions of this work.

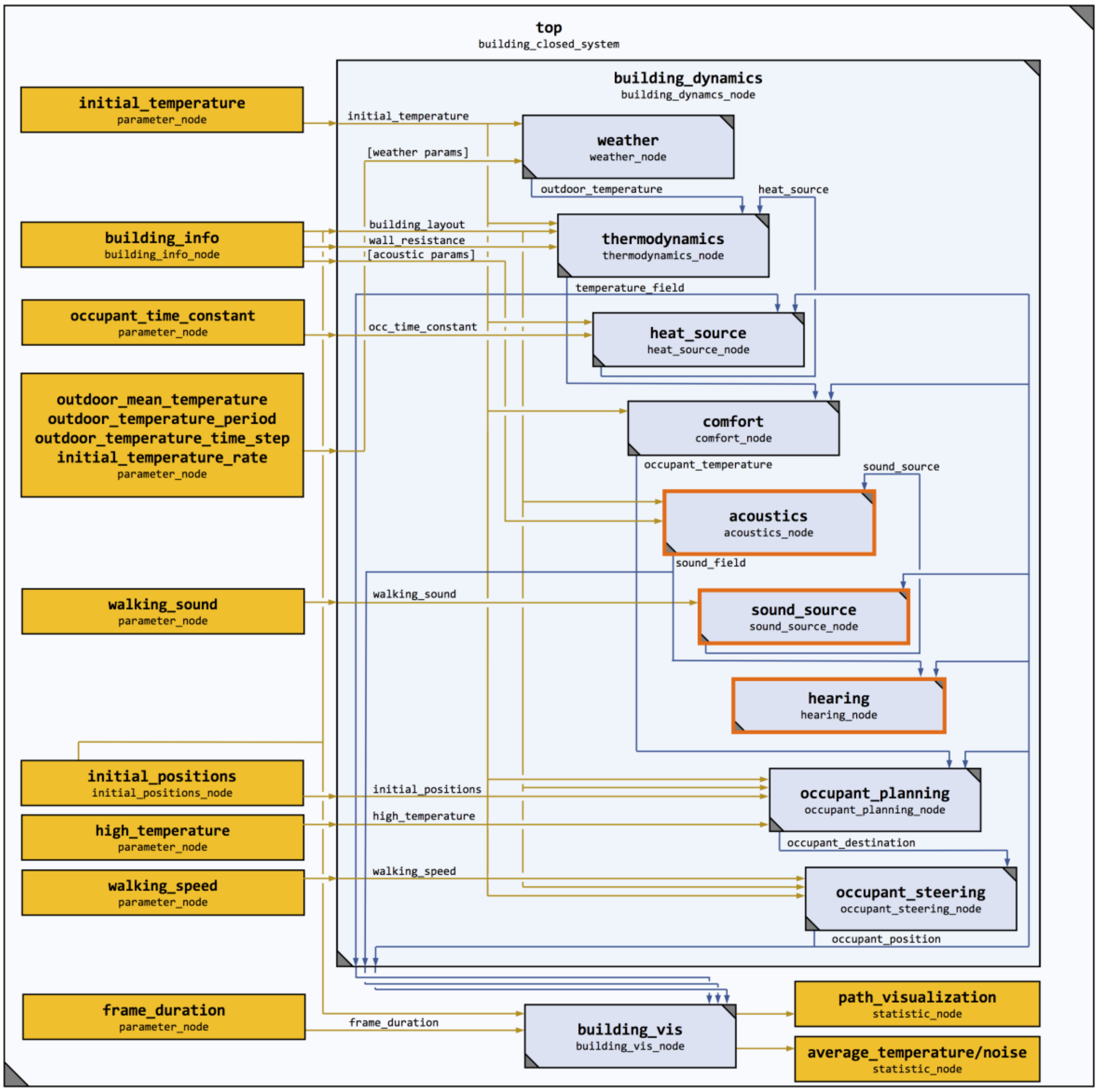


Figure 6. Platform including the acoustics simulation.

In this study, we simulated a scenario similar to the one detailed in Section 4.1 where environmental temperature affects occupant behaviour. However, in this case, the Footsteps model is used to calculate occupant movement and environmental sound, visualized in the form of a heat map. Figure 7 shows different simulation snapshots highlighting the sound propagation. Figure 7a shows the sound produced as the occupants enter the office. In Figure 7b, the occupants walk to reach their targets. In Figure 7c, the occupants are working at their workstations. Hence, no footstep sound is produced. In Figure 7d, occupants leave their meeting rooms due to excessive heat (which is calculated, yet not visualized in this example).

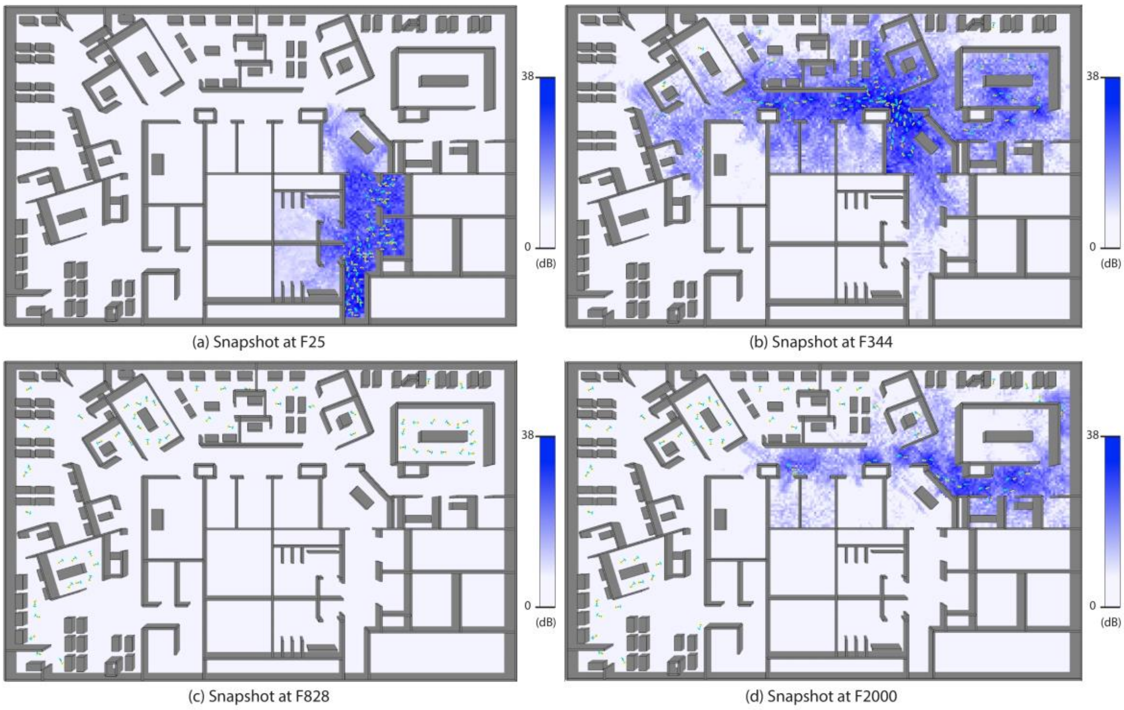


Figure 7: Joint simulation of environmental sound (visualized), temperature and human occupancy

A link to the simulation videos can be found here: https://youtu.be/UvEn9yLMi9Y

5. Discussion and observations

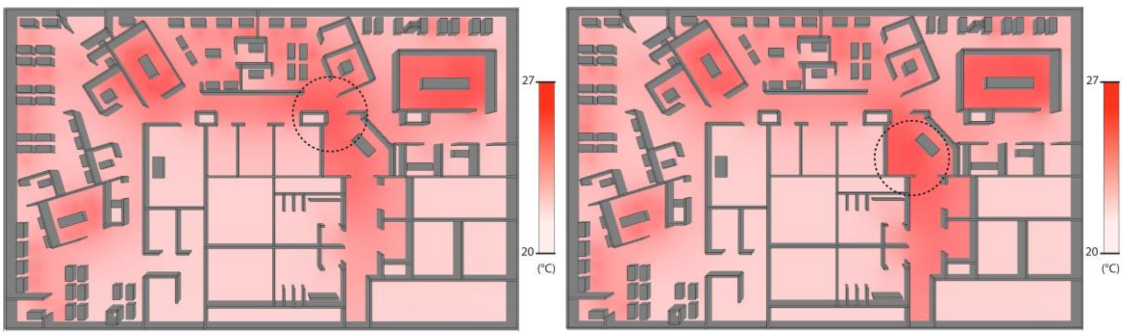
Based on the conducted case studies, we collected some insights that capture building-occupant relations spanning across simulation domains.

5.1 Impact of Occupant Movement Models on Thermal Analyses.

The joint modelling of building-occupant interactions enables the analysis of the impact that different occupant movement models produce on environmental features, such as temperature. If several occupants are simultaneously located in the same space, bottlenecks may arise, which reduce occupant flow thereby increasing the temperature produced by occupants' latent heat in the space. The occurrence of bottlenecks is highly dependent on the algorithm that directs the occupant movement.

Figure 8 compares two aggregate temperature analyses using two different occupant movement models, namely the Social Force model and Footsteps, as previously described in Section 4.2. In this case, however, we visualize the aggregated temperature rather than the aggregated paths. This analysis adds a temporal dimension since it accounts for the time required to traverse the paths. It can be noticed that these models produce different temperature heat maps. The Social Force model produced congestion in proximity to the building entrance, while Footsteps created congestion in the lobby leading to different heat maps. While the Social Force model directs agents to simultaneously traverse the narrow passage, the Footsteps model distributes them more evenly in space, while still producing bottlenecks in a more open area.

While no definitive model exists to represent human movement in buildings (Kapadia et al. 2011), our platform supports a systematic comparison among models to provide insights on the implications of using a specific model in a determined scenario.



(a) Occupant movement using the Social Force model

(a) Occupant movement using the SteerSuite model

Figure 8: Aggregated temperature comparison using different models

5.2 Impact of a Building's Design on Acoustics Analyses

In this study, we analyse how different building features, such as floor properties, impact the propagation of sound originating from occupant footsteps.

Figure 9 compares the aggregated sound map produced by simulating the occupant behaviour scenario detailed in Section 4.3 in two building layouts with different types of floors: regular and sound-absorbing. As expected, the sound-absorbing floor produces significant less sound in spaces, potentially leading to improved acoustics conditions for the occupants working in areas adjacent to the main corridor.

In this example, we produced different sound maps by modifying the “walking sound” input parameter. In future work, we plan to extract floor material information from a Building Information Model and use it as input to our framework.

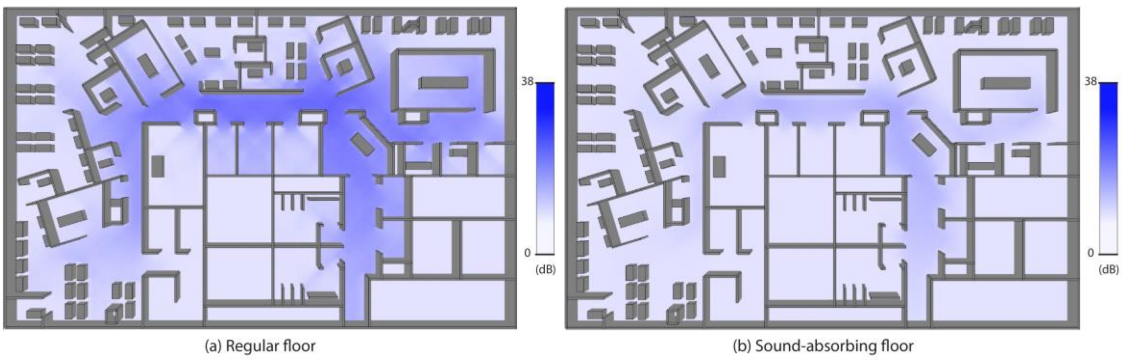


Figure 9: Impact of floor types on sound propagation

5.3 Joint multi-purpose analysis of space-centric and occupant-centric features

The platform supports multi-purpose analyses of building-occupant interactions both from space-centric and occupant-centric perspectives. Figure 10 shows space-centric aggregated temperature and noise maps. This visualization provides insights on how different workstations experience different temperature and sound levels depending on their location in space and occupancy levels. These insights can be used to redesign the building and test how optimal environmental conditions could be achieved. Analyses of such a kind could also be incorporated into generative design approaches (Nagy et al. 2017) to inform the dynamic exploration of a vast number of design solutions.

The platform also records occupant-centric data, such as the temperature and noise levels experienced by the occupants over time. In Figure 10, we also highlight how an occupant, depending on the location of their work station and their behaviour patterns, experiences different environmental conditions. This kind of analysis could be combined in the future with advanced comfort models which account for the occupant demographics (Soebarto et al. 2019).

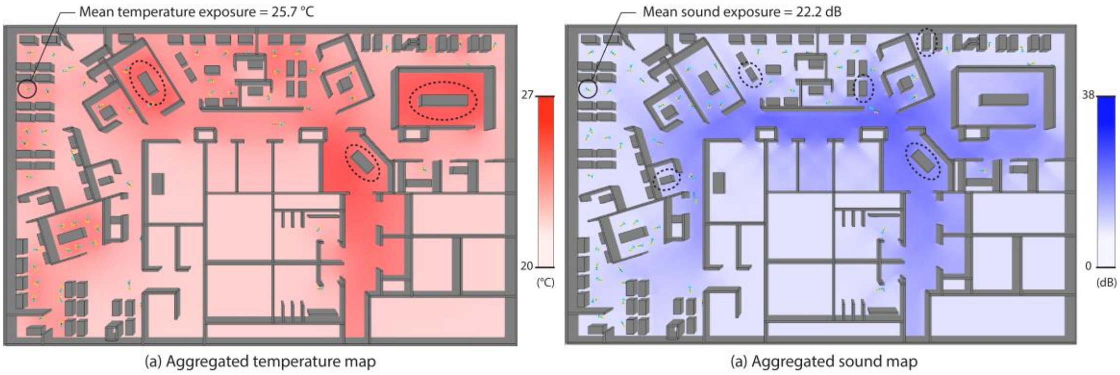


Figure 10: Aggregated space-centric and occupant-centric information

6. Platform Evaluation

The aim of JOIN is to facilitate the integration of independent, cross-domain, black-box solvers. Table 1 summarizes key features of JOIN that distinguish it from other established approaches.

Table 2 reports the results of an experiment aimed at measuring the computational overhead of JOIN compared with vanilla black-box solvers. In Experiment 1, we simulate occupant behaviour using the Social Force model, while in Experiment 2, we use Footsteps. In each experiment, we record the overall computational time as well as the time spent in each solver. The results indicate that JOIN eases the integration of different solvers with negligible performance overhead (around 0.1% of the overall computation time). The overall performance of the system depends on the solvers used, their update rates, the scale and complexity of simulated environments, the number of agents considered, the steering technique used, and the number and types of environmental conditions simulated.

Type	**Approach**	**Example**	**Key Features**
Model-Dependent Simulators	The simulation code includes a model that represents a real-world process or system. They consist of monolithic, stand-alone systems.	EnergyPlus (Crawley et al. 2001)	Supports the simulation of building energy consumption and water use.
		ESP-r (Aasem et al. 1994)	Enables building performance simulations including heat, air and light.
Co-Simulation Approaches	Multiple simulators run simultaneously while exchanging information. They often require the modification of existing simulators to communicate and be controlled by another program.	Building Controls Virtual Test Bed (Wetter, 2011)	Combines established energy simulators such as EnergyPlus and Radiance, in one framework based on Ptolemy II
		Modelling tool by Hong et al. (2016)	Integrates an occupant behaviour functional mock-up unit (obFMU) with EnergyPlus using a functional mockup interface (FMI)
Model-Independent Simulators	The simulation code does not refer to any particular model that represents a real-world process or system. They require models to be developed according to a common set of conventions.	Ptolemy II	Uses an assortment of paradigms to model sequential processes, continuous-time, discrete-events or process networks, providing a complex modelling environment.
		Modelica	Heavily relies on equation-based modelling, which differs from familiar imperative programming.
		TRNSYS kernel	Facilitates numerical convergence among components at fixed time steps
		JOIN (Proposed approach)	Uses DEVS conventions with unrestricted event times. It uniquely combines crowd simulation, planning, footsteps, noise and heat in a unique platform.

Table 1. Comparison of JOIN against existing selected established simulators

Type	Approach	Example	Key Features
Model-Dependent Simulators	The simulation code includes a model that represents a real-world process or system. They consist of monolithic, stand-alone systems.	EnergyPlus (Crawley et al. 2001)	Supports the simulation of building energy consumption and water use.
		ESP-r (Aasem et al. 1994)	Enables building performance simulations including heat, air and light.
Co-Simulation Approaches	Multiple simulators run simultaneously while exchanging information. They often require the modification of existing simulators to communicate and be controlled by another program.	Building Controls Virtual Test Bed (Wetter, 2011)	Combines established energy simulators such as EnergyPlus and Radiance, in one framework based on Ptolemy II
		Modelling tool by Hong et al. (2016)	Integrates an occupant behaviour functional mock-up unit (obFMU) with EnergyPlus using a functional mockup interface (FMI)
Model-Independent Simulators	The simulation code does not refer to any particular model that represents a real-world process or system. They require models to be developed according to a common set of conventions.	Ptolemy II	Uses an assortment of paradigms to model sequential processes, continuous-time, discrete-events or process networks, providing a complex modelling environment.
		Modelica	Heavily relies on equation-based modelling, which differs from familiar imperative programming.
		TRNSYS kernel	Facilitates numerical convergence among components at fixed time steps
		JOIN (Proposed approach)	Uses DEVS conventions with unrestricted event times. It uniquely combines crowd simulation, planning, footsteps, noise and heat in a unique platform.

Table 2. Results from two experiments aimed at quantifying the computational overhead of JOIN. In Experiment 1, we used a Social Force model to represent human behaviour. In Experiment 2, we used a Footsteps model. The overhead of JOIN is calculated by subtracting the sum of time spent in each solver (s) from the overall simulation time (o).

7. Conclusion and Future Work

We propose JOIN, an extensible and multi-purpose platform for simulating building-occupant interactions that span across multiple levels, domains, time-scales and models.

JOIN supports the communication between solvers with negligible computational overhead, thus removing technological barriers associated with combining different models into an integrated system. Furthermore, it combines a wide range of simulators including high-level occupant planning, low-level occupant movement, heat and sound in an integrated framework. However, to preserve encapsulation between solvers, a modeller needs to explicitly state which information is needed by other solvers, possibly leading to overhead costs. Additionally, users need to manually select the model used and the analyses to conduct. In the future, we aim at creating templates for specific evaluations. Evacuation scenarios, for example, may compute occupant movement using the Social Force model and will analyse the walking paths and evacuation times. Day-to-day operations, instead, may use the Footsteps model to conduct environmental analyses and compute user satisfaction.

In this study, we assigned agents a representative schedule that determines the occupant movement targets. Established approaches are used to compute crowd movement, such as the Social Force model (Helbing and Molnar, 1995) and Footsteps (Singh et al., 2011). Furthermore, we demonstrated how simulations can be developed to explore the effects of latent heat ad footstep noise on occupant comfort and behaviour. Additional work is required to address additional acoustic concerns (e.g. HVAC, occupant voices, equipment, and outdoor vehicular traffic) and to develop more complex scenarios which account for both social, psychological, environmental, and organizational aspects of human behaviour.

The proposed approach could be extended to calculate established metrics in the building performance simulation (BPS) community, including energy consumption and comfort (visual, thermal, acoustic). This can be achieved by incorporating within JOIN key functionalities of established simulation tools such as EnergyPlus and ESP-R.

Improving the human productivity and experience in the building environment (low noise and visual distraction, short travel times, pleasing views) is also a worthy potential application area for simulation. Future work will involve simulating and validating human behaviour in existing settings and conducting user studies to evaluate the usability of this platform for analysing occupant-building relations in existing and not-yet-existing settings.

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References

Aasem, E. O., J. A. Clarke, J. L. M. Hensen, N. J. Kelly, J. MacQueen, and C. O. R. Negrao. 1994. "Current Building Systems Modelling Potential of ESP-r." In *Proc. 4th International Conference on System Simulation in Buildings, Liege, December*, 5–7. Citeseer.

Crawley, Drury B., Linda K. Lawrie, Frederick C. Winkelmann, Walter F. Buhl, Y. Joe Huang, Curtis O. Pedersen, Richard K. Strand, Richard J. Liesen, Daniel E. Fisher, and Michael J. Witte. 2001. "EnergyPlus: Creating a New-Generation Building Energy Simulation Program." *Energy and Buildings* 33 (4): 319–331.

Curtis, Richard B., Bruce Birdsall, W. Fred Buhl, Ender Erdem, Joseph Eto, James J. Hirsch, Karen H. Olson, and Frederick C. Winkelmann. 1984. "The DOE-2 Building Energy Analysis Program." *Lawrence Berkeley Laboratory Report# LBL-18046*.

Gaetani, Isabella, Pieter-Jan Hoes, and Jan L. M. Hensen. 2016. "Occupant Behavior in Building Energy Simulation: Towards a Fit-for-Purpose Modeling Strategy." *Energy and Buildings*. Vol. 121, pp. 188-204

Goldstein, Rhys, Simon Breslav, and Azam Khan. 2013. “Using General Modeling Conventions for the Shared Development of Building Performance Simulation Software.” In *Proceedings of the International Building Simulation Conference*.

———. 2014. “Towards Voxel-Based Algorithms for Building Performance Simulation.” In *Proceedings of the IBPSA-Canada ESim Conference*.

———. 2018. “A Symmetric Formalism for Discrete Event Simulation with Agents.” In *Proceedings of the 2018 Winter Simulation Conference*, 584–595. IEEE Press.

Goldstein, Rhys, and Azam Khan. 2017. “Simulation-Based Architectural Design.” In *Guide to Simulation-Based Disciplines: Advancing Our Computational Future,* edited by Saurabh Mittal, Umut Durak, and Tuncer Ören, 167–82. Simulation Foundations, Methods and Applications. Cham: Springer International Publishing.

Goldstein, Rhys, Azam Khan, Olivier Dalle, and Gabriel Wainer. 2017. “Multiscale Representation of Simulated Time:” *SIMULATION*. Vol. 94(6), pp. 519-558.

Goldstein, Rhys, Alex Tessier, and Azam Khan. 2011. “Space Layout in Occupant Behavior Simulation.” In *Conference Proceedings: IBPSA-AIRAH Building Simulation Conference*, 1073–1080.

Haldi, Frédéric, and Darren Robinson. 2011. “The Impact of Occupants’ Behaviour on Building Energy Demand.” *Journal of Building Performance Simulation* 4 (4): 323–38.

Helbing, Dirk, and Peter Molnar. 1995. “Social Force Model for Pedestrian Dynamics.” *Physical Review E* 51 (5): 4282.

Hesham, Omar, and Gabriel Wainer. 2016. “Centroidal Particles for Interactive Crowd Simulation.” In *Proceedings of the Summer Computer Simulation Conference*, 7. Society for Computer Simulation International.

Hong, Tianzhen, Hongsan Sun, Yixing Chen, Sarah C. Taylor-Lange, and Da Yan. 2016. “An Occupant Behavior Modeling Tool for Co-Simulation.” *Energy and Buildings* 117 (April): 272–81.

Huang, Pengfei, Mubbasir Kapadia, and Norman I. Badler. 2013. “SPREAD: Sound Propagation and Perception for Autonomous Agents in Dynamic Environments.” In *Proceedings of the 12th ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, 135–144. ACM.

Janak, Milan. 1997. "Coupling Building Energy and Lighting Simulation." In *Proc. Building Simulation*, 2:313–319.

Kapadia, Mubbasir, Nuria Pelechano, Jan Allbeck, and Norm Badler. 2015. *Virtual Crowds: Steps Toward Behavioral Realism*. Vol. 7. Synthesis Lectures on Visual Computing.

Kapadia, Mubbasir, Matt Wang, Shawn Singh, Glenn Reinman, and Petros Faloutsos. 2011. "Scenario Space: Characterizing Coverage, Quality, and Failure of Steering Algorithms." In *Proceedings of the 2011 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, 53–62. ACM.

Maleki, Maryam, Robert Woodbury, Rhys Goldstein, Simon Breslav, and Azam Khan. 2015. "Designing DEVS Visual Interfaces for End-User Programmers." *SIMULATION* 91 (8): 715–34.

Morrow, E. 2010. "MassMotion: Simulating Human Behaviour to Inform Design for Optimal Performance." *The Arup Journal* 1 (45): 38–41.

Morrow, Erin, Ian Mackenzie, Gaurav Nema, and Daniel Park. 2014. "Evaluating Three Dimensional Vision Fields in Pedestrian Micro-Simulations." *Transportation Research Procedia* 2: 436–441.

Nagy, Danil, Damon Lau, John Locke, Jim Stoddart, Lorenzo Villaggi, Ray Wang, Dale Zhao, and David Benjamin. 2017. "Project Discover: An Application of Generative Design for Architectural Space Planning." In *SimAUD 2017 Conference Proceedings: Symposium on Simulation for Architecture and Urban Design*.

Parys, Wout, Dirk Saelens, and Hugo Hens. 2011. "Coupling of Dynamic Building Simulation with Stochastic Modelling of Occupant Behaviour in Offices–a Review-Based Integrated Methodology." *Journal of Building Performance Simulation* 4 (4): 339–358.

Schaumann, Davide, Simon Breslav, Rhys Goldstein, Azam Khan, and Yehuda E. Kalay. 2017. "Simulating Use Scenarios in Hospitals Using Multi-Agent Narratives." *Journal of Building Performance Simulation* 10 (5–6): 636–52.

Schaumann, Davide, Seonghyeon Moon, Muhammad Usman, Rhys Goldstein, Simon Breslav, Azam Khan, Petros Faloutsos, and Mubbasir Kapadia. 2019. "Toward a Multi-Level and Multi-Paradigm Platform for Building Occupant Simulation." In *Proceedings of the Symposium on Simulation for Architecture and Urban Design*, 169–76. Atlanta: Society for Computer Simulation International.

Singh, Shawn, Mubbasir Kapadia, Billy Hewlett, Glenn Reinman, and Petros Faloutsos. 2011. "A Modular Framework for Adaptive Agent-Based Steering." In *Symposium on Interactive 3D Graphics and Games*, PAGE–9. ACM.

Singh, Shawn, Mubbasir Kapadia, Glenn Reinman, and Petros Faloutsos. 2011. "Footstep Navigation for Dynamic Crowds." *Computer Animation and Virtual Worlds* 22 (2–3): 151–58.

Soebarto, Veronica, Hui Zhang, and Stefano Schiavon. 2019. "A Thermal Comfort Environmental Chamber Study of Older and Younger People." *Building and Environment* 155 (May): 1–14.

Vangheluwe, Hans, Juan De Lara, and Pieter J. Mosterman. 2002. "An Introduction to Multi-Paradigm Modelling and Simulation." In *Proceedings of the AIS'2002 Conference (AI, Simulation and Planning in High Autonomy Systems), Lisboa, Portugal*, 9–20.

Ward, Gregory J. 1994. "The RADIANCE Lighting Simulation and Rendering System." In *Proceedings of the 21st Annual Conference on Computer Graphics and Interactive Techniques*, 459–472. ACM.

Wetter, Michael. 2011. "Co-Simulation of Building Energy and Control Systems with the Building Controls Virtual Test Bed." *Journal of Building Performance Simulation* 4 (3): 185–203.

Woodbury, Robert. 2010. "Elements of Parametric Design." July 30, 2010.

Yan, Da, William O'Brien, Tianzhen Hong, Xiaohang Feng, H. Burak Gunay, Farhang Tahmasebi, and Ardeshir Mahdavi. 2015. "Occupant Behavior Modeling for Building Performance Simulation: Current State and Future Challenges." *Energy and Buildings* 107 (November): 264–78.

Zeigler, Bernard P., Tag Gon Kim, and Herbert Praehofer. 2000. *Theory of Modeling and Simulation*. Academic Press.

Zimmermann, Gerhard. 2010. "Agent-Based Modeling and Simulation of Individual Building Occupants." *IBPSA-USA Journal* 4 (1): 269–276.

8. Appendix

Table 3 reports detailed results for the experiments conducted.

Atomic Node Type	Node Name	Experiment 1: Social Force (seconds)	Experiment 2: Footsteps (seconds)
Input	sim.top.building_info	0.076572	0.073318
	sim.top.initial_positions	0.049075	0.050856
Visualization	sim.top.building_vis	760.647092	751.356959
Heat	sim.top.building_dynamics.weather	0.000016	0.00001
	sim.top.building_dynamics.thermodynamics	31.035482	39.466907
	sim.top.building_dynamics.heat_source	0.909435	1.291859
	sim.top.building_dynamics.comfort	0.780003	1.057764
Sound	sim.top.building_dynamics.acoustics	2449.136672	2501.086877
	sim.top.building_dynamics.sound_source	0.039849	0.079798
	sim.top.building_dynamics.hearing	0.727681	1.167683
Occupant Behaviour	sim.top.building_dynamics.occupant_planning	0.045754	0.072610
	sim.top.building_dynamics.occupant_steering	152.499128	234.922865

Sum of time spent in each solver	3395.946759	3530.627506

Table 3. Computational time spent in each solver after two experiments. In Experiment 1, we use social force model to compute occupant movement, in Experiment 2 we use footsteps.