Designing a Multi-Agent Occupant Simulation System to Support Facility Planning and Analysis for COVID-19

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The COVID-19 pandemic changed our lives, forcing us to reconsider our built environment, architectural designs, and even behaviours. Multiple stakeholders, including designers, building facility managers, and policy makers, are making decisions to reduce SARS-CoV-2 virus transmission and make our environment safer; however, systems to effectively and interactively evaluate virus transmission in physical spaces are lacking. To help fill this gap, we propose OccSim, a system that automatically generates occupancy behaviours in a 3D model of a building and helps users analyze the potential effect of virus transmission from a large-scale and longitudinal perspective. Our participatory evaluation with four groups of stakeholders revealed that OccSim could enhance their decision making processes by identifying specific risks of virus transmission in advance, and illuminating how each risk relates to complex human-building interactions. We reflect on our design and discuss OccSim's potential implications in the domains of 'design evaluation,' 'generative design,' and 'digital twins.'

CCS Concepts: • **Human-centered computing → Systems and tools for interaction design**; **Interactive systems and tools**; Visualization techniques; • **Computing methodologies → Modeling and simulation**.

Additional Key Words and Phrases: human-building interaction, virtual human, occupancy simulation, space analysis, virus transmission, space occupancy visualization

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1 INTRODUCTION

The design of buildings and interiors influences human behaviour and affects people's comfort, experience, and safety in the built environment [8, 19]. Therefore, in the fields of Architecture and Human Building Interaction (HBI), there have been several attempts to predict human behaviours within a given built environment in the early stages of

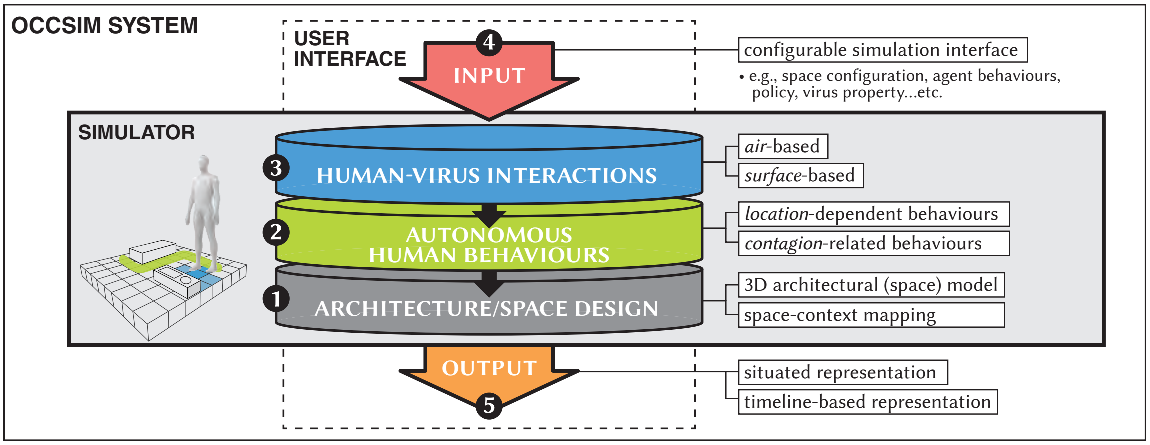

Fig. 1. OccSim automatically generates occupancy behaviours (virtual humans) in relation to a given 3D building model and simulates virus transmission through interactions with the building and other occupants. As an analysis tool, users can assess the potential risks of virus transmission in the built environment from a large-scale and longitudinal perspective.

design [2, 17, 56]. Similar to simulating virtual humans with agency for evaluating ergonomic comfort in the product design domain [39, 48], *occupancy simulation* techniques have been applied in early design stages to evaluate emergency egress scenarios [45, 50], shopping mall congestion [17], and hospital processes [56]. Still, most of these works focus on the mobility of occupants to test the efficiency of various layouts, but not the social and physical interactions among occupants and the built environment throughout the day.

The COVID-19 pandemic added new dimensions to an already complex design problem. Designers and building facility managers now need to consider the risk of virus transmission via surfaces and air circulation within the built environment. Despite existing systems that only follow simple measures such as physical distancing [3, 52], or analyzing the short-term impacts of virus spread [75], we argue that virus transmission in the building is inevitably linked to *longitudinal* aspects of dynamic human-building interactions—such as the sequence or timing of accumulated interactions along the journey of a particular occupant or occupants. For example, a particular area could contribute to a high incidence of virus transmission due to the large number of passersby throughout the day. Also, a single individual could asynchronously affect other occupants over time by contaminating a shared environment, potentially triggering a "super-spreader" event. Given the known mechanisms of transmission and the breadth of human behaviours that can contribute to, or mitigate, an outbreak, it is paramount to provide decision-makers and designers with the ability to analyze their decisions within the context of relevant human-building interactions and their relationships to potential virus spread [4, 21, 69].

To address these issues, we took a *research-through-design* approach [77], and explored a system that helps users evaluate the potential risk of virus transmission within a given built environment. We began by generalizing three key design considerations from the literature and casual discussions with health experts. Based on the insights, we designed *OccSim*, a multi-agent occupancy simulation system that simulates customizable occupant behaviours and visualizes the resulting *virus-human-building* interactions on an *architectural*-scale and from a *longitudinal* perspective (Figure 1). We finalized our study by evaluating the system with potential users and discussing the future design implications.

For realistic occupant and virus transmission simulation, we modelled human behaviours throughout the day, influenced by each occupant's role and the building layout. To address COVID-19, we also added contagion-related behaviours, such as *breathing*, *sneezing*, *coughing*, *surface touching*, and *face touching*, and triggered each according to statistical distributions. These dynamic human-building interactions (e.g., touching the built environment, talking in an enclosed space) are relevant for analyzing spatial and temporal aspects of virus transmission.

In addition to the simulation, we provided two interfaces to translate occupancy simulation as a type of decision-making support for facility planning: *customization* and *visualization*. Whereas most of the existing occupancy simulation tools are based on pre-defined configurations [56], the OccSim interface let users freely customize space configurations (e.g., enable desk usage, add partitions) and occupant behaviours (e.g., schedule, role, mask-wearing) to see the impacts of each design decision. Users can analyze the results through *situated visualization*, and *timeline-based visualization* techniques. These visualizations inform users of the routes of virus transmission for a specified set of conditions, and enable users to better analyze potential risks for virus transmission prior to implementing design decisions or policies.

Rather than aiming to validate the simulation and its results, the purpose of the current investigation was to gauge stakeholders' reflections about the design of the system and to obtain their opinions on its potential value and limitations as an analysis tool. Therefore, as our evaluation study, we conducted independent interviews involving four groups of potential users: *architects*, *small business owners*, *building facility managers*, and *public health experts* (e.g., policymakers). Our results confirmed that our system could enhance their decision-making process by visualizing otherwise unseen information, and helped users to understand a complex set of *virus-human-building* interactions for any given space setup in an intuitive way.

A broader contribution of this work is an exploration of the *design space* of a multi-agent occupancy simulation system for use as a decision-making support during the design process. Despite the fact that occupancy simulation has been actively investigated in the field of building simulation, we argue that how to apply this technology in an interactive tool to support users' facility planning and analysis procedures has not been fully explored in the HCI community. Accordingly, the contributions of this paper are threefold: i) design considerations to create utility for a breadth of users, ii) the OccSim prototype (design & implementation), and iii) user feedback for designing occupancy simulation-based design analysis tools. Although our current prototype focused on analyzing the risk of virus transmission within the context of COVID-19, the design considerations and reflections from the current paper can also generally inform space analysis tools that incorporate various other human factors such as spatial ergonomics, productivity, and social and physical comfort.

2 RELATED WORK

Simulation has been applied as a critical approach to pre-evaluate early design intent and decisions in both HCI and Architecture. Our research builds upon existing work on 'simulation-driven design evaluation' systems by incorporating knowledge from multiple disciplines. The first subsection below explains the position of our work as the notion of HBI, while subsequent sections discuss the novelty of our work from the perspective of various other research domains (e.g., virtual human, occupancy modelling, occupancy visualization, and virus transmission).

2.1 Space Occupancy Evaluation in HCI & HBI

Built environments greatly influence the way occupants behave, leading to different energy consumption rates and occupant satisfaction [19, 58]. Therefore, HCI expanded research into the design of future buildings and assimilated an understanding of human behaviours [1, 38, 40, 64] as the notion of HBI. Driven by the *evidence-based design* paradigm [54], analyzing the resulting experience of the building by capturing space occupancy *in-the-wild* has been one major approach inline with ubiquitous computing (Ubicomp) studies [2, 64, 68]. For example, Lee et al. [40] captured how people occupy space within social contexts, and defined a concept of socio-spatial comfort to inform future buildings. However, these works can only be performed when using already constructed and occupied environments, which would not help decision-makers prevent hazard scenarios (e.g., virus transmission, emergency escape) in the earliest stages.

Prior to construction, and as part of design evaluation, *simulation* is an accepted method to analyze space occupancy, and to test and support the decision-making process [33]. Inspired by *space syntax* [29], researchers suggested metrics to simulate human behaviours on given space configurations [2, 47, 51, 63]; but it is often challenging to analyze complex human behaviours in a quantitative way. Another way has been simulating *occupants* in buildings [5, 17, 23, 30, 57]. For instance, Feng et al. [17] simulated crowds in a shopping mall and analyzed the results in terms of mobility, accessibility, and coziness to make better design decisions. Our paper builds upon this line of work, and investigates how to design an interactive system that helps people analyze their built environment using occupancy simulation in the early decision-making process. Knowing that architectural design and facility planning can have a large impact on the COVID-19 pandemic, we especially focused on 'virus transmission', which requires a complex set of knowledge in human-building interactions.

2.2 Simulating Virtual Humans with Agency in Interactive Systems

In the field of HCI, there have been efforts to employ virtual humans in interactive systems with a goal of simulating the resulting experience of given design elements [36, 39, 48]. In terms of designing products, the focus has been on predicting and evaluating use-poses [39] or scenarios [53], in relation to design changes. Some systems applied a constraint-based solver to interactively update joint positions [35, 48], while SmartManikin used a data-driven approach to make a virtual human automatically respond to real-time design changes.

In architectural-scale designs, simulating the *locations* or the moving *trajectories* of people were considered as more significant [49, 66]. Systems were proposed to populate digital humans in the spaces to evaluate the efficiency of factory layouts [48] or service design journeys [36]. By integrating agency into virtual humans, we can easily evaluate the design with multi-occupant scenarios, such as crowd-level evaluations for pedestrian vision [45], mobility [17] and evacuation scenarios [50].

Still, most existing work on virtual humans has focused on simulating individual interactions between *human* and *building* as one-time activities, but the COVID-19 pandemic has taught us that it is also important to understand how each 'human-building interaction event' could influence others in the long term. For example, if one occupant sneezes at a particular space, virus particles will be released and could persist in the built environment due to aerosolization [72, 74], and possibly affect future events occurring near those contaminated areas. Our work extends the existing virtual humans' agency by making *virtual humans* aware of, and able to react to, the dynamic changing status of the *building*. Our work overcomes the limitation of the *designer-oriented* design evaluation by taking into account *real-life use* aspects through human simulation.

2.3 Stochastic Methods for Occupancy Modelling

In the field of building energy modelling, there is a growing interest in modelling human-building interactions at much greater levels of detail than what is practised in industry [15]. In particular, stochastic modelling paradigms such as Markov chains, logistic regression, and survival analysis have been investigated for simulating the behaviour of occupants [14]. In this paper, we handle transitions between tasks using a discrete-time Markov chain, where an occupant's state at a given time step depends on its previous state [73]. Chosen mainly for convenience, Markov models are simpler than logistic functions when there are more than two possible states resulting from a transition event; this is the case, for example, when an occupant can transition from their current task to any of a number of different tasks. Markov models also allowed us to use consistent time steps for both occupant behaviour and virus transmission, rather than incorporating survival analysis with randomly generated durations between transitions. Our approach is similar to the freely available Occupancy Simulator [12], except we focus on actions related to virus transmission instead of building energy. Compared to existing work, we provide an interface to fully configure the behaviour of occupants, which enables users to customize the simulation to fit their contexts or test different scenarios. This way, our system could also provide transparency and build trust towards autonomous human behaviours in the system.

2.4 Visualizing Space Occupancy Data

Visualizing space occupancy is essential to capture insights from the data collected by real-world sensors or building simulations. A widely applied technique is to interpolate data directly within the 3D building [26, 62]. Hailemariam et al. [26] introduced interactive visualization methods to embed the building performance data onto the 3D model rendering, while Tessier et al. [62] visualized 2D plots on the corresponding IoT sensor locations of the 3D building. Moreover, 3D skeletonized features [40, 62] and video game characters [55] were applied as a solution to communicate occupants' behaviours in the space. Still, the critical limitation with these approaches is the difficulty in understanding the holistic overview of the data.

The *heatmap* is a common technique used in occupancy analysis to provide an overview of longitudinal datasets [2, 57, 65]; however, it comes at the cost of conveying complex human behaviours with temporal dynamics. To overcome these challenges, Breslav et al. [9] introduced stylized computer animation to visualize trajectories based on a multi-length time scale, while Lee et al. [40] proposed a hybrid expandable heatmap technique, which represents multiple layers of interactive heatmaps for each time interval.

In this paper, we suggest the integrated method. Similar to the aforementioned approaches, we situated the virus transmission effects and corresponding occupant behaviours on the 3D model of the building and human to help users understand aspects of virus transmission in an intuitive way. In addition, we provided a spatio-temporal overview using a *set* of data visualizations from three perspectives: *space*-oriented, *occupant*-oriented, and *object*-oriented. These perspectives all use a shared time interval. We aim to investigate the values and the usages of each approach throughout the user studies.

2.5 Virus Transmission and Physical Space

The built environment, and the interactions therein, influence the spread of respiratory viruses. Infected individuals disperse virus particles into the environment via respiratory activities (e.g., breathing, speaking, coughing). The virus can then spread through the environment via air-based diffusion and circulation, while also transferring to and from objects through touching interactions with surfaces. Although the relative contributions of each route likely depend on the scenario [6, 32, 61], studies of virus transmission within physical spaces have often restricted their scope to either air-based [10, 60, 67] or surface-based transmission routes [37, 42]. Including both pathways is pertinent for simulations related to COVID-19, particularly given the persisting uncertainty of the role each might play in the current pandemic.

Simulation of specific scenarios within confined spaces (e.g., elevator, restaurant, grocery store) has been used to evaluate the risk of transmission [10, 60, 67]; however, single room scenarios are unlikely to capture complexities of transmission dynamics at the architectural-scale. Treating spaces within a building as separate or isolated overlooks important aspects of connectivity. For example, ventilation systems and doors create the possibility for air-based transfer beyond the physical boundaries of a single room or office, while shared spaces could contribute to surface-based transfer between communities. Moreover, the layout of spaces and furniture impacts airflow and traffic patterns. Broader consideration of the occupancy and design of physical spaces is crucial for understanding and mitigating transmission within the built environment.

Human behaviours also shape the spread of infectious pathogens. Notably, personal protective behaviours (e.g., physical distancing, hand washing, mask wearing) are commonly recommended to reduce the risk of transmission [69]. Rather than simulate populations of identical individuals, epidemic models should include differences in individual and social behaviours, and how perceived risk might alter those behaviours [4, 21]. The ability to selectively modify agent behaviours can improve the realism of, and effects of deviating from, baseline behaviours [20]. Better understanding the influence of behaviour on the spread of COVID-19 will be key to improving control efforts and informing healthy re-opening and return-to-work design options and policies.

3 DESIGN CONSIDERATIONS

In this section, we highlight three key design considerations to develop a *system* that simulates and analyzes potential risks of virus transmission in the building, with the goal of helping people make better decisions in space design, facility planning, and policy making. These considerations were derived based on the insights from our literature review (section 2.5) as well as an informal discussion with health experts that preceded the completion of the prototype. The informal discussion involved five health experts (2 epidemiologists, 2 physicians, 1 microbiologist) via the Zoom videoconferencing platform, and we freely discussed the topic around 'designing a system to simulate COVID-19 transmission to support space & facility planning.' The major insight was that a simple mobility simulation technique would not suffice to analyze virus transmission in the building, and that the system should support customizing, simulating, and analyzing a complex set of human-building interactions with a longitudinal perspective. We further elaborate on these three aspects below.

3.1 Context-Responsive Automatic Occupant Behaviours

Besides architectural topology, *human behaviours* constitute a crucial aspect of virus transmission [4, 69]. All five health experts confirmed the importance of layering occupancy behaviour in the building, and highlighted the complexity and randomness of interactions within environments that could lead to infection. Therefore, we aim to integrate agency into virtual humans to automatically incorporate dynamics of *human behaviour* within the building, similar to [39], but on an architectural-scale. Whereas the existing Building Information Model (BIM) only contains topological and constructional information, we argue that contextual information must be embedded in the building model to make the human behaviour simulation reflect the contexts of interaction [55]. Moreover, in addition to macro-level mobility aspects presented in prior work [17], micro-level behaviours such as *breathing* and *touching* must be incorporated for COVID-19 transmission scenarios.

3.2 Configurable Simulation Parameters

Compared to existing virus simulations [42, 67], discussions with health experts revealed the importance of providing high flexibility for customizing configurations within the simulation tool. They highlighted that customizing human behaviours and comparing the results before and after interventions are especially important in policy decision-making,

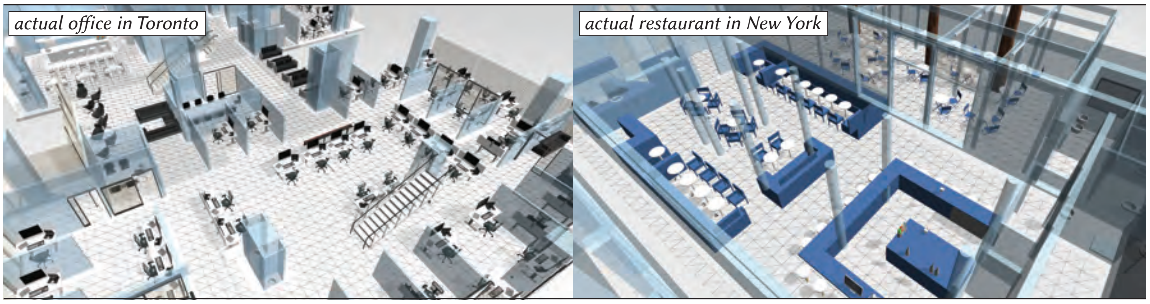

Fig. 2. Images of the two building models used for this paper (Figure 1-1): an office in Toronto and a restaurant in New York. Note that OccSim can import any 3D model of a space to be evaluated, and also enables adjusting minor space configurations within the tool.

requiring people to understand the granular efficiency of a particular behaviour (e.g., masking) or space configuration rules (e.g., capacity). Therefore, to help users make better decisions, we aim to support the customization of *behaviours* and *physical spaces* within the tool to facilitate evaluation and comparison of their effects between simulation conditions.

3.3 Analyzing with Large-Scale & Longitudinal Aspects

Whereas systems used to evaluate the potential for virus transmission have typically focused on relatively small spaces with simple geometry (e.g., meeting room [76], supermarket [67], classroom [60]) over a short-term period, we aim to extend the system to cover longitudinal aspects of human behaviours at an *architectural*-scale. Multiple human-building interactions occur over time (e.g., *touching* the built environment, *moving* around), and the *temporal* and *spatial* dynamics of each interaction influence virus transmission throughout the building [71]. Therefore, the simulation needs to help users analyze the space using a longitudinal perspective, and support demonstrating the impacts of building occupancy over time.

4 OCCSIM SYSTEM

We introduce OccSim, a multi-agent occupancy simulation that replicates realistic human behaviours, and corresponding virus transmission, within the context of the architectural environment (Figure 1). Our system employs dynamic human-building interactions (e.g., touching the built environment, talking in an enclosed space) that are relevant for analyzing spatial and temporal aspects of virus transmission. Also, OccSim informs longitudinal aspects of virus transmission at an architectural-scale. We applied OccSim using two different 3D models of real-world buildings: an office and a restaurant (Figure 2).

4.1 Autonomous Human Behaviours in relation to a 3D Building Model

We designed virtual humans with agency that automatically and realistically behave within a given architecture model (Figure 1-2). Within the context of COVID-19 transmission, we highlighted two types of behaviours: context-related (e.g., chatting in a meeting room, working at a personal desk), and contagion-related (e.g., *breathing*, *sneezing*, *touching*).

4.1.1 Context-related Behaviours. We first listed all the context-related behaviours as shown in Figure 3-1. Then, we created a state-transition matrix, which defines the transition probability and average time spent in each behaviour state. Different transition matrices can be applied to differentiate occupant behaviours of different roles (e.g., office worker, office manager, janitor, customer).

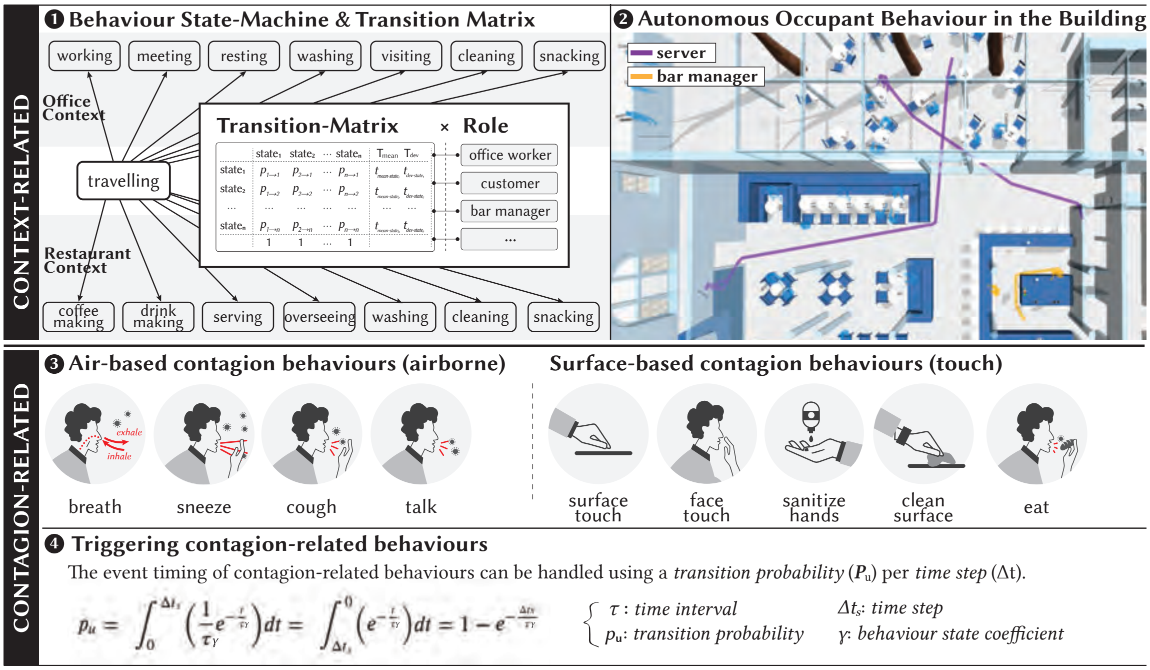

Fig. 3. OccSim simulates dynamic occupant behaviours in two ways (Figure 1-2). First, context-related behaviours and corresponding mobilities were simulated over time using a Finite State Machine (FSM) and Transition-Matrix defined for each role. OccSim also simulates nine different contagion-related behaviours for each occupant using a distribution model that responds to building positions (e.g., talking is triggered more often in meeting rooms than at personal desks).

OccSim moves virtual humans within the building model based on given behaviours, through navigation and path-finding. In order for virtual humans in the system to find the appropriate location corresponding to a given state, we embedded contextual information on the 3D model of the building (Figure 3-2). Since the two models we used in this paper are both real-world buildings (Figure 2), we prepared a mapping based on data collected from on-site observation and interviews. For future buildings, designers can freely assign the contexts based on their design intent.

4.1.2 Contagion-related Behaviours. Due to their significance in virus transmission, we modelled a number of contagion-related human behaviours within the building (Figure 3-3). For air-based contagions, we included *breathing*, *sneezing*, *coughing*, and *talking*. For surface-based contagions, we added *surface-touching*, *face-touching*, *hand-sanitizing*, *surface-cleaning*, and *eating*. Each of these behaviours triggers different qualities of how the virus interacts with occupants and spaces.

To trigger contagion-related behaviours asynchronously (e.g., occupants can *cough* while simultaneously *touching* a surface), we designed the system to handle contagion-related behaviours using transition probability (P_u) per time step (Δt_s), as depicted in Figure 3-4. The probability was calculated using average time intervals (τ) for each behaviour we defined, and compared with uniform random values for each event trigger. Moreover, we associated the contagion-related behaviours with high-level behaviour states. Independent contagion-related behaviours (*coughing*, *breathing*) can occur at any time; however, state-dependent contagion behaviours occur only when the agent is at the location associated with the state. For example, *eating* would not occur while in the '*bathroom*' state. A state-dependent coefficient (γ) was

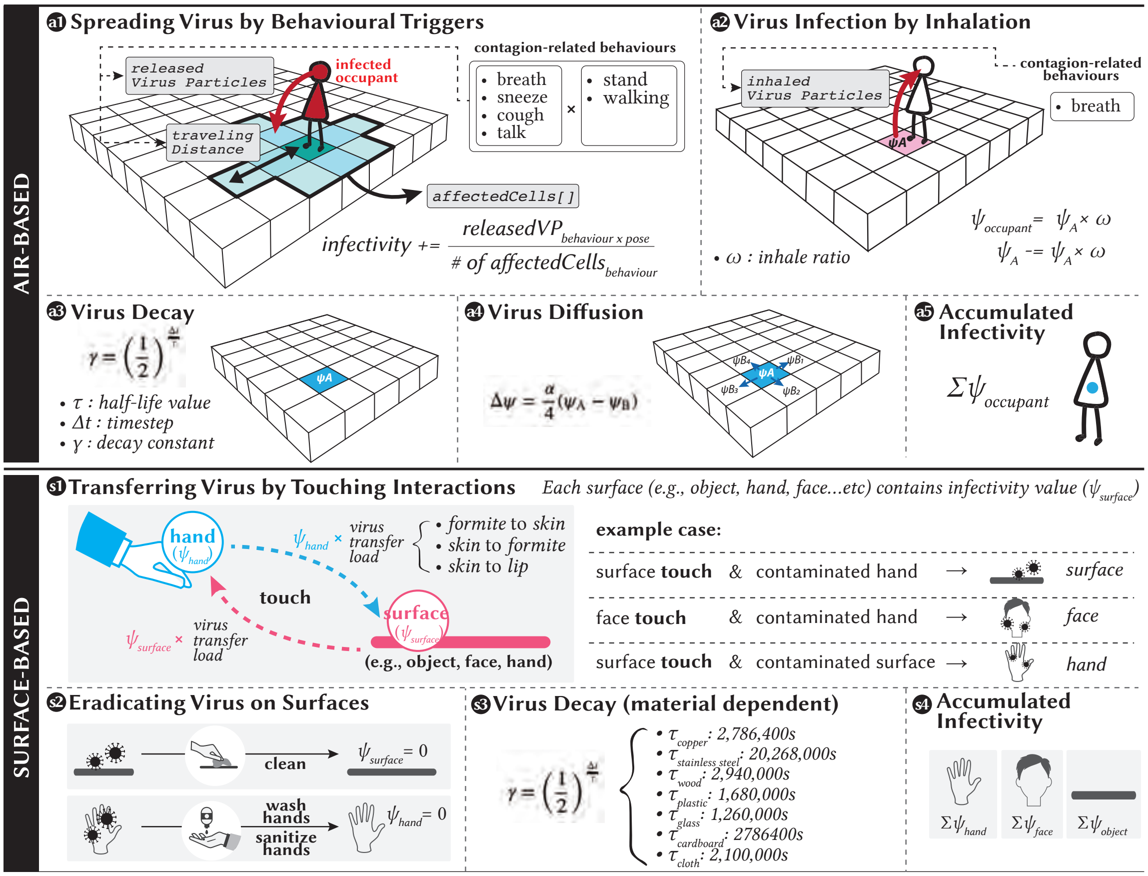

Fig. 4. OccSim supports two modes of virus transmission (Figure 1-3). For *air*-based virus transmission, the system keeps track of the contamination value of each *grid cell* of the space, and updates the value over time based on diffusion and decay. Then, *virus transfers* between an occupant's lungs and the environment are triggered according to the real-time behaviours of each occupant, including *breathing* or *talking* (Figure 3). *Surface*-based virus transmission accounts for *touch* interactions between the occupant and the built environment. The system keeps track of the contamination of each surface to calculate the appropriate magnitude of virus transfer during each interaction event.

applied in the formula to adjust the time interval value at a given behaviour state. For example, a change of state from '*focused-working*' to '*meeting*' would increase the probability of *talking*.

4.2 Simulating Virus-Human-Building Interactions

OccSim highlights the importance of considering complex *virus-human-building* interactions occurring in the world, and simulates them accordingly. All elements in the building environment (air, objects, hands, faces) possess a *contamination* value, meant to roughly correspond with the number of virus particles (or virions) either on or within that element. If left alone, contamination decays over time, based on a material-dependent rate. Also, occupant behaviours cause the air-based and surface-based contamination to change instantaneously (Figure 1-3).

4.2.1 Air-based Transmission. The '*air*' in the model is divided into grid cells (Figure 2), each of which stores the contamination (ψ) of the air above it. When an air-based contagion behaviour is triggered for an *infected* virtual human, the system spreads virus particles from the location of the occupant to the surrounding cells (Figure 4-a1). The contamination values of the nearby air cells sharply increase in the event of a *sneeze* or *cough*, or in regular increments due to an infected occupant *talking* or *breathing*. The number of virus particles released and their travelling distance differs according to each behaviour. All virtual humans *breathe* and accumulate virions through inhalation of contaminated air (Figure 4-a2). If located within a contaminated cell, the occupant will inhale a proportion of virions from the air of that particular location.

The diffusion rate was modelled based on the contamination gradient, transferring an amount of contamination from one air volume to its neighbour at every time step (Figure 4-a4). Note that building obstacles (e.g., walls) block grid cells so that they are assumed to have no air, and thus do not participate in contamination diffusion, as depicted in Figure 2. In addition to diffusing at a constant rate, the contamination of each grid cell decays over time, using the half-life (τ) of COVID-19 in air (Figure 4-a3).

4.2.2 Surface-based Transmission. Various *objects* (e.g., desks, counter tops, appliances), *hands*, and *faces* are modelled as surfaces with *contamination* values (ψ) that increase or decrease due to direct touch interactions (Figure 4-s1). Upon touching a surface with a hand, the contamination values of the hand (ψ_{hand}) and the surface (ψ_{obj}) update according to an associated *virus transfer load* parameter. For example, if a virtual occupant with a contaminated *hand* touches their face, it triggers a face contamination event, leading to an intake of the virus and an associated decrease of contamination on the hand. Also, if an occupant touches a contaminated *surface*, the contamination of their hands increases while the surface contamination decreases by that same amount. Behaviours associated with eradicating the virus on a surface (e.g., surface cleaning, washing hands, sanitizing hands) set the contamination level of that surface to zero (Figure 4-S2). Contamination values decay over time using different half-life values (τ) for each surface material (Figure 4-S3).

4.3 User Interface: Simulation Configuration

OccSim provides an interface to let users customize the simulator by setting up space configurations and occupant behaviours (Figure 5). This helps users to evaluate the impact of changing conditions on the virus transmission, and thus can inform future decision-making. Four types of conditions can be customized: *architecture*, *space configurations*, *occupant behaviours* and *virus*.

In the *architecture* panel (Figure 5-A), users can import the base 3D model of the building created from any external 3D architecture design tool, such as Autodesk Revit or Rhino3D. They can also set the context of the building, such as restaurant or office, which will update the default parameters in the (*space panel*) and (*agent panel*) accordingly.

The simulation conditions can be set using a combination of information accessible through four separate tabs. The first tab is the *basic setup panel* (Figure 5, B-1), which enables users to define parameters such as the 'maximum number of occupants,' 'simulation speed,' or 'air grid resolution.' Users can also enable or disable each type of virus-human interaction (air-based or surface-based) based on their analysis focus.

In the *space panel* (Figure 5, B-2), users can adjust space configurations. Users can manually activate and deactivate portions of the space by clicking on select pieces of furniture or rooms, or automatically set deactivated objects and areas through randomization. Higher-level configurations (e.g., moving / adding the walls, furniture, partitions) can be done using mouse interactions in the main perspective view (Figure 2).

Fig. 5. OccSim provides an interface to let users customize various parameters (e.g., occupant behaviours, space configuration, virus properties) and evaluate the effects of changing conditions on virus transmission. This image illustrates one of many control panels available in the interface for occupant customization. Refer to the video to see the complete set of input settings accessible through the interface.

The *agent panel* is for customizing each occupant's behaviour (Figure 5, B-3), such as the *initial health status*, *role*, *entering time*, *leaving time*, *mask wearing status*. Not to overload users during customization, we group a set of occupant properties together and assign the number of occupants to each preset. For example, the first row of Figure 5 indicates that the system will generate four susceptible workers who will enter the office at a random timing between 8am and 8:20am. The state transition matrix for different *roles* initiates with a default value, but users can also modify the *role panel* to customize occupants (Figure 5, B-5) and distinguish between workers in the IT industry and Sales, for instance.

Knowing that COVID-19 is associated with one of many viruses that pose a risk, we added a *virus panel* (Figure 5, B-4) to customize the properties of the virus users wish to simulate, including half-life value, diffusion coefficient, and virus transfer load. The default values are for COVID-19, based on data collected from literature.

4.4 User Interface: Visualizing Virus Transmission

We provided two types of representations: *situated* visualization and *timeline* visualization (Figure 1-5). The former method could help users to intuitively understand the potential effects of virus transmission on the built environment, while the latter method could support users to analyze temporal aspects of how the virus spread through air and surface interactions so that better design decisions can be made. For every time step (Δt) of the simulation, we keep track of six types of simulation result: contamination of each occupant's *lung* (ψ_{lung}) and *hand* (ψ_{hand}), contamination of each *air grid cell* (ψ_{cell}) and *object* (ψ_{object}), as well as the behaviour states and location of each virtual human (2D coordinate).

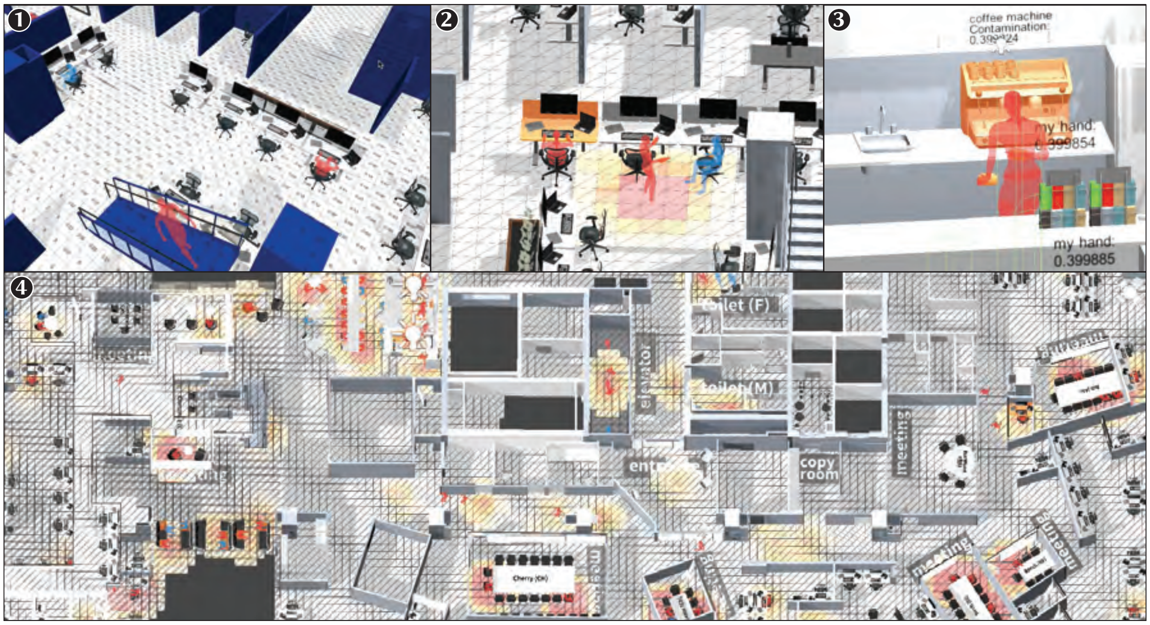

Fig. 6. We provided *situated* visualization that depicts virus transmission on the 3D building model in real-time. We applied a gradient-shader and text representation on 3D objects, 3D avatars, and air cells.

4.4.1 Situated Visualization. To help users understand virus transmissions in relation to complex environmental aspects, we applied a situated visualization technique on the 3D building model and represented data in real-time for each location. To demonstrate the air contamination status, the system generates a grid on each floor of the building and sets each cell with a contamination value (ψ_{cell}) (Figure 6-1). A heatmap-shader was added to provide a crude overview of location-based contamination levels (Figure 6-4). The contamination of surfaces (e.g., objects, occupants' hands) and occupants' lungs were represented in a similar way. We display the exact contamination value next to the surface, and also added a gradient-shader on the 3D model of the objects (Figure 6-3). All these visualizations can be toggled on and off within the visualization panel.

We made the interface similar to traditional 3D design tools (Figure 2) and let users interact with the 3D model of the building using a mouse. Users can zoom, rotate, and tilt the model, which enables them to follow the movement of an individual occupant or focus on a specific region of space to observe virus transmission (e.g., Figure 6-2).

4.4.2 Timeline-based Visualization. When the hours-long simulation is complete, we provided a *timeline-based* visualization database that illustrates all longitudinally simulated results, using the same time interval (Figure 7, bottom). The plots are grouped into three perspectives, with the x-axis always assigned to represent simulation time. First is *space*-oriented visualization. Inspired by the *expanded heatmap* technique [40], we generate a map of space contamination and occupant movements on the 2D floor plan at each time step (Figure 7-1). Second is the *occupant*-oriented visualization. For each occupant, we plotted the accumulation of virions and contamination of hands, as well as occupant behaviour state changes (Figure 7-2). Third is the *object*-oriented visualization. For each interactable object in the building, we plotted the accumulated contamination of the surface, and which occupants interacted with it. We expect

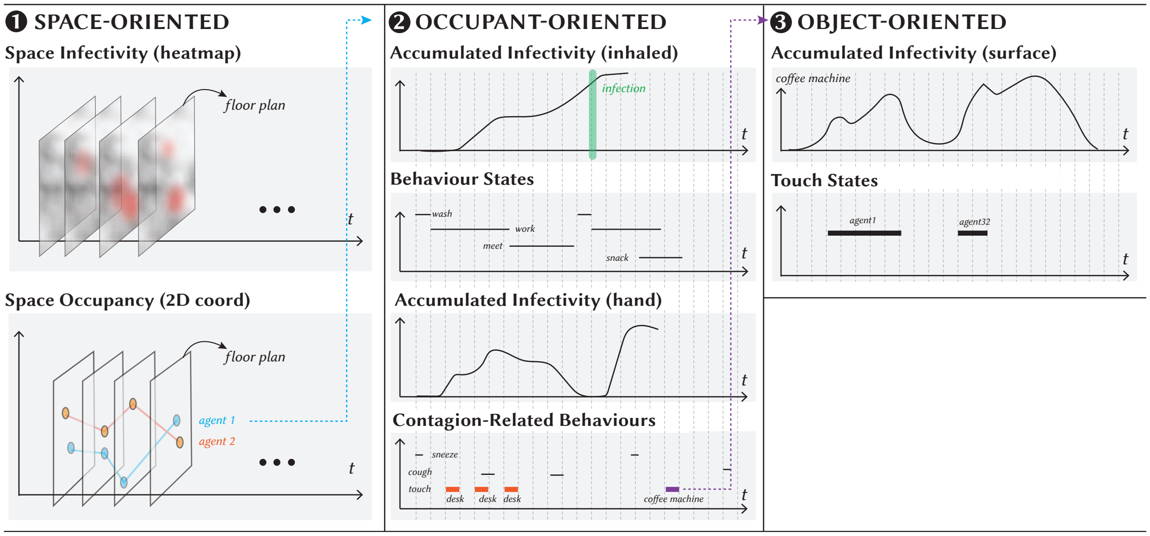

Fig. 7. In addition to situated *real-time* visualization, we provided a *set* of data visualizations from three perspectives: *space*-oriented, *occupant*-oriented, and *object*-oriented—all using a shared time interval, each of which could be used for different purposes.

this visualization database could help users not only have an overview of longitudinally simulated results, but also enable data tracing to analyze relations between virus transmission and specific human-building interactions.

4.5 Implementation

The 3D building models used for our base setup were originally created using architectural design tools (Autodesk Revit & Rhino3D), exported as an FBX file, and imported into our system. Each model originally included information on each 3D element (e.g., furniture, walls, doors), from which our system generated 'grid cells' and the 'navigation mesh,' and defined 'interactable (touchable) objects' using these model categories. To map the contexts in the 3D model, we manually assigned *tags* to each 3D object; for example, adding 'snacking' and 'resting' tags to the table geometry in the kitchen. In our current version, adding or modifying contexts can done in the back-end. We did not provide an interface for customizing contexts.

OccSim was built in C#, using *Stateless* [31] to manage behaviour and health state-machines. The simulation time step can be customized, but was set to *1000ms* as default. We then linked our base simulation with *Unity* to visualize the simulation in 3D space (building and virtual occupants) in real-time. Unity was also used to create the user interface, and to navigate virtual occupants within the building model. In terms of managing the data, simulation presets (e.g., behaviour transition matrix, virus parameters, occupants' properties) were all stored using JSON format to increase human-readability. However, results for each time step of the simulation were stored in a SQLite database. The database provides the ability to run queries on the data and easily access the large amount of data generated by the simulation. The data were then plotted using Python and Bokeh.

5 USER EVALUATION

We aimed to get early feedback of our system from a variety of potential users of OccSim, who are interested in making informed space design decisions (e.g., furniture configurations) or policies (e.g., occupancy rate, mask wearing) to

STAKEHOLDER GROUP		#	OCCUPATION	TASKS RELATED TO COVID-19	EXPERIENCE
A	Architect / Space Designer	A1	interior designer	• considering comfort & safety in the design process	4 years
		A2	architect & researcher	• considering comfort & safety in the design process	6 years
B	Building Facility Managers	B1	workplace coordinator	• manage daily operations from maintenance perspective • set up space to provide physical distancing • creating checklists and task lists for cleaning & sanitization	3 years
		B2	workplace manager		12 years
		B3	workplace manager		8 years
C	Small Business Owners	C1	pharamacy owner	• reconfigure the interior of the pharmacy. • reschedule staff's routine, guide customers differently	31 years
		C2	pharamacy owner		29 years
D	Public Health experts	D1	epidemiologist	• infection prevention and control (focused on workplaces)	4 years
		D2	epidemiologist	• chronic disease and injury prevention	5 years

Table 1. We conducted an evaluation study with four types of potential users: architect & interior designer, building facility managers, small business owners, and public health experts. More details for each participant appear in the Table.

prepare for safe re-opening of environments during COVID-19. Our current goal was to evaluate OccSim's utility and usability with users of varying backgrounds and levels of expertise through our prototype, and to discuss potential and future implications. The validation of the accuracy of our simulation is ongoing and beyond the scope of this paper, and will be reported in the future.

5.1 Participants

We recruited nine participants from four groups of potential users: 'designers', 'building facility managers', 'small business owners', and 'public health experts' (Table 1). Two *designers* were interviewed to understand the potential of our system for designing *new* buildings or interiors. We also interviewed two *building facility managers* and two *small business owners* (e.g., pharmacy) who are focused on *re-configuring* the existing environment or determining new occupancy rules applicable for the specific space. Lastly, we recruited two epidemiologists in Public Health who are working to create reasonable policies regarding space and occupant controls to minimize infection risks.

5.2 Procedure

We conducted a one-hour, semi-structured interview with each participant. All interviews were performed virtually using Zoom due to the pandemic lockdown. The interview consisted of four phases. We started by providing an overview of the interview structure and asked them to put their interest in human-building-virus interaction within the context of their occupation and work environment. The second phase was *system testing*. We provided a short tutorial about OccSim in conjunction with an overview of the interface, interactions, simulator algorithms and design strategies. With the exception of a few interviews where time or internet connectivity was limited, we provided mouse and keyboard access to let the participants test our system. The third phase was *system evaluation*. We sequentially went through the major features of the OccSim system, and had users evaluate our system design decisions, interactions, and usability. Each stakeholder reflected on their specific experiences to discuss how each feature could be helpful for them. Lastly, we finalized the interview by discussing future possibilities of our system in various domains and industries. For the analysis, we transcribed their feedback and comments from the interview recordings. We applied thematic coding [25] to identify how stakeholders find OccSim useful in their decision-making process and what they think about the current design features of OccSim.

5.3 Results

In general, all participants confirmed the potential to apply *occupancy simulation* as an interactive *evaluation system* to support decision-making for COVID-19. D2 highlighted, *"A lot of potentials are in understanding different design factors and their impacts on the risk of transmission. It could be used not only for designing spaces upfront, but also for adapting existing spaces to deal with COVID-19 and also beyond COVID."* Despite the complex dynamics behind OccSim (human-building interactions, virus transmission), they quickly understood the concept and the system interface, and shared multiple scenarios and thoughts on how they would apply OccSim into their daily decision-making processes.

5.3.1 ***Configuring Occupant Behaviours and Space.*** All the participants highlighted *flexibility* and *customizability* as significant advantages of our system. They valued that the simulation could be customized to fit their personal environment or situations. C1 highlighted, *"Most businesses follow the generalized guidelines, even though their interior layouts and the frequency of ventilation all vary. There was a case where a group of people were infected, because the Center for Disease Control and Prevention overlooked the impact of one infected visitor at a particular pharmacy building."* C2 was thrilled to see the possibilities that facility management could be *personalized* as well, similar to other movements such as 'product customization' or 'personal fabrication.'

Configurability of physical spaces within the simulation system was especially appreciated for comparison studies in their decision-making process. Participants provided multiple scenarios for the comparisons, such as 'spacing in shelters (D2),' 'position of the partitions (A1),' 'staff scheduling strategies (C1),' and 'capacity of the building (D1).' C2 commented, *"What could happen when an infected person stays in my pharmacy for one minute? Then what about for five minutes? I would like to make my own standard based on these comparisons."* Although the system is extensively flexible, the participants pointed out the possible shortcoming of 'providing too many configurable options,' which could overwhelm users during the early exploration stage. Although we enabled users to load pre-defined presets for the simulation, additional ways to manage the parameters were requested, such as custom grouping (C2) or parameter graph generation (A1).

5.3.2 ***Interacting with Autonomous Human-Building Interaction Model.*** All participants appreciated the concept of autonomous human behaviour interactions that respond to the building environment. D2 highlighted, *"Considering the full gamut of how virus gets into the mouth via face-touching and surface-touching is super important, people in Infection Control don't think about this whole process."* Although some were concerned about the level of randomness in OccSim's human behaviours (A1), most of them agreed that randomness demonstrates the dynamics of real-world human behaviours, and health experts indicated that getting results from multiple simulation runs could be a solution to minimize the effects of such randomness.

The participants (B1, B2, B3, D1, D2) saw the potential that OccSim's *human-building interaction dataset* could provide in the future. D1 mentioned that OccSim not only provides interaction data among the *human*, *building*, and *virus*, but also informs how each interaction influences the other in a long-term perspective. D2 highlighted as, *"People who do infection control would be very interested since it simulates contact tracing, which shows the reasonings."* B3 indicated that this could be valuable in facility management in general, not limited to COVID-19, as there are so many possible metrics we can achieve from this dataset, such as acoustic comfort or congestion.

Still, some participants (A1, B2, C1, C2) highlighted the necessity of an explainable interface for OccSim agency. A1, who was not familiar with simulation technology, had trouble understanding how human behaviours can be applied for the buildings that do not yet exist (i.e., not re-configuring an existing building). The study showed that the *role panel* and *agent panel* (Figure 5) contributed to establishing trust towards agency by revealing the related parameters and their values; however, layering additional information was suggested, such as desired range or uncertainty of each value. C1 commented, *"I see different certainty levels between the value of breathing intervals and washroom intervals. If each parameter shows the certainty level, I could trust the system better and customize it with higher confidence."*

5.3.3 ***Analyzing Virus Transmission through Visualization.*** The participants valued both the situated visualization and the timeline-based visualization; however, they indicated that the preferred method could vary based on when and how they used OccSim. The *situated visualization* in the 3D model of the building seemed to have potential for the early stage of using the system. The participants (A1. B1, B2, B3, C1, C2, D2) stated that a 3D graphical representation helped them to *understand* how the system was working concerning occupant's real-time behaviours, which also leads to trust towards our autonomous system. B3 mentioned, *"By observing human behaviours and the corresponding virus situation in the 3D building, I was able to understand the situation better"*. The participants especially highlighted that 3D representation could be the best way to represent the impact of multiple dynamic behaviours, such as crowding (D2), congestion (B3), and relations between different behaviours (B1). Although this technique has critical shortcomings that users cannot have an overview of the entire space, the participants referred to the CCTV metaphor, and aimed to zoom in and observe the space of their interest for a longer period of time.

Still, the participants indicated the importance of *timeline-based representation* for their actual decision-making process. For instance, A1 commented, *"During the design process, it is important to analyze multiple design options quickly. Watching people walking around in real-time isn't as helpful as being able to see the longitudinal result of the simulation at once."* Still, C2 clarified that 3D representation itself was not an issue, but there should be a way to see the longitudinal results together with the space. They pointed out that the *temporal aspect* in the simulated dataset is the key to iterate between coarse-level and micro-level analysis.

Although the participants appreciated the large contact tracing *dataset* that OccSim provides, they requested additional guidance for browsing the dataset. C1 suggested adding a hierarchical interface for data browsing by mentioning *"It would be great if the interface could inform me where to look at first. For example, the data plot can highlight three top risk regions of the current design; I can start from there and try backward analysis by referring to related occupant-oriented plots or analyzing temporal dynamics."* Besides that, designers and health experts also indicated the potential for quantifying the simulated output, such as scoring the design option based on the contamination rate or occupant infection rate.

5.3.4 ***Potential Uses and Applications of OccSim.*** In addition to evaluating the design of the built environment, the participants highlighted other application scenarios for OccSim in their decision-making processes. First, OccSim was also valued as a *policy evaluation tool* regarding space utilization. Similar to varying aspects of design, the participants stated various space utilization strategies to test, such as 'building capacity rule (D1),' 'mask wearing rule (B1, B2, C2, D1)' or 'space blocking (B1, D1).' C2 stated *"Before the pandemic, customers could freely take a seat in the waiting area. But now I need to provide guidance, and I don't know how to arrange them!"*

Second, the participants discussed the potential of using OccSim as an *occupant analysis tool*, highlighted especially by the business owners who have responsibilities for human resource management in a given built environment. For example, C1 mentioned, *"As a manager of the pharmacy, one of my major tasks is to make sure that all my staff are in a safe environment. Using OccSim's occupant-oriented output visualization, I can evaluate if any of the staff are in a vulnerable position. If so, I can adjust their work schedules."* Moreover, D1 and D2 in Public Health commented on using a similar approach at a larger scale; analyzing the risk of occupants in different industries or different roles, which could help governments manage and monitor labourers.

Third, OccSim was valued as a *recommendation tool* to inform how to manage building facilities and improve the existing building. Inspired by the timeline-based representations, which inform how the contamination changes over time, per object or space, the participants pointed out the possibilities of generating 'data-driven space utilization guidelines.' Whereas the building facilities has defined the cleaning schedules (3 times per day) and signage locations (in front of the meeting rooms) simply based on the guidelines from World Health Organization (WHO), B1 and B3 commented that they could elaborate them based on the simulated results regarding contamination frequency. Moreover, C1 indicated the plan to buy two air cleaners, and the potential to find their optimal placement based on simulated data.

Fourth, OccSim was also found to have potential as a *learning tool*, especially for the participants who did not have deep knowledge in virus transmission (B2, C1, C2). They stated that the tool helped them understand unseen phenomena in the real-world. For instance, C1 indicated, *"By observing OccSim animations, I could better understand how one's sneeze can affect the entire space in long-term. I should be more strict with enforcing masks among customers."*

Lastly, the participants also stated the possibility of OccSim as a *communication tool* to share knowledge among all the stakeholders related to a particular built environment. Health experts pointed out that it could be a way to transfer expert knowledge (of virus transmission) to general occupants and ensure a shared consensus about using the space. D1 stated, *"You know, literally thousands of people died in long-term care homes, and that was largely because they share bedrooms in long-term care homes. OccSim provides a way to explain to people why it matters and why it should be changed."* Moreover, C1 also remarked that OccSim is a way to increase transparency in space occupancy and safety for visitors. He stated that customers often went out of the building until their prescriptions were ready as they did not trust the environment, and sharing 3D animated results from OccSim in every pharmacy could increase comfort among occupants.

6 DISCUSSION

As a result of the COVID-19 pandemic, virus transmission is now considered an important factor for not only re-configuring the existing built environment, but also for planning future buildings and setting space utilization policies. This work is a preliminary investigation into designing *a multi-agent occupancy simulation system* that helps people to understand and evaluate risks associated with virus transmission within the built environment, concerning complex human-building interactions. We took a *research-through-design* approach to explore a system that combines multi-disciplinary knowledge, including the fields of HCI, HBI, interactive system design, architecture, and epidemiology. Whereas the risks of virus transmission have not been fully analyzed or predicted at an architectural-scale, and have relied on the post-evaluation of known outbreak cases, we confirmed the applicability of using occupancy simulation as an early virus risk analysis tool, with a longitudinal and large-scale perspective.

Our prototype system has several limitations. First, despite simulating virus transmission using the parameters from the literature, the simulated results from OccSim are not yet validated. Future work needs to assure that our system can re-create and compare results to known outbreak scenarios or aligns with results obtained from higher resolution Computational Fluid Dynamics (CFD) simulations. Second, we did not take into account the airflow in the built environment, which limits the system's utility in evaluating Heating Ventilation and Air Conditioning (HVAC) design and scheduling. Also, our current behaviour model does not include crowd behaviours, such as queuing or grouping, which also play a major role in virus transmission. Nevertheless, our prototype was robust enough to propose our novel concept, and to evaluate the utility and usability of OccSim using potential stakeholders. In the following section, we reflect on our design and feedback from our participatory evaluation study. Although our prototype focused on evaluating risks of virus transmission, our insights are not limited to analyzing transmission; instead, we believe that insights gained can be applied to other space occupancy analysis systems in general.

6.1 Designing Virtual Humans with Agency to Evaluate Built Environment

Virtual humans that respond to design can open up new possibilities for interactive design systems. Unlike previous occupancy simulations that correlated the virtual humans only with the topology of the 3D model [17, 55, 57], we embedded contextual information into the 3D building geometry. This approach made it possible to use occupancy simulation as a space design analysis and planning tool, by simulating realistic occupant behaviours according to how users adjust their designs. Although thus far we have only applied our system to office and restaurant contexts, we believe that embedding contextual information in the 3D building models could provide potential for minimizing the gap between the design and use phases. In the future, the digital building ontology [24] can be extended to account for multiple sets of human-building interactions and contexts.

Our study highlighted the importance of building trust towards virtual human agency and simulated human behaviours prior to applying it for evaluating designs, similar to the findings from other autonomous systems [59]. In OccSim, the agent panel (which shows all the related parameter values) and the occupant logs (occupant-oriented visualizations) contributed to an increase in the transparency of our behaviour model; however, it became troublesome when a simulation included many occupants. An alternative to having users manually adjust behaviour-generating parameters is to use a data-driven approach, which seeks to reproduce the behavioural patterns of occupancy data collected in existing environments [44]. Data-driven behaviour can still be customized with user-supplied information, if desired [23]. Nevertheless, a number of challenges and pitfalls arise whenever human behaviour is simulated for predictive purposes, regardless of the extent to which agent actions are driven by measured data or user input. For example, a reliance on existing data may lead users to overestimate the validity of the simulation results, which may not account for behavioural influences that were not present when the data were collected. Future systems need to further explore how to explain the autonomous human behaviour model within the tool and visualize confidence levels associated with each simulated behaviour [43]. Furthermore, as with other applications using virtual humans, future work needs to explore the level of detail required to realistically simulate the desired breadth of human-building interactions.

6.2 Designing Occupancy Simulation System to Support Decision-Making

The role of *simulation* in the decision-making process is to predict and demonstrate potential scenarios in the virtual world, so that people can analyze multiple options prior to enacting a decision. Our study showed that OccSim can support this procedure by providing a high level of flexibility in configuring the occupancy simulations (customizing both human behaviours and space configurations), so that users can freely explore and evaluate design options within the tool. The ability to specify flexible configurations was also seen as a way to initiate a '*personalization paradigm*' [16] in the domain of space and architecture design. A similar need for flexible and adaptable simulation tools has been noted for epidemic modelling, particularly for users with varying levels of technical expertise interested in assessing a wide variety of contexts [28]. Still, we revealed that having too many configuration options could overwhelm some users who are not expert designers (e.g., small business owners, facility managers). As future occupancy simulation systems might include a more complicated, context-specific set of parameters, we need to further explore how to manage all the available parameters or optimize the parameters in the simulation-driven evaluation tool.

Furthermore, the system needs to help users analyze the simulated results so that they can make proper design adjustments for improving their built environment. Knowing that incorporating the relationships between occupants' behaviours and resulting virus transmission is especially significant for epidemic analysis [4, 21, 69], we found that our timeline-based *dataset* of *human-building-virus* interactions could supplement the limitations of previous occupancy simulations [17, 57]—which only return the final simulation output. The participants indicated that these additional details could help deepen the analysis of simulation outputs by better linking, and revealing, cause and effect, not only for virus transmission, but for other human factors in general (e.g., acoustic comfort, ergonomic, congestion). However, a critical limitation is that it could not support the intuitive comparison of multiple simulated outputs. Future work needs to extend the existing work on a *comparison assistant interface* [11] into spatio-temporal domains, to support comparing results generated from different simulations. Such enhancements would likely facilitate future studies to understand how different users apply OccSim for informing and actually implementing design decisions and policies.

6.3 Visualizing Occupant Behaviours & Virus Transmission for Analysis

When analyzing space occupancy (e.g., occupant behaviours, virus contamination), it is important to understand both *spatial* and *temporal* aspects of data. Similar to the findings from previous works [13, 26, 41], our study demonstrated that *situated visualization* (using 3D model of the building and humans) could intuitively deliver *spatial* aspects, even for the non-expert participants who did not have a deep understanding of virus transmission. Animating the human behaviours using a 3D virtual human helped the participants understand and learn about the behavioural impacts on space contamination. Despite its advantages, our 3D situated visualization could not provide a longitudinal overview. Inspired by the comments that highlighted the importance of iterating between a coarse-level overview and micro-level details, we suggest a hybrid visualization method that combines 3D situated visualization with temporal filters (daily-based, hourly-based, minute-based). In addition to visualizing spatial information in multi-dimensional time [7, 18, 34, 40], additional interaction techniques are needed to provide the proper amount and types of data based on each time interval. For example, the system can automatically adjust the view points of the 3D model (perspective view, top-down view) and the visualization methods (heatmap, geometrical grouping, path-tracing, avatar tracer) based on the given time interval.

Additionally, although our current work focused on visualizing a single simulation, the participants mentioned that performing multiple simulation runs within the same setting is needed to minimize the effects of randomness in human behaviours. To enable users to catch patterns that appear across multiple iterations, while alleviating the burden of manually reviewing all results, future work must explore interactive visualization techniques to represent converging aspects of data, such as using *morphing* [27].

6.4 Potential Applications Ideas

In addition to using OccSim as a *qualitative* visualization-based analysis tool, feedback received during our study supported the idea of producing *quantitative* evaluations by aggregating the results of many simulation runs. Some quantitative outputs highlighted by the participants were 'infection rate,' 'space contamination rate,' 'object contamination frequency,' and 'frequency of congestion.' We believe that these statistical *virus risk metrics* could complement the more commonly used spatial analysis metrics in computational design paradigms such as generative design [46].

Moreover, we believe that OccSim's interaction model and situated visualization technique could also be applied in *digital twin* systems by simulating virus transmission in the digital replica. Using computer vision techniques, we can recognize and analyze human behaviours as well as occupant positions [22, 40, 62] in real-time. Extending Wilson [70]'s work, which visualizes 'surface touch events' using depth cameras, we believe that OccSim could represent both air and surface contamination based on real-time occupant movements and interactions, and provide the broader level of building awareness in ubiquitous computing field.

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