PANDEMIC RESILIENT HOUSING

Modelling dormitory congestion for the reduction of COVID-19 spread

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Abstract. In response to pandemic-related social distancing measures, this paper presents a computational model for simulating resident congestion in Singapore's migrant worker dormitories. The model is presented as a tool for supporting evidence-based building design and management. In contrast to agent-based or network-based building analysis, we demonstrate a method for implementing a schedule-based building simulation. In this paper we present the key functions and outputs of the computational model as well as results from analysis of a case study and its design variants. Learnings on the comparative advantages of schedule modification versus physical design modification in assisting social distancing are presented in a discussion section. In the conclusion section we consider applications of our learnings to other dense institutional buildings and future directions for evidence-based design for resilient buildings.

Keywords. Collective, collaborative & interdisciplinary design; Computational design research & education; Disrupted practices, resilience, and social sustainability; Simulation, visualization and impact projection.

1. Introduction

1.1. SINGAPORE'S RESPONSE TO COVID 19

Early in 2020 outbreaks of the COVID-19 pandemic intensified in areas of dense urban housing throughout the world. In April 2020, when Singapore saw a surge in COVID-19 cases in high-rise, high-density dormitories for migrant construction workers. In response, a series of safe-distancing recommendations (for example, maintaining at least one meter spacing between individuals) and de-densifying measures were passed by the Singapore government under the Infectious Disease Act (Ministry of Health, 2020). While these measures have been successful in reducing disease spread during periods of quarantine, worker dormitories are now reopening to normal function even as the global pandemic continues.

The design community has been called upon to support the return to a 'new-normal' where everyday activities resume, but with new safe-distancing measures. In the context of migrant worker housing in Singapore, the Ministry

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of Manpower concurrently released an advisory for existing dormitories to implement safe living measures and also a joint media release with the Ministry of National Development on improved standards for dormitory design (Ministry of Manpower, 2020; Ministry of National Development, 2020). The release of these articles show that the Singapore government is invested in finding a response to building management in the short term and building design in the longer term, with the implication that designers of urban housing and building managers must work together to develop a solution for pandemic resilient housing. We understand resilience in this context to refer to a capacity of socio-technical systems surrounding the built environment not only to recover from a disturbance, but to learn from, anticipate and adapt to these disturbances (Hassler, 2014; Hollnagel, 2014).

1.2. MIGRANT WORKER HOUSING IN SINGAPORE

Currently there are nearly 300,000 migrant construction workers living in Singapore (Ministry of Manpower, 2020). For the most part, they are housed in high-rise high-density worker dormitories. Ethical considerations for research on migrant worker housing are considerable. Dormitory residents in Singapore are often dependent on their employer to maintain their housing and immigration status (Moroz et al., 2020). Pandemic response measures, in particular quarantine, have recently limited their freedom of movement. The research in this paper has been developed in an effort to assist in increasing the safety of this housing environment during the period of the pandemic.

1.3. COMPUTATIONAL MODEL FOR PANDEMIC-RESILIENCE

To support an evidence-based design approach to pandemic related worker dormitory management and dormitory modifications, a knowledge gap exists: designers can not predict how de-densifying measures will impact patterns of social contact during the dynamic movement of residents. These daily movements create momentary peaks in congestion, where individuals arrive simultaneously in constrained areas like corridors, making 'safe-distancing' measures difficult to follow.

To address the knowledge gap on dynamic patterns of congestion in dormitory use we have developed a computational model of worker movements within a case-study dormitory. Our model is intended to support both building managers and architects as they seek to adjust building use schedules and building configuration to support safe-distancing measures during the pandemic. In our model, the building schedule supplements the rules and behaviors typically in a multi-agent model, using methods similar to a schedule-calibrated model (Goldstein et al., 2010; Goldstein et al. 2011). The use of a building schedule as a key input for our model presents value for building managers seeking to re-calibrate their schedules, and also permits us to generate close-to-reality scenarios for an environment where human movements have a degree of prescribed regularity due to safe-distancing measures.

2. Methods

Through our literature review we identified both building managers and architects as primary actors in the adaptation of dormitories to pandemic social-distancing measures. We designed our computational model to accept input from both of these actors: a building schedule adapted to building management and a building network diagram adapted to spatial configuration. Each key input is described in detail along with its associated function in the following methods sections. Our workflow, described in detail below, first generates a master schedule for all agents in the simulation via a *Scheduler* function, where each agent represents a resident. Based on the master schedule, a second *Pathtracer* function generates dimensionally accurate itineraries for each agent in the simulation. With the outputs from these two functions we conduct two forms of analysis: a global measure of use intensity for building spaces, and a congestion analysis which provides feedback on design variants. We have used the visual programming interface Grasshopper for Rhinoceros 3D in the creation of the model.

2.1. SCHEDULER FUNCTION

The first function in our computational model generates a master schedule for all agent movements in the dormitory simulation from a set of simple parameters provided by the user (figure 1). The user is prompted to input a set of data points for each defined activity taking place in the simulation. Examples of activities included in the current model include 'wake up', 'morning shower', 'morning departure,' etc. The list of activities is open to modification by the end user.

For each activity the following datapoint entries are entered: 1) name of the space; 2) earliest use; 3) latest use; 4) minimum visits; 5) maximum visits; 6) minimum stay; 7) maximum stay. The user also defines the number of agents in the simulation. Within the constraints defined by the above inputs the *scheduler* function randomly generates itineraries for all agents in the simulation. Randomness is constrained within the bounds defined by the user inputs. Commencement of each activity is allowed to vary randomly within the bounds of inputs 2 and 3. The number of repetitions of each activity varies randomly within the bounds defined by inputs 4 and 5. Duration of each activity is random within the bounds defined by inputs 6 and 7.

The *scheduler* outputs a color-coded time-sheet representing timelines for all agents in the simulation with each activity assigned a different color. It provides a visual feedback to the end-user on the distribution of agent activities over time. A .csv file data of the schedule is output and feeds into the *Pathtracer* function.

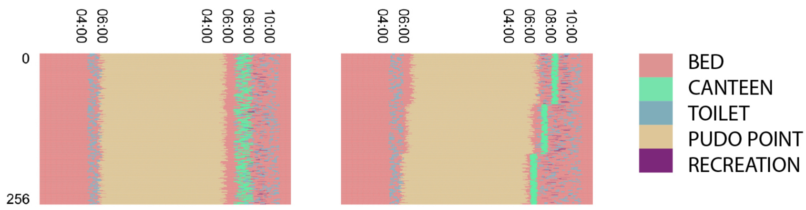

Figure 1. Baseline schedule (left) see section 3.2, staggered schedule from design scenario 1, (right) see section 3.3.

2.2. PATH-TRACER FUNCTION

The path-tracer function generates all paths traveled by agents in the dormitory based on the master schedule. The user input for this function is a network representation of the dormitory case study, as a list of labelled nodes and edges. Nodes represent functional spaces, like bedrooms, and edges represent spatial linkages, like corridors.This network representation is a three-dimensional, dimensionally accurate reflection of the building geometry, traced from the building floor plans. The creation of the network representation is a non-trivial manual activity which requires the assistance of an experienced design professional. The creation of this network representation is summarized in figure 2.

The *Pathtracer* function matches each agent to an available node for each of the activities/rooms within the agent's schedule. Bed nodes are 'checked-out' after assignment, whereas other nodes permit multiple simultaneous agent assignments. When there is a choice between available spaces for an activity, for example a toilet, the agents are assigned the node closest to their point of origin.

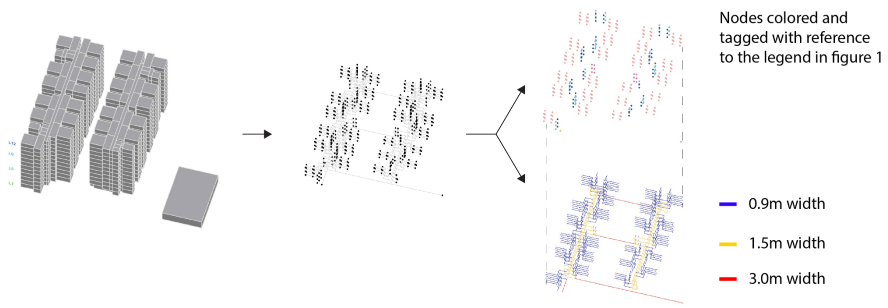

Figure 2. Conversion of case study dormitory to a network representation. Volumetric model (left) is extracted and converted to nodes and edges (middle), which will be tagged according to function (right top) and lateral dimension (right bottom).

Agent paths through the dormitory are generated using a shortest path algorithm to identify routes between origin/destination pairs. We have used the

A star algorithm (Hart, Nilsson, and Raphael, 1968). The time taken for the agent to move from origin to destination is calculated by dividing the path length with a constant walking speed. We account for the walking time by replacing the time spent by the agent at the origin, i.e. the agent leaves the origin space earlier and arrives at the destination exactly on time.

The function outputs the location of every agent for every second in the simulation period as a data tree of points where each branch contains a list of points representing a single agent's location at a given time interval. Simulations presented in this paper start from 00:00:00 and run till 23:59:59; for a total of 86400 seconds.

2.3. EVALUATION METRICS

We use two metrics to evaluate simulation outputs. A first metric, *Usage*, is defined as the total times an edge has been occupied by any agent over the course of the simulation period. A second metric, *Congestion*, is defined as the ratio of the total number of agents on an edge at a given time interval to the capacity of that edge as defined by its area and social-distancing guidelines (figure 3).

These two metrics will be familiar to readers of urban network analysis or traffic simulation. Usage is similar to betweenness though as explained above it is not an all-to-all calculation (Sevtsuk, A. 2017). Congestion in traffic simulation is defined as the ratio of traffic along an edge to the capacity of that edge, and is similar to the definition we provide for the purposes of our model (Poon et al 2004).

To compute congestion at a time t denoted as $C_i(t)$, we first compute the volume of traffic at edge E_i , denoted as $T_i(t)$. A_t represents an agent's position at time t in a given set S. is a constant representing the minimum area required per agent based on applicable social-distancing restrictions. In the case of Singapore, we are using a value of $1m^2$. $Area_i$ is the floor area of E_i.

```
def Congestion_i ( E_i , t ) :
        T_i (t)  = count [ every A(t) in set S, if A(t) lies on E_i ]
        C_i (t) = T_i (t)  x  α  / Area_i
        return C_i (t)
```

Figure 3. Pseudo code definition of congestion index .

2.4. VISUALISATION OF RESULTS

We visualize evaluated simulation outputs using both a 3-dimensional spatial representation and a two-dimensional temporal representation. The first two visualization outputs are three-dimensional views of the graph model, representing the Usage (figure 4 left) and Congestion (figure 4 right) metrics via the color and thickness of the graph edges. figure 4 shows results from our case study baseline scenario. The three-dimensional representation emphasizes spatial understanding of agent movement, highlighting areas where usage or congestion are relatively high.

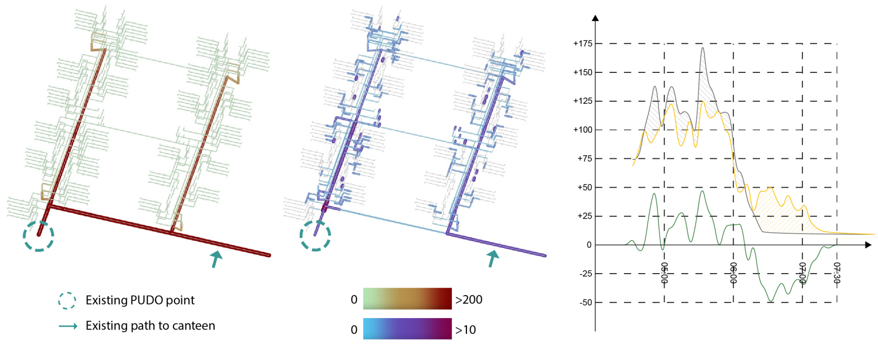

Figure 4. Usage diagram of baseline configuration (left). Maximum congestion diagram of baseline configuration (middle). Deriving deviation of cumulative congestion between baseline and and design scenario 1 during 4:30am to 7:30am (right) (see sections 3.2 and 3.3). .

The three-dimensional visualization, however, can not tell us when moments of high congestion happen. To understand congestion temporally we output a linear time-series graph showing cumulative congestion within the network over time. Cumulative congestion refers to the sum of congestion measurement for all edges in the network at a given time interval.

In our results we present comparisons between a baseline simulation run for a case study and a series of design variants. To better articulate this comparison the time-series graphs presented are the difference or deviation between the design variant and the baseline congestion. The method of calculation of this deviation value is shown in figure 4 on right: cumulative congestion for the baseline scenario and design scenario 1 are shown in grey and yellow respectively. The deviation between the two values is shown in green (see sections 3.2 and 3.3).

3. Results and Discussion

3.1. MIGRANT WORKER DORMITORY CASE STUDY

In this section we present results from applying our computational model to a worker dormitory case study and a series of design variants. We obtained an anonymous dataset of floor plans and images of our case study by liaising with a local industry contact. The dormitory consists of two twelve-story housing blocks and a separate structure for a canteen.

In all simulation runs described in this paper we have used 256 agents, constrained to the first three floors of the case study building, with agents further constrained to use only the vertical circulation core closest to their allocated bedroom. These constraints were imposed due to the computational cost of simulating the full building with its total population of 1024. Instead of simulating the full building with a sparse population, we chose to simulate a portion of the building with the full population.

3.2. BASELINE MIGRANT WORKER DORMITORY SCENARIO

In our baseline model we assigned a schedule corresponding to a typical work day in a migrant worker dormitory based on our review of literature (figure 1, left). The baseline schedule includes: morning preparation, transport to site, return from site, dinner at dormitory and other recreational activities within the facility. Agent start times fall in the range between 4:30am to 5:30am, with departure by 6:30am, as government regulated start and end time of work falls between 7am to 7pm (National Environmental Agency, 2007). Dinner timing between 7:00pm to 9:30pm is blocked out, with subsequent end of the day between 10:00 to 11:00 pm.

The usage diagram (figure 4, left) shows that the most heavily used spaces lie between the canteen and the pick-up drop-off point and the vertical circulation points on the ground level. The congestion diagram (figure 4, right) provides a more nuanced view, showing us that the vertical circulation areas at every level are points of higher congestion. The subsequent design scenarios presented in this paper are attempts to relieve congestion in these heavily-used spaces through changes in schedule and design interventions.

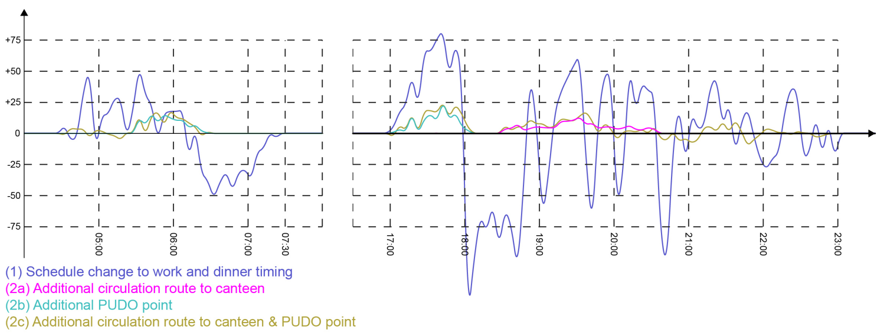

Figure 5. Cumulated congestion index deviation per minute generated for each design configuration.

3.3. SCENARIO 1: STAGGERED SCHEDULE

In a first scenario we simulated a modified schedule which splits the population of agents into three cohorts (figure 1, right). These cohorts are assigned a staggered work and dinner timing. A buffer time of 15 minutes between dinner timings is added to permit disinfecting of the tables between cohorts.

In the morning, before 6:30am, the deviation score is consistently positive for the variant indicating less congestion (figure 5). A negative score for this scenario occurs between 6:30am to 7:30am due to the fact that all agents in the baseline have left the dormitory by this point in time. In the evening as agents return to the dormitory, the advantage of a staggered arrival/departure schedule is again indicated by a consistently positive deviation score between 5:00 to 6:00pm.

Disadvantages of the staggered dormitory schedule appear during the evening meal time. The deviation score fluctuates widely between 6:00pm to 8:45 pm. This fluctuation can be broken down into 3 pairs of "dips" in the graph, occurring during each of the three dinner periods, caused by large numbers of agents moving in and out of the canteen over a short period of time. These peaks in congestion are the result of agents having a smaller range of possible entry/exit timings within the shorter 45 min periods.

3.4. SCENARIO 2: REDESIGN OF COMMON SPACES

In a second set of simulations we test if we can improve congestestion at shared spaces by adding an extra pickup-drop-off point and an extra path to the canteen. Configuration 2a adds an alternative route to the canteen. Based on a study of the existing floor plan, we find that there is a high possibility of constructing a second pathway to the canteen through the center of the residential block. Configuration 2b adds an additional pick up drop off point. The addition of a second PUDO point on the site would require the building owner to extend the driveway from the carpark to reach the proposed site, a possible design intervention. Configuration 2c combines both proposals together.

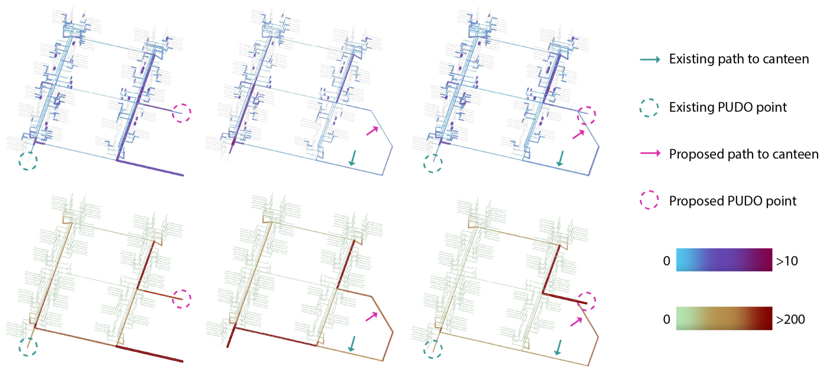

Figure 6. Usage index diagram (top row) and maximum congestion index diagram (bottom row) for configuration 2a, 2b and 2c (left to right).

Each design change improves dormitory congestion during the period it is in use as shown in figure 6. Creating an additional circulation route to the canteen (2a) creates a reduction in congestion during the meal time hours (18:30-20:30). The addition of a new pick-up drop-off point results in decreased congestion during the period when agents are departing from and arriving at the dormitory (5:30-6:30, 17:00-18:30).

While the combination of the two design scenarios (2c) resulted in a consolidation of the benefits of each, there are however some unexpected consequences of the combination. Combining the two scenarios results in an increase in usage and congestion of the area where the new PUDO point connects to the path to the canteen (figure 6). The ability to anticipate these unexpected add-on effects of combining design scenarios is one of the advantages our tool could provide end-users grappling with tradeoffs between means of implementing social distancing in worker dormitories.

3.5. DISCUSSION

Our dormitory congestion model has allowed us to demonstrate the comparative benefits of schedule changes and design changes with respect to a baseline configuration of a case study. By visualizing these benefits both spatially and temporally we are able to draw more nuanced conclusions about each scenario and compare schedule-based interventions and adaptations of physical design.

Our results show that while a staggered schedule does reduce average congestion over the course of the simulation, it also led to momentary but dramatic spikes in congestion as agents moved in and out of spaces (like the canteen) over short periods of time (figure 5). These results help us understand how staggered schedules lead to alternating periods of spatial over- and under-utilisation, and create obstacles to social-distancing measures. Future work could allow us to recommend adequate timings, additional flexibility, or additional space for socially distanced entry and exit to/from communal spaces.

Our results also suggest that implementing multiple design changes together will not necessarily have the same impact as implementing them in isolation. This is the case, for example, in configuration 2c where the combination of a new path to the canteen and an additional pick-up drop-off point has resulted in under-utilization of the initial drop-off point, as seen in the Usage diagram in figure 6. This result suggests that the model could assist end-users to plan for combinations of design interventions that complement rather than interfere with one another.

Comparison of the effectiveness of schedule-changes against physical design changes for social distancing is also permitted by our results. In figure 5 we see that while spatial changes (2a-c) have offered moderate decreases in congestion, schedule changes in contrast have resulted in a much wider amplitude of change with both greater reductions in congestion, but also moments of sharp increase. These initial findings suggest that schedule modification can be of great potential benefit in social distancing, but that it can lead to sudden crowding at spatial and temporal choke-points if not properly planned. Computational tools of the kind proposed in this paper can help anticipate these consequences and inform design changes to avoid choke-points.

4. Conclusions

In this paper we have presented a computational model for understanding population congestion in a dense institutional context, applied here to social distancing in the COVID-19 pandemic. This model presents a novel ability to allow for exploration of both spatial and temporal scenarios and compare tradeoffs between the two. The preliminary results shown here demonstrate the potential this approach has for facilitating informed decision-making across the building design and building management silos.

A limitation of the model as shown here is its reliance on approximations of dormitory schedules and operations instead of field-based measurements. Field data would permit the creation of a more accurate baseline model, as well as validation of simulation results relative to real-world values. Unfortunately pandemic controls on free-movement and access have prevented us from gathering these data as of this writing. We are continuing to pursue means of ethically and safely obtaining these data, and hope to present these findings in future.

Finally, beyond the horizon of the COVID-19 pandemic we believe that the methods and findings described in this paper can contribute to the creation of a more resilient urban habitat where building design/adaptive reuse and building management can be planned together. Beyond robustness of construction, we believe that a building's configurational capacity to limit congestion and adapt to new uses (like social-distancing) should be central in our understanding of its resilience. Computational methods, such as those presented in this paper, offer a path toward quantifying configurational resilience and incorporating it in an evidence-based design process.

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