Resilient by design: Informing pandemic-safe building redesign with computational models of resident congestion

F. Peter Ortner and Jing Zhi Tay

Abstract
This paper describes a computational design-support tool created in response to safe-distancing measures enforced during the COVID-19 pandemic. The tool was developed for a specific use case: understanding congestion in crowded migrant worker dormitories that experienced high rates of COVID-19 transmission in 2020. Building from agent-based and network-based computational simulations, the tool presents a hybrid method for simulating building resident movements based on known or pre-determined schedules and likely itineraries. This hybrid method affords the design tool a novel approach to simultaneous exploration of spatial and temporal design scenarios. The paper demonstrates the use of the tool on an anonymised case study of a high-density migrant worker dormitory, comparing results from a baseline configuration against design variations that modify dormitory physical configuration and schedule. Comparisons between the design scenarios provide evidence for reflections on pandemic-resilient design and operation strategies for dormitories. A conclusions section considers the extent to which the model and case study results are applicable to other dense institutional buildings and describes the paper’s contributions to general understanding of configurational and operational aspects of resilience in the built environment.

Keywords
Design for resilience, evidence-based design, design support, agent-based model, schedule-based model, network analysis

Introduction
COVID-19 outbreaks in migrant worker housing and the role of design and building operation
The first wave of COVID-19 in 2020 spread predominantly in dense urban environments. High-rise high-density housing, due to the large number of residents and their close proximity to one another, presented a
particularly vulnerable residential configuration. One well-documented case of COVID-19 spread in high-density housing occurred in Singapore, one of the world’s densest nations, which saw an out-break beginning in April 2020 among migrant construction workers housed in dormitories. This paper takes on the Singaporean migrant worker dormitories as a case study: a housing configuration that showed evidence of vulnerability during the pandemic and where evidence-based design intervention was needed. The migrant worker dormitory outbreak in Singapore was successfully brought under control by September of 2020 through application of a series of measures including extensive testing of residents, quarantining, safe-distancing and de-densification.

Designers worked throughout the world in 2020 to make modifications to the built-environment that would permit necessary human activities to take place while keeping spread of the COVID-19 pandemic in check. Many of these modifications were created to support what has come to be called, ‘safe-distancing’: a prescribed physical separation between individuals, intended to reduce risk of contagion. Safe-distancing measures have been applied in Singapore not only to all workplaces, but also to all migrant worker dormitories. Beyond safe-distancing between individuals, additional measures have been proposed for Singapore’s migrant worker dormitories to decrease congestion and risk of contagion: limitations to beds per room, increases to per capita living space, and caps on the number of residents sharing toilets and showers. Safe-distancing and de-densification seek to reduce COVID-19 transmission by decreasing congestion: the number of people in close proximity to one another in a shared space.

In addition to redesign of dormitories, safe-distancing measures have also required modifications to the temporal patterns, or schedule, of dormitory use. In this paper we interpret the need to modify both dormitory physical configuration and schedule as a challenge to architects and dormitory operators to work together to reduce risk of COVID-19 spread among residents. In response this paper presents a design-support tool usable by both architects and building operators that simulates resident congestion in spatial-temporal design scenarios for a dormitory case study with the intention to support safe-distancing and de-densification efforts for reduction of air-borne disease spread. By supporting evidence-based improvements to building design and operation for safe-distancing, the broader goal of this research is to contribute to understanding of resilience in the built environment, that is, a capacity of the complex system of building components and residents to maintain normal function in spite of disruption.

Background information on migrant worker housing in Singapore

To understand the case study of a migrant worker dormitory presented in this paper, some background information on migrant labour and housing in the Singaporean context is needed. This information touches on ethical issues concerning research on vulnerable populations, globalised labour and ties into larger questions of pandemic resilience and urban housing.

Singapore is often described as a nation without hinterland, housing nearly six million inhabitants on an island about half the size of metropolitan London. Its population density is among the highest in the world, and market forces and government policy both reinforce the need to optimise the use of land. Many resources cannot be grown or produced in the country and are imported. A good portion of the workforce in Singapore has also historically been drawn from overseas, especially in the construction sector.

In 2020 there were more than 300,000 migrant workers inhabiting a variety of housing types in Singapore, of which the highest densities were from the Purpose-Built Dormitories (PBDs). The largest purpose-built dormitory in Singapore is the Sungei Tengah Lodge, which houses up to 25,000 residents in 10 housing blocks of 13 stories each.

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. Pandemic response measures, in particular quarantine, have limited their freedom of movement. The research in this
paper was developed to assist in increasing the safety of this housing environment during the period of the pandemic. The authors hope that contributing to a better understanding of congestion in high-density migrant housing in Singapore can provide evidence in a larger discussion on the future of migrant work in Singapore and in other countries facing similar challenges.1

Knowledge gaps for evidence-based design responses to the COVID-19 pandemic

A knowledge gap confronts architects, building managers, and government officials seeking to control COVID-19 spread through safe-distancing: there is limited ability to predict how congestion of building residents will occur dynamically during the entire day as a result of the aggregation of many aleatory movements. These dynamic peaks in congestion can cause breakdowns in safe-distancing measures even under de-densified conditions. Current regulatory and design responses seek to limit occupant densities through standard rules, without taking into account how the combination of occupant movements and spatial configuration produce peaks in congestion.6 While modifications to the layout of rooms, for example reduction of chairs or beds, can reduce occupation in static scenarios, it is currently difficult to predict how changes to design and/or schedule will impact patterns of peak congestion throughout the day. Several types of computational tools have been employed historically to address similar design problems, from which we borrow several features described in our methodology.13,14,15,16,17,18,19

While existing commercial software tools support agent-based simulations for the built environment, the tools we reviewed did not present the combination of design-process integration with social-distancing analytics required by the dormitory case study we address in this paper. PTV’s Viswalk provides large-scale agent-based simulation of pedestrian walking well-suited to identifying congestion and bottlenecks in the shorter itineraries of egress simulations of train stations, airports, events, etc.20 We did not find examples of functionality or use cases for Viswalk where agents visit multiple scheduled destinations over extended periods of time. Closer to the problem of simulating social distancing in migrant worker dormitories is the capability provided by Anylogic’s discrete event models which generate multi-day reports on utilisation of rooms and staff within architectural spaces like a single-story hospital emergency department.21,22 This commercial software, however, does not provide data specific to social-distancing and has the disadvantage of existing separate from architectural design software, limiting its ability to be integrated with iterative redesign scenarios of the sort our research targets.

Addressing the knowledge gap on spatio-temporal congestion relevant to safe-distancing we present in this paper a computational design support tool permitting simulation of redesign and scheduling scenarios for a case-study migrant worker dormitory. The tool is created to provide feedback both on the spatial and configurational drivers of congestion, relevant to architects, as well as the temporal aspects, relevant to dormitory operators.

In this paper we describe key inputs, functions and outputs of the tool in a methods section. We also explain how the tool combines elements of agent-based analysis, network analysis and schedule-based analysis. We present results of test runs on a baseline scenario and several redesign variations, demonstrating the value the tool could present to a user seeking to reduce congestion in a dormitory and improve affordance for safe-distancing. In conclusion we consider broader applications of the tool beyond migrant worker dormitories and its relevance to the study of resilience in the built environment.

Methods

Design tool dataflow

Figure 1 shows the dataflow for our tool in which we define two distinct users: dormitory operators and architects, or dormitory designers. Designers are those proposing direct modifications to design via changes to
spatial dimensions or configurations, that is, connectivity between spaces. Dormitory operators as used here designates any person who plans the schedule of dormitory operations, that is, the timings when certain activities may take place. A third persona, the dormitory resident, is included as a key stakeholder in the data flow shown in Figure 1. Dormitory residents for the purposes of the tool would contribute recommendations or assessments of design or schedule features, feeding into implementation by the users. Surveys of dormitory residents and their integration into the dormitory design-support tool are withheld from this paper and reserved for future publication.

Dormitory operators provide the first key input for our design-support tool: a building schedule detailing the start times and durations for dormitory activities. The dormitory designer is expected to provide the second key input: a dimensionally accurate building circulation network file. These inputs are described in detail below. The building schedule feeds into a scheduler module (M1 in Figure 1) which generates itineraries and timings for all agents in the tool’s simulation. The master-itinerary for all agents then feeds into a path tracer module (M2 in Figure 1) which plots out the movements of all agents in the simulation within the building circulation network. The path tracer outputs two visualisations of congestion, one emphasising spaces with high congestion, the other emphasising times of high congestion, which feed back to the users of the tool who may choose to modify their inputs in pursuit of different or better results. The scheduler and path tracer modules have been created using Python scripting and the visual programming interface Grasshopper for Rhinoceros 3D.

Scheduler module: from simple schedule inputs to many agent itineraries

Our first set of key inputs are schedule parameters used to generate a master schedule providing location data points for all agents at all time values for the simulation. The user is prompted to input a list of all relevant activities to be included for the dormitory residents. The current model includes activities like ‘return from work’, ‘arrive in canteen’, ‘arrive in bedroom’, etc.

A list of inputs is required for each defined activity: (1) space name; (2) first use; (3) last use; (4) min. number of visits; (5) max. number of visits; (6) min. visit duration; (7) max. visit duration. The user will also designate the number of agents to run in the given simulation. These values provide the overall controls of the movements of the agents during the simulation period.

The scheduler module generates itineraries for all agents falling within the bounds defined by the inputs listed above. These itineraries vary by a random factor with commencement of each activity constrained by inputs 2–3, number of repetitions constrained by 4–5, and duration constrained by 6–7. The resulting agent
itineraries reflect without replicating the variability of resident activity in existing dormitories, while leaving
decisions about how much constraint to place on agent schedules to the end user.

The system of inputs described here requires that all agents fall within the constraints of a pre-defined use-
persona, in this case for migrant workers, with a limited and predefined pattern of using the building. Persona-
based schedules are appropriate to our case study on migrant worker dormitories where work-day schedules
are repetitive but could find applications for other institutional buildings like universities, hospitals or indus-
trial buildings.22,23

Two outputs are generated by the scheduler module; a visually legible timesheet and a complete and
extensive comma-separated values (CSV) data file. The timesheet is a graphic element that is generated within
the design environment, representing a colour-coded timeline for all agents in the simulation with each
activity assigned a different colour (Figure 2). It provides visual feedback to the end-user on the distribution of
agent activities over time. The CSV file acts as the input for the next module in the tool, the path tracer. With
these two outputs the user can choose to make overall modifications to the schedule by adjusting the scheduler
parameter inputs and checking them via the colour-coded time sheet or to make minor edits to the output
schedule by manually editing the values of the CSV file.

Path Tracer module: scheduled-based simulation of agent movements

The next key input for our computational model is a network representation of the dormitory case study, as a
list of labelled nodes and edges (Figure 3). This network representation is a three-dimensional, dimensionally
accurate reflection of the building geometry, traced from the building floor plans. Generating the building
network representation of the case study dormitory has been achieved manually for the purposes of this paper,
carried out by a design professional working with detailed floorplans and exercising judgement in the carrying
out the following steps: (1) circulation spaces are represented by line segments along their centrelines; (2)

Figure 2. Baseline schedule (left) represents of a typical dormitory working day. Staggered schedule (right) reflects
design variation 1. Pickup drop-off point is abbreviated as PUDO.
floors; (5) intersections between edges split the edges into separate line segments; (6) each node is assigned a unique identifier using the ‘name’ attribute of the geometry in the Rhinoceros interface (i.e. BED 3–1–2 indicates bed number 2 in bedroom 1 of level 3.) Lists of nodes and edges are imported into the Grasshopper scripting interface to generate an undirected network. Node identifiers are imported into Grasshopper as a separate meta-data list.

With the input of the building network representation the path tracer module assigns each agent to an available node for each of that agent’s scheduled activities. Some nodes, like beds or toilets, permit single or one-at-a-time assignment, whereas most permit occupation by multiple agents at the same time. Agents are automatically assigned to nodes closest to their point of origin when there are multiple options for an activity.

Having assigned each agent to a list of nodes, the path-tracer then generates the paths taken by each agent over the course of the simulated day. It first extracts origin-destination pairs of nodes for each agent movement. For each origin-destination pair a shortest path through the building network is generated using the A* algorithm. A constant walking speed is used to calculate the time taken by the agent to move from origin to destination. Walking time is then subtracted from the time of departure, so that each agent leaves their origin ‘early’ and arrives precisely ‘on-time’.

The path tracer simulates the location of every agent for every second in the simulation period. The case study simulations presented in the results section of this paper starts from 00:00:00 and run till 23:59:59; a total of 86,400 s. The final output from the path tracer, before analysis and visualisation, is a data tree where each branch contains a list of points representing an agent’s location at a given time interval.

Analysis: Usage and congestion

Two metrics are employed to analyse the outputs from the path tracer module. The first analysis measures the number of times a space is used over the course of a typical day, providing a general overview of congestion ‘hotspots’. We have called this metric, usage, and define it as the sum of all instances of an agent moving over a given graph edge during the course of the simulation period. Usage has close analogues in the domain of urban network analysis, where it is similar to the betweenness metric, although it does not calculate all paths from all nodes, but rather only the agent itineraries generated by the path tracer. Similar to betweenness, the usage metric attempts to predict aggregate footfall in a

**Figure 3.** Conversion of case study dormitory to a network representation. Volumetric model (a) is extracted and converted to nodes and edges (b), which are tagged according to function (c) and lateral dimension (d).
given space. Usage is also analogous to the ‘utilisation’ metric which measures frequency of use for a given space in a discrete event model.22

The second analysis estimates how crowded a given space will become at any given time of the day, by taking into account how big that spaces is, and how many people it should normally accommodate given safe-distancing guidelines. We have called this metric congestion, and for the purposes of our simulation it is defined as the number of agents present at a graph edge during a time slice, divided by the number of agents that the edge should accommodate given its area and safe-distancing guidelines. As we have defined it, congestion values less than one indicate that safe-distancing guidelines would be possible to follow, whereas values greater than one indicate that safe-distancing cannot be successfully employed in that space. Congestion, as we define it, is similar to the definition used in traffic simulation, where it is equal to the ratio of traffic along a roadway at a given time relative to the capacity of the road. As in traffic simulation it helps us understand where traffic bottlenecks may occur in a constrained system of many moving agents.15

Congestion at a time \( t \) is calculated by first counting the traffic \( T_i \) of agents lying on edge \( E_i \), where \( A(t) \) represents the position of each agent at time \( t \) (see Figure 4). Subsequently, to calculate congestion of node \( E_i \) at time \( t \) \( C_i(t) \), we take the ratio of traffic \( T_i \) to capacity, where capacity is equal to the area represented by the edge \( E_i \) in square meters divided by a constant \( \alpha \). The constant \( \alpha \) is the safe-distancing factor, equal to the minimum area assigned per agent. Given the 1 m safe-distancing measure mandated in Singaporean workplaces, we have assigned a value of 1 m² to \( \alpha \).4

Our tool has two distinct types of visualisation output, a spatial visualisation and a time-based visualisation. The spatial visualisation is three-dimensional and provides an overview of where usage and congestion hotspots occurred in the building during the simulation (Figures 5 and 6). Higher levels of congestion are indicated by increasing the thickness of the edge and changing its colour. The three-dimensional visualisations show aggregate results for the full simulation period. Comparing between design variations provides visual feedback if a design change, for example a new corridor, has been successful in alleviating congestion in the model.

The temporal visualisation, in contrast, helps the user understand when congestion is happening in the simulation, as opposed to where. This information is presented as a linear time-series graph showing the cumulative congestion level for the entire model (y-axis) at each time \( t \) (x-axis) (Figures 5 and 7). The linear graph of cumulative congestion gives us an overview of how a design variation performs over the course of the simulation period and provides the basis for us to draw quantitative distinctions between design variations in our results.

```python
def Congestion (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 \alpha / Area_i
    return C_i (t)
```

Figure 4. Pseudo-code for computation of congestion. Visualisation of building usage and congestion in space and time.
To facilitate comparisons of congestion peaks between multiple design variations we introduce a deviation graph which presents the difference between the design variation’s cumulative congestion value and that of the baseline design. In Figure 5 on the right the deviation graph for design variation 1, curve (c), is shown lying along the x-axis. Above it the congestion curve for the baseline design, curve (b), and design variation 1, curve (a), are shown. The difference between curve (b) and curve (a) is equal to the deviation value plotted as curve (c). A positive value in the deviation graph indicates that the proposed design variation out-performs the baseline configuration during that time interval, as shown in the area hatched in grey. In Figure 7 we compare between design variations by overlaying their deviation graphs. In Figure 8 we compare deviation values over certain time ranges and summarise with the cumulative deviation score for each design variation.

Results and discussion

Case study analysis of a migrant worker dormitory and design variations

The results we present in this section have been generated by applying the design tool described above to a case study of a work dormitory. Below we analyse both a baseline scenario for the dormitory as well as several design variations which modify either the building schedule or configuration.

The dormitory case study information has been generously shared by a local industry contact and has been anonymised for the purposes of publication. Similar to other Singaporean Purpose-Built Dormitories, this is a high-rise high-density dormitory configuration combining two twelve story housing blocks and a low-rise canteen building on a single site. It is capable of housing more than a thousand residents even with safe-distancing restrictions in place. Upper levels of the dormitory have a repeated design, consisting of twelve and eleven apartments for the two blocks, respectively, each fitted with four beds, kitchen and toilets, along with two lift cores and two recreation rooms per block. The ground level contains twelve and six apartments with two recreation rooms per block and additionally a pickup and drop off (PUDO) point, circulation routes to the
canteen and other ancillary spaces (such as administrative offices and carparks, which are ignored for our analysis).

Dormitory de-densifying measures as proposed in Singapore have been applied to our model, with no more than 10 beds appearing per room. Our simulations use a further constrained population size of two hundred

Figure 6. Usage index diagram (top row) and maximum congestion index diagram (bottom row) for design variations.
Figure 7. Congestion index deviation plot for each design variation. Plotted values are the average of the cumulative congestion for every edge in the model over a five-minute time range. Design variation 1: testing staggered timings for reduced congestion.
and fifty-six agents constrained to the first three floors of the building to improve the run time required for each simulation. Agents are further constrained to use only the vertical circulation core closest to their allocated bedroom, in accordance with prevailing safe-distancing measures. As the floor plans and space use are similar on upper floors of the case study building, removing them from the simulation affects both the maximum and minimum range of our congestion and usage results. Given these limitations, in our results we emphasise the value of the current simulations in making evidence-based comparisons between design variations.

**Baseline schedule and analysis for the dormitory case study**

To generate a baseline set of results for our case study dormitory we first developed a baseline schedule based on a ‘typical work day’ for a Singaporean migrant worker dormitory. This schedule is based on relevant literature as well as an interview with a local dormitory operator. A typical work day for a migrant worker in the construction industry begins between 04:30 and 05:30 for morning showers or prayers in order to meet the strict timings for transportation to the worksite organised by their employers. The timings implemented in our baseline schedule follow the government regulated start and end times of 07:00 to 19:00 for most types of construction work. The workers typically have breakfast and lunch on site and return for dinner at the dormitory. Most purpose-built dormitories have a canteen to serve these workers during the evenings and on their off days. Their dinner time will fall between 19:00 to 21:30, depending on the work schedule and the individual’s preference. In the evening time is spent at recreation facilities, watching television or calling loved ones at home. Their day will typically end between 22:00 to 23:00. Given this general schema for a Singaporean migrant worker’s day, we created the baseline schedule shared in Figure 2, left.

**Figure 5.** Shows the results of analysis for the baseline schedule with an un-modified network representation of the case study dormitory. Ground-floor destinations which all agents must move through are reflected as hotspots in the usage analysis (Figure 5, left) with the corridors connecting the canteen and the pick-up drop-off point showing highest overall use. Providing more detail, the congestion analysis (Figure 5, middle) shows that vertical circular spaces at every level show higher level of congestion, reflecting the narrower dimensions of these spaces in combination with their use by many agents. The time series graph of cumulative congestion for the baseline shows peak congestion (Figure 5, right) at around 05:30, with a steep drop off by 06:30.

| Time Range  | Variation | 1 Schedule change | 2a Add canteen route | 2b Add PUDO | 2c 2a + 2b | 3a Add 2 lifts | 3b 3a + 2c |
|-------------|-----------|-------------------|----------------------|-------------|------------|--------------|------------|
| 0400 to 0500 |           | 72.65             | 0.00                 | 0.00        | 0.00       | 0.00         | 0.00       |
| 0500 to 0600 |           | 235.22            | 65.54                | 65.54       | 65.57      | 6.80         | 73.49      |
| 0600 to 0700 |           | -239.25           | 58.21                | 58.21       | 58.25      | 11.21        | 67.02      |
| 1800 to 1900 |           | -736.18           | 19.23                | 19.23       | 21.89      | 14.27        | 32.78      |
| 1900 to 2000 |           | 2.97              | 0.00                 | 0.00        | 14.47      | 26.48        | 33.19      |
| 2000 to 2100 |           | -24.49            | 0.00                 | 0.00        | 18.80      | 21.21        | 35.62      |
| 2100 to 2200 |           | 135.72            | 0.00                 | 0.00        | 0.00       | 11.69        | 11.69      |
| 2200 to 2300 |           | 9.03              | 0.00                 | 0.00        | 0.00       | 0.39         | 0.39       |
| Cumulative deviation from baseline congestion values | | -544.33 | 142.97 | 142.97 | 178.98 | 92.05 | 254.19 |

**Figure 8.** Summary table of congestion deviation for each design variation.
Beginning with a design variation relevant to dormitory operators we tested the congestion impacts of staggering worker schedules. In this test we created three groups of agents, assigning each a different time range for work and for dining: the two activities resulting in the greatest congestion level. By offsetting each group’s time range by 45 min and assigning a 30-min meal duration we were able to fully separate each group from the other two during mealtime (Figure 2, right).

Analysis of this design variation shows mixed benefits. In the morning the staggered times result in improvements over the baseline before 06:30 but perform less well than the baseline after 06:30 as agents are held back and released to ‘work’ at later times (Figure 7). From 17:00 to 23:00 the deviation value for design variation 1 swings back and forth between large improvements over the baseline and dips below the baseline (Figure 7). This oscillation is the result of periodic overcrowding during mealtime as each cohort is forced to move almost simultaneously in and out of the circulation spaces leading to the canteen to accommodate the staggered timing. Once agents arrive in the canteen, however, the congestion of that space is better than the baseline result. These results show the limitations of schedule staggering as a solution for safe-distancing in migrant worker dormitories.

**Design variations 2 and 3: Testing dormitory reconfiguration for reduced congestion**

To test how the design tool might support decisions on dormitory redesign for reduced congestion, we next ran the simulation for a set of reconfigured variations of the case study dormitory. These design variations were created in response to observations of congestion hotspots in the baseline design. As shown in Figure 5 the PUDO point and canteen show the highest values for both usage and congestion. Introducing redundant paths to these two high-traffic areas functions would seem a likely measure to improve safe-distancing; we study these options in design variations 2a-c. Finally, as congestion has been observed at every level near areas of vertical circulation, in variation 3a and 3b we test the effect on congestion of inserting additional lift cores.

**Figure 6** presents the usage and congestion diagrams for each design proposal as well as the baseline. The values represented are the maximum usage and maximum congestion of each variation during a twenty-four-hour simulation.

Variations 2a, 2b and 2c explore the effects of adding circulation space at the ground level of the dormitory. Variations 3a and 3b test the effect of adding additional vertical circulation spaces. Variation 2a adds an alternative access point to the canteen, linking the canteen to an underused lateral pathway between the two housing blocks. Variation 2b introduces a secondary PUDO point adjacent to the canteen. Variation 2c combines proposals 2a and 2b to test if the improvements made in each variation is additive. Variation 3a adds a new lift at the centre of each housing block. Finally, variation 3b combines all proposals, again, to test if the improvements are additive.

Usage analysis, shown in the top row for each design variation in Figure 6, indicates that paths leading to the canteen at ground level are the greatest contributors to the maximum usage index of the dormitory. Maximum usage analysis for variations 2a, 2c and 3b demonstrates that providing alternate pathways to common areas diverts existing traffic flow, creating new traffic hotspots of lower intensities at areas that were previously underutilised.

Congestion analysis, shown in the bottom row for each design variation in Figure 6, provides a more nuanced understanding of patterns of movement, reflecting for example that in variation 2c the newly added access to the canteen results in a bottleneck only in the upper half of the housing block corridor. This analysis provides understanding of the ratio of momentary surges in traffic relative to the size of the space in which they occur. The congestion analysis for variation 2c suggests that the new path connecting to the canteen may be adequately sized, but that the internal corridor for the housing block remains undersized and in need of further design study. Congestion analysis of variation 3a suggests that adding new lifts alone is not an
effective solution to mitigating maximum congestion, as the narrow corridors at the ground level still retain high values for congestion.

To support more precise comparison of congestion improvements between design variations our tool generates the comparative time series graphs shown in Figure 7. The graph for variation 2a (Figure 7) shows that cumulative congestion improves modestly over the baseline during mealtimes from 18:30 to 20:30. This is an expected result given that the design variation provides additional access to the canteen. Figure 7 further shows that variation 2b improves over the baseline when agents are exiting the dormitory from 05:30 to 06:30 and returning from 17:00 to 18:00. Again, this modest improvement is expected from a design intervention that adds a new PUDO point. The combination of the two design variations in 2c results in a combination of the improvements from the two individual design interventions, with some minor fluctuations. Interaction between the two interventions is limited, however, as they are used at different times during the schedule. If the new PUDO point and the canteen access were in use simultaneously we would expect greater complexity in the outcome. A further finding represented in Figure 7 is that variation 3a (addition of two lift cores) provides only modest improvements over the baseline.

Finally, for design variation 3b, we see that the cumulation of the design proposals results in a modest net improvement in congestion (Figure 7). In Figure 8, where we summarise the cumulative improvements in congestion over the baseline, variation 3b is highlighted as the best net improvement in congestion overall. We would pair this result with a qualitative observation: by facilitating easy access to the canteen and recreation spaces in the evening hours, this design variation might also improve the liveability of the dormitory for its residents.

**Discussion: Comparing results between schedule changes and dormitory reconfiguration**

A final question that our results permit us to address is whether there is a comparative advantage to schedule changes versus dormitory reconfiguration in reducing congestion and thus facilitating safe-distancing. In Figure 7 the cumulative congestion deviation values are overlayed between design variation 1 and design variations 2a-3b. While the staggered schedule introduced in variation 1 does result in the largest individual improvements over the baseline, these improvements are accompanied with large negative swings. The improvements shown in variations 2a-3b, in contrast, are less than half as large as those demonstrated by variation 1, but do not result in the pattern of oscillation from low to suddenly high congestion. Aggregating the total congestion deviation (equal to the area between the curve and x-axis in Figure 7) for each of these variations in Figure 8 we can see that variation 1 does not result in a net improvement in congestion over the baseline. Variations 2a-3b, while they make smaller individual improvements, do result in net improvements over the course of the day. Finally, variation 3b shows evidence of the greatest net improvement in cumulative congestion.

While our initial tests with the design tool seem to suggest that design reconfiguration provides a better overall improvement to dormitory congestion in comparison to schedule changes, more work is needed to confirm this result and by no means do we suggest that schedule changes cannot be employed as a safe-distancing measure. The data also suggests what other considerations must be taken into account when implementing schedule adjustments (e.g. which hotspots to monitor, and when/where to regulate foot traffic.) Our design tool could be used to iterate between design and schedule adjustments to ensure that adequate timing, flexibility and overflow spaces are provided to prevent the fluctuations in congestion observed with our test of a staggered schedule (design variation 1 in Figure 8).

Furthermore, schedule changes present a decided cost advantage in comparison to design reconfiguration. The introduction of new vertical circulation or vehicular access points is both costly and time consuming, so that the improvements in congestion shown in variations 2 and 3 may in the end not be economical to achieve. We would intend for the design tool to provide evidence supporting broader negotiations between the
dormitory designer, its operator and its residents as they seek safe, economically feasible and more liveable outcomes for returning the dormitory to working operations in the post-COVID-19 ‘new normal’. The data shown here is part of this negotiation, but without integrating understanding of cost and meaningful feedback from the residents it is only part of the overall picture.

**Conclusions: Computational design for resilience in the built environment, COVID-19 and beyond**

The computational design tool presented in this paper proposes a method both for simulating resident congestion in a dense institutional building, and for using these simulations to inform decisions on building operation and redesign for safe-distancing in the context of the COVID-19 pandemic. By taking both building schedule and building layout as input and outputting spatial and temporal analysis, the tool seeks to support cooperative decision making between the domains of building operation and building design. The results presented above give a preliminary indication of how changes to schedule and design could be proposed and evaluated together, to identify the best outcomes for safe-distancing in a case study of high-rise high-density worker dormitory.

The ability of a building’s design to improve outcomes for residents during a pandemic can be considered an example of resilience, that is, the capacity of a system (here a building and its inhabitants) to return to normal function after a disruption.7,8,9,10,11 By measuring and comparing the capacity of several design variations to accommodate pandemic-related safe-distancing regulations, this research provides not only a tool for evaluating an aspect of resilience in the built environment, but also an evidence-based method of design for resilience. These contributions remain confined to the narrow parameters of the case study addressed in this paper but are intended to provide a step toward broader understanding of resilience in the built environment and design methods capable of generating more resilient building designs across typologies.26

The work presented in this paper also raises questions requiring further study on ethics of design methods for resilience, in particular the question of for whom the design tool should work—or who is the appropriate end user. The design tool presented in this paper targets the building designer and building operator as primary users, with inputs and outputs that specifically target these two user profiles. This predetermination of user profile is pragmatic considering that architects and dormitory operators have been working extensively in 2020 and 2021 to protect dormitories from COVID-19 spread and are in need of tools to support this effort.2,3,6 However, more could be done to provide computational affordances for the integration of crucial information from the building residents. The authors remain engaged in an effort to obtain this information and see its integration with the design tool as a necessary future step for a comprehensive and ethical approach to answering the question of how to make housing safer and more liveable for migrant workers.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Singapore University of Technology and Design (Start-up Research Grant: Design for Resilience and Circularity).

**ORCID iDs**

Frederick P. Ortner  ⓒ https://orcid.org/0000-0002-3376-7852

Jing Zhi Tay  ⓒ https://orcid.org/0000-0002-4822-704X
References

1. Moroz H, Shrestha M and Testaverde M. Potential Responses to the COVID-19 Outbreak in Support of Migrant Workers. Washington, DC: World Bank, 2020.
2. Ministry of National Development. Joint MND-MOM Media Release on New Dormitories with Improved Standards for Migrant Workers [Internet]. Singapore: Ministry of National Development. 2020 [cited 2020 Nov 26]. Available from, https://www.mnd.gov.sg/newsroom/press-releases/view/joint-mnd-mom-media-release-on-new-dormitories-with-improved-standards-for-migrant-workers
3. Ng M and Seow J. New dorm standards good for workers but will come with inevitable cost hike: Dorm operators. The Straits Times 2020 Jun 4.
4. Parliament Singapore. Infectious diseases act (Workplace Measures to Prevent Spread of COVID-19) Regulations 2020. Chapter 137 Sect 73, Singapore: Ministry of Health of Singapore. Apr 1, 2020
5. Ministry of Health. Update on border and community measures [Internet]. Singapore: Ministry of Health. 2020 [cited 2020 Nov 19], Available from, https://www.moh.gov.sg/news-highlights/details/updates-on-border-and-community-measures
6. Ministry of Manpower. Advisory for dormitory operators on implementation of Safe Living measures in foreign worker dormitories [Internet]. Singapore: Ministry of Manpower Singapore. 2020 [cited 2020 Nov 19], Available from, https://www.mom.gov.sg/covid-19/advisory-for-dormitory-operators-on-safe-living-measures-foreign-worker-dormitories
7. Holling CS. Resilience and Stability of Ecological Systems. Annu Rev Ecology Systematics 1973; 4(1): 1–23.
8. Hassler U and Kohler N. Resilience in the built environment. Building Research Information 2014; 42: 119–129.
9. Hollnagel E. Resilience engineering and the built environment. Building Research Information 2014; 42(2): 221–228.
10. Hill AC. The resilient design imperative: a Call for Action. Technology|Architecture + Design 2019; 3(1): 11–15.
11. Meadows D. Limits to Growth and the COVID-19 epidemic. Chelsea Green Publishing [Internet]. 2020 [cited 2021 Aug 13]; Available from, https://www.chelseagreen.com/2020/limits-to-growth-covid-epidemic/
12. Ministry of Manpower. Foreign workforce numbers [Internet]. Singapore: Ministry of Manpower Singapore. 2020 [cited 2020 Nov 19], Available from, https://www.mom.gov.sg/documents-and-publications/foreign-workforce-numbers
13. Hillier B and Hanson J. The Social Logic of Space. Cambridge, UK: Cambridge University Press, 1984.
14. Ulicny B and Thalmann D. Towards Interactive Real-Time Crowd Behavior Simulation. Computer Graphics Forum 2002; 21(4): 767–775.
15. Poon MH, Wong SC and Tong CO. A dynamic schedule-based model for congested transit networks. Transportation Research Part B: Methodological 2004; 38(4): 343–368.
16. Goldstein R, Tessier A and Khan A. Schedule-calibrated occupant behavior simulation. In: SpringSim ’10: Proceedings of the 2010 Spring Simulation Multiconference, Orlando, Florida, April 11–15, 2010. San Diego, CA: Society for Computer Simulation International; 2010. p. 1–8.
17. Sevtsuk AOE. Capturing Urban Intensity. In: Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)/Singapore, Singapore, 15-18 May 2013, pp. 551–560. CUMINCAD 2013.
18. Sevtsuk A. Analysis and Planning of Urban Networks. In: R Alhajj and J Rokne (eds). Encyclopedia of Social Network Analysis and Mining. New York, NY: Springer; 2014, pp. 25–37.
19. Patt TR. Multiagent approach to temporal and punctual urban redevelopment in dynamic, informal contexts. International J Architectural Computing 2018; 16(3): 199–211.
20. PTV Group. PTV Viswalk.https://www.ptvgroup.com/en/solutions/products/ptv-viswalk/(accessed 28 September 2021).
21. The AnyLogic Company. Discrete Event Modeling, https://www.anylogic.com/use-of-simulation/discrete-event-simulation/(accessed 28 September 2021).
22. The AnyLogic Company. Emergency Department-Simulation Models in AnyLogic Cloud, https://cloud.anylogic.com/model/6e194505-23a9-4029-8b3d-411b99d61451?mode=SETTINGS&tab=GENERAL (accessed 28 September 2021).

23. Goldstein R, Tessier A and Khan A. Customizing the Behavior of Interacting Occupants using Personas. In: IBPSA-USA SimBuild Conference, New York City, New York, August 11-13, 2010.

24. Hart PE, Nilsson NJ and Raphael B. A formal basis for the heuristic determination of minimum cost paths. IEEE Transactions on Systems Science Cybernetics 1968; 4(2): 100–107.

25. National Environment Agency. Construction Noise Control [Internet]. 2020 [cited, 2020 Nov 19]. Available from, https://www.nea.gov.sg/our-services/pollution-control/noise-pollution/construction-noise-control

26. Ceré G, Rezgui Y and Zhao W. Critical review of existing built environment resilience frameworks: directions for future research. International J Disaster Risk Reduction 2017; 25: 173–189.