Connect or Adapt: Analytic Framework for the Planning and Design of Resilient Spatial Networks

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ABSTRACT: A high level of connectivity is one of the key objectives in the planning and design of many urban developments. However, during an epidemic event, a frequent practice to control the spread of the disease is to control the access, e.g., through measures of safe distancing (social distancing) or zone isolation (lockdown). These measures conflict with the objective to increase the connectivity of spaces, i.e., the increment of connectivity would also increase the possible movement of people between places and thus increase the risk of disease spreading. Therefore, the evaluation of the development layout and the resilience of its spatial network with the consideration of both connectivity and separation becomes an important task. To understand how the connectivity of spaces affects the spread of a disease, this paper proposes an analytic framework based on the spatial mapping of human movement at the urban and architectural scale. This approach allows for the evaluation of the effects of isolating spatial nodes on the disease spreading process in a spatial network. Our paper explores how the connectivity of nodes affects people flow and identifies the morphological and typological features of a spatial layout that relates to that connectivity. Next, it evaluates the dynamic effects of altering the network structure on movement and clustering of people through a series of link removal analyses. Our findings suggest that for the scale of our case study, a compact university campus in Singapore, complete zone-separation or isolation measures may not be necessary. Instead, breaking the high edge-betweenness links can increase the spatial separation while reduce physical interactions and close contacts by forcing people to take less frequented route detours. By framing the spaces of such a built environment as a complex adaptive system, the results provide important insights into human-centered design and interventions for public health at the building and urban scale.

KEYWORDS: Spatial connectivity, lockdown, disease control, post-pandemic, COVID-19
PAPER SESSION TRACK: **PUBLIC HEALTH: Public Health and Public Space**

1 INTRODUCTION

1.1 Background

Increasing connectivity is one of the key objectives of many urban developments, because the accessibility and efficiency of space use improves as the connectivity between spaces increases (Cervero 2004; Gopalakrishnan et al. 2021). Previous studies indicated that strong spatial connectivity could attract higher traffic and more visits of people (Jiang 2009; Chin and Wen 2015), Increasing connectivity does not only improve the accessibility between spaces but also has significant effects on fostering social integration, which can contribute to more cohesive communities (Eom and Cho 2015). Previous studies suggested that a connected space can increase walkability and thus have a positive effect on health (Eom and Cho 2015). Vibrant and accessible urban form was also found to generate a better community in terms of social cohesion (Mouratidis and Poortinga 2020).

However, during an epidemic event, a common and effective practice to control the disease is social distancing. This is because the spread of a person-to-person infectious disease happens when two persons interact physically in a space. In the case of COVID-19, the virus is transmitted through droplets (Wu et al. 2020) and spread through the air or aerosols (Galbadage et al. 2020), meaning that a sufficient physical distance between people can protect the susceptible person. Therefore, various levels of distancing measures---from the collective to the individual level---have been implemented widely during the COVID-19 epidemic. At the large scale, borders were closed to reduce the interactions between countries, states and cities (Dickens et al. 2020; Koh 2020). At the individual scale, people have been working from home whenever possible. They also have been distancing themselves from each other while leaving their home for essential activities, including shopping, and traveling on public transportation (Williams 2020). In other words, the concept behind these zone isolation and social distancing measures has been to reduce the connection between spaces and people.

These disease control measures counter the objective to increase the connectivity of spaces, i.e., the increment of connectivity also increases the possible movement of people between places and thus increase the risk of disease spreading. As such, the evaluation of the architectural layout and the resilience of a spatial network with the consideration of both connectivity and separation becomes a critical issue. To understand how the connectivity of spaces affects the spread of disease, this paper proposes a framework to analyze the human movement process in the architectural-urban scale against the features of its spatial design, and to evaluate the possible effects of space isolation to the spreading process in a spatial network. This study combines structural analysis, which focuses on network and spatial configurations, with circulation analysis which analyzes the movement of people through the network (Boeing et al. 2021). Network vulnerability is a commonly discussed issue in complex network analysis on connectivity, e.g., power grid networks (Bompard et al. 2010; Wang et al. 2011), cargo shipping networks (Ducruet et al. 2010; Viljoen and Jourbert 2016), and human movement networks (Wen and Chin 2015; Morelli and Cunha 2021). Based on a network vulnerability measurement, Wen and Chin (2015) developed a framework to analyze a building-to-building network within a campus to identify the vulnerable links, i.e., the links that if removed, would increase the separation within the network, and propose a way to generate the isolation zones by removing those links during a disease outbreak.

1.2 Research design

Using the Singapore University of Technology and Design (SUTD) Campus as a case study, our paper explores how the connectivity of nodes affects people flow and identifies the morphological and typological features of a spatial design that relate to that connectivity. Our study evaluates the dynamic effects of altering the network structure on movement and clustering of people through a series of scenario analyses. From the point of view of complex network studies, we can assume that people tend to take the shortest path to move from one node to another, and this shortest path could shape the spatial distribution of the intensity of human movement to a significant level, through the emerging pattern in the spatial network (Jiang 2009; Chin and Wen 2015). Adding barriers to block the connections---spatial zoning---is a strategy to generate and increase the separation of places. In other words, adding barriers forces people to take an alternative path and thus increases the separation of people. In our study, we intended to test how the zoning of places could improve the separation of spaces and to what degree the accompanying effects in terms of spatial distancing could be maximized. By framing the spaces of a built environment as a complex adaptive system, the results provide important insights into human-centered design and interventions for public health at the urban and building scale. Especially in the event of a pandemic like COVID-19, it is salient for planners and designers to consider an evidence-based public health process as routinely as that of sustainability, with planning principles and design elements at varying scales guided by empirical data (Azzopardi-Muscat et al., 2020).

2 MATERIALS AND METHODS

2.1 SUTD Campus and network dataset

SUTD is one of six autonomous universities in Singapore. Its permanent campus opened in 2015. The academic buildings of the campus cover an area of approximately 83,000 m^2 and are currently composed of four interconnected buildings --- 1, 2, 3, and 5, with 4 slated for future development (see Figure 1). The spatial organization of the campus adopted two main concepts, ‘Circulation’ and ‘Interaction’ (Schroepfer 2017) --- with horizontal, vertical, and diagonal flows connecting the spaces of the four buildings. UNStudio --- the architectural firm behind the SUTD project --- conceptually designated two main axes of circulation, the 'Learning Spine' and the ‘Living Spine' which intersect at a central interaction zone --- the Campus Centre. Several interaction zones also serve as connective point, i.e., skybridge connections between Buildings 1 and 2 and 5, vertical staircases at the corners of buildings, circular staircases at the Campus Centre and a garden leading up to the Level 3 Sky Garden. An efficiency of circulation and multiple zones of interaction define the user experience on the campus.

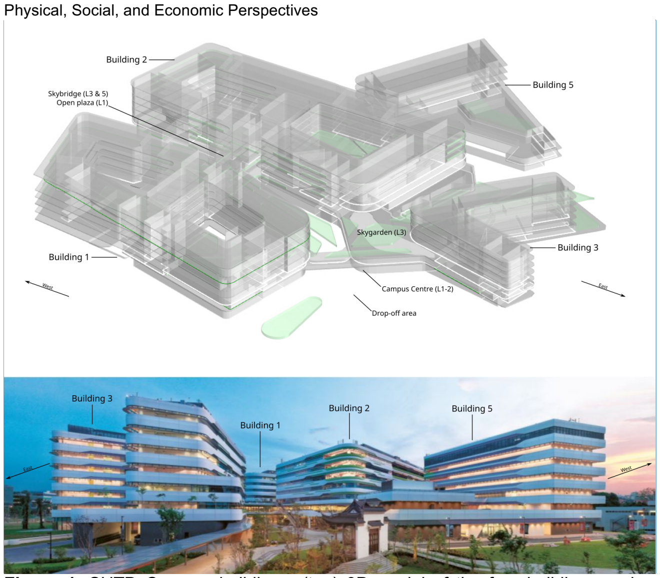

Figure 1: SUTD Campus buildings: (top) 3D model of the four buildings and connections between buildings and (bottom) the photo of the case study buildings from the northeast exterior. Source: (Photograph by Daniel Swee)

In our study, we extracted node points from the main program areas and defined edges by connecting each node point to other program areas which are spatially accessible via doorways and corridors. We assigned the Euclidean distance between the nodes to their corresponding edges as is the case for spatial networks. We also consolidated adjacent elevator cores and stair lobbies as a single node and connected them directly and to all other vertically adjacent lobby nodes, considering elevator and stair cores as 'vertical streets' with lobbies on each floor as node points.

2.2 Analysis framework

Our study of SUTD was organized in three major steps: (1) a set of visualization of the network centrality measures in 3-dimensional physical space, for an overview understanding on the connectivity of spaces using quantification metrics from complex networks; (2) an experiment of continuously removing high betweenness edges to increase separation of nodes were performed and the corresponding outcomes of the edge removals were also presented; (3) the current intensity of activity in the main connection nodes of the campus was recorded, presented and discussed.

In the first step, we used the following three centralities (degree, closeness, and betweenness centrality) for measuring the connectivity of nodes (Freeman 1978; Barrat et al. 2004). Degree centrality shows the number of connected links for each node. Closeness centrality measures the distance (in steps) from a node to the rest of the network. Betweenness centrality captures the critical level of a node in terms of being the connection between communities. The three centralities are the simplest yet useful measurements in complex network analysis for the measurement of important levels of nodes within the network.

The second step in our study was an experiment to assess the effect of edge removal to the separation degree of the spaces. The procedures include three phases: (1) identify of high betweenness edges, (2) remove the top ranked edges iteratively, and (3) calculate the effects of the removal. For the first step, edge-betweenness index --- a variant of betweenness centrality for edges (Girvan and Newman 2002) --- was used because the removal of edges with high values of this index would have strong impact on separating the network structure into zones (Wen and Chin 2015). In the second phase, the edges were ranked in descending order and the edges with the top 50 edge-betweenness indexes were removed iteratively. During each removal, two node-level indexes were calculated for the evaluation of the effects: closeness centrality and PageRank.

Closeness centrality measures the 'closeness' of a node to the rest of the network---i.e., the reciprocal of the average shortest path lengths from one node to all other nodes. This means that closeness centrality can capture the opposite of the 'separation' level (Freeman 1978; Wen and Chin 2015). By removing the links, the intention is to increase the separation of nodes and to create the zoning effects within the network. Therefore, the removal of links increases the separation level and decreases the closeness. In other words, by monitoring the reducing trend of closeness, the effectiveness of the links removal can be evaluated. Since the removal of links potentially splits the network into disconnected components, we used the Wasserman and Faust improved version of closeness (Wasserman and Faust 1994) through the Python NetworkX package, which takes the multiple components of a network structure into account.

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The average closeness centrality was used to evaluate the overall separation level of the network in each of the iterations.

PageRank is a metric for measuring the proportion of people (originally simulating random internet surfers) visiting each node after entering an equilibrium state (Brin and Page 1998). In our study, we intended to understand how people move when the network structure changed---some links were removed. To this end, PageRank is a suitable measurement for capturing the proportion of people who would visit each node. We calculated the Shannon Evenness Index based on the PageRank scores to evaluate the level of evenness of the distribution of nodes' proportion of people. The measurement of evenness is to evaluate how people would move and be spatially distributed with some spatial links removed. In theory, when critical paths (typically the most connected and convenient paths) are blocked, people use alternative paths and thus the proportion of people is divided and split into different nodes. Hence, the increment of evenness of the system. Here, we intended to explore how that evenness would change and to what level the removal of links could increase the evenness of the distribution of people.

In the third step, we collected the movement data via people counters to explore empirically the human movement patterns within the campus (Wong et al. 2021). We installed several SensMax Outdoor People Counters at the entrance/exit points of five nodes: (1) the Level 1 Campus Centre, (2) Level 3 Sky Garden, (3) Level 1 Open Plaza, (4) Level 3 Skybridge and (5) the Level 5 Skybridge (see Figure 1 for locations). Buildings 2 and 3 are connected at Level 1 and 3 through the first two nodes (Campus Centre and Sky Garden). The Level 3 Sky Garden node is also linked to Building 1 through a skybridge. Buildings 1 and 2 are connected at the middle part of both buildings through the next three nodes (Open Plaza and two skybridges) at Levels 1, 3, and 5. The data were recorded over seven weeks and aggregated by hours for analysis. The variations in space use volume over various times of the day and different days of the week were analyzed for potential patterns in space use. The data collected was completely anonymous, thus respecting the privacy of the user.

3 RESULTS

3.1 Spatial network connectivity

Figure 2 shows the spatial distribution of the three node centralities measurements. The high degree centrality nodes are located at the lift lobbies, i.e., the vertical circulation nodes (Figure 2(a)). The major lift lobbies showed the highest values, whereas the peripheral corner of each floor showed lower degree values. This indicates that the lifts have more connections than the other types of places. For closeness centrality (Figure 2(b)), the middle part of Building 2 becomes the core region with the lift lobbies being the centre of this core. The lift lobbies of Building 2 located in the Campus Centre and the lift lobbies in the central part of Building 1 are the secondary core area of closeness centrality. This indicated that these spaces can easily connect to the rest of the campus. The spatial distribution of both degree and closeness centralities were similar between floors, i.e., similar horizontal pattern was found on all the floors. However, the betweenness centrality measures showed a different pattern between floors. The high betweenness centrality nodes appeared only on certain floors, e.g., the Level 3 entrance from the sky garden to Building 2 and the two skybridges between Buildings 1 and 2. This indicated the places that were bridging distinct groups of spatial nodes in the campus. On the other hand, the peripheral corners showed the lowest betweenness centrality. To understand the strongly connected node community, a community detection algorithm (Louvain modularity algorithm) was run with the network data. In Figure 3, the nodes in the same colours indicated the community---strongly inter-connected nodes. Overall, these network metrics provided an understanding of the spatial connectivity structure of the SUTD Campus.

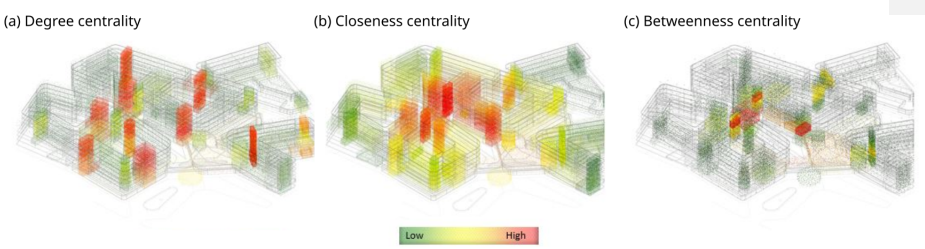

Figure 2: The three network centrality measures in 3D: (a) degree centrality, (b) closeness centrality, and (c) betweenness centrality.

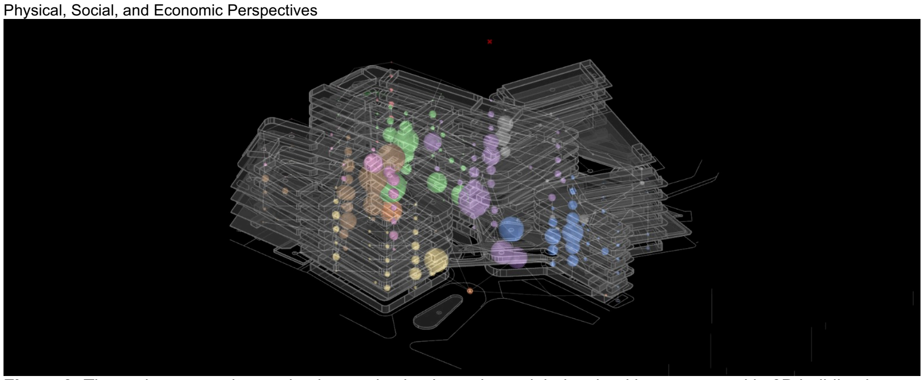

Figure 3: The node community results detected using Louvain modularity algorithm, presented in 3D building layout.

3.2 Zoning the campus by the removal of high edge-betweenness links

The following paragraphs discuss our experiment of links removal. We targeted the links with the highest edge-betweenness because these links were the most critical connections of the network in terms of connecting various parts of it, i.e., different communities. The high edge-betweenness links were also known as the 'bridges' or 'shortcuts' because these links were usually connecting the 'long-step-distance' nodes. Thus, these nodes usually suggest a larger traffic of human movements. Figure 4 visualizes the nodes grouped into different communities using the Louvain modularity algorithm. The nodes are labelled with the building numbers (1, 2, 3, and 5). The node positions were calculated using the spring layout algorithm (an algorithm for assigning nodes and edges positions based on network structure). A total of nine communities were identified. It is interesting to show that the Buildings 1 and 2 were split into three communities each. In other words, the spatial connectivity network structure was more complex than the building space layout structure.

The top 50 edge-betweenness links were coloured and labelled in Figure 4. The top ten links (red) are the long 'bridges' that connect nodes located at various spatial locations and communities. Some nodes were linked with more of these bridges, e.g., the Campus Centre at both, Levels 1 and 2, and the drop-off area (Building 1, Level 1). Thus, the removal of the top 50 links would isolate these nodes. Two high edge-betweenness links were important: No. 5 - Level 2 skybridge and No. 6 - Level 1 open plaza. The Level 2 skybridge connects the Campus Centre (Building 2) with the library (Building 1) whereas the open plaza connects the study area at Level 1 for these two buildings. To disable these links, some form of spatial barrier would need to be put in place, or access to the spaces (e.g., corridors/rooms) would need to be limited.

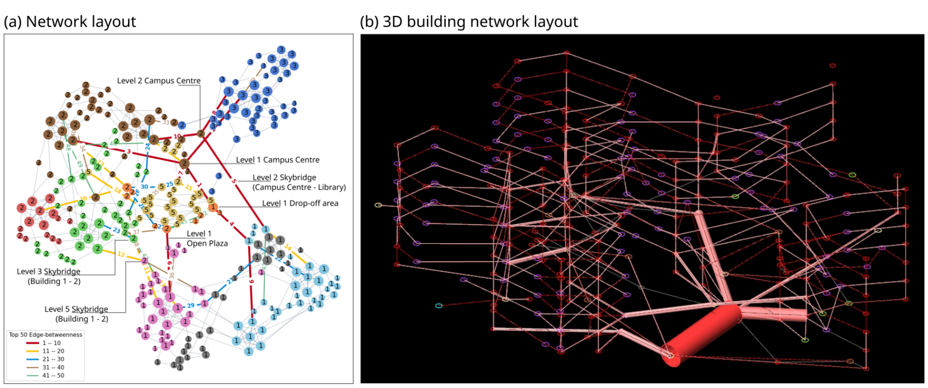

Figure 4: The campus network in (a) network layout and (b) 3D building model layout. In (a), the nodes were labeled by the building numbers, colored by a community detection method (Louvain modularity algorithm), and sized by the PageRank scores. The edges were ranked from 1st to 50th by edge-betweenness.

Figure 5 shows the changes of average closeness and the PageRank evenness in the process of iteratively removing the top 50 links. The trend of average closeness was a decreasing trend, which was expected and reasonable because the removal of links would increase the separation within the network---more steps were needed to reach the other nodes overall, hence the reciprocal of the average shortest path length would decrease. The blue dashed vertical line (removal of the top 6 links) indicated the first significant decrease---a drop from 0.16 to 0.14---and decrease less significantly afterward. This is because the removal of the top 6 links would split the Buildings 1 and 2 at the ground floor, leaving only the higher floors skybridges connected. Most of the spaces would then be separated and the people would need to take a longer detour to access the other building (if necessary). While most people work/study only at their offices or classes in one building, the interaction between buildings could then be reduced and controlled by only closing 6 of the links.

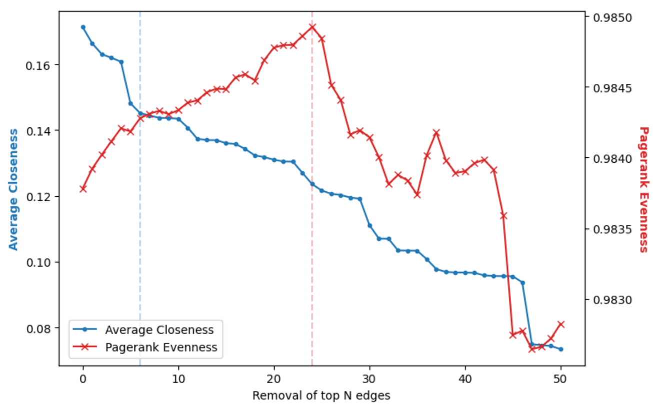

Figure 5: The changes of average closeness (in blue, left vertical axis) and PageRank evenness (in red, right vertical axis) by the removal of the links with the top 50 edge-betweenness. The first data points indicate the original campus network (no removal).

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On the other hand, the evenness of PageRank increases from the initial of the removal process until the top 24 links were removed. The increment trend was expected and reasonable because when the top betweenness links were removed, the separation increased, and people would take detours---this forces the traffic flow of people towards other nodes. However, while a lot of links were removed, some links became more critical in terms of connecting spaces, i.e., the new bridges which absorb a large traffic in the movement process. In our case study, the evenness of PageRank reached a peak value at top 24 links (Figure 5, red dashed vertical line). This means that the removal of the 25th highest edge-betweenness link would start to generate the new 'bridges' that attract the flows. A significant decrease occurs from top 24 to top 32, where evenness values were similar to the initial evenness value.

3.3 Intensity of human activity in major connection nodes during the COVID-19 pandemic

Figure 6(a) shows the daily total number of people passing by five major connective nodes that were located at two central 'interaction' zones, on different floors: the Campus Centre at Level 1 and above it, the Sky Garden at Level 3; and the open plaza (Level 1) at the middle section between Buildings 1 and 2, with the 2 sky bridges above it at Level 3 and level 5. The traffic at the ground level (both Level 1 Campus Centre and open plaza) were significantly larger than the upper levels. The Level 3 Skybridge (connecting Buildings 1 and 2) had more flow than the Level 5 Skybridge. This means that during the data collection period, the spaces on the lower floors were more occupied than those on the higher floor. This is reasonable because users would not go to a higher floor if their offices/classrooms were located at lower floors. Our study also showed the differences of the magnitude of the differences of space use between lower and higher floors. Because the Level 3 Sky Garden is not sheltered, the usage of this node was a lot lower than that of the Ground Floor, which also serves as a connection from the dormitories/Building 5 to the front entrance (drop-off point) of the campus and Building 1. The open plaza between the study area of Buildings 1 and 2 is open to the public and building management control measures are not applied in this location. In contrast, the Levels 3 and 5 skybridges can only be accessed within the building---only students, staff or visitors who 'check in' the Campus can enter the building. This Level 1 plaza is also a major access point to the neighbouring Buildings 1 and 2 study areas. It is well-used by students both on weekdays and weekends. These are some of the reasons explain the higher space use in the Level 1 open plaza compared to the skybridges.

Figure 6(b) shows the location-based normalization of the flow of people---the proportion of counts by day at each location. Four lines (except that of the Level 1 open plaza) show similar patterns---a slight increase from Monday to Wednesday or Thursday, then a decrease on Friday and drop to a lower level on weekends. The space use of the open plaza was more stable than that of the other four locations---the proportion of use was similar from Monday to Saturday, with a slight decrease on Sunday. The reason for this may be that the node is public and not spatially constrained.

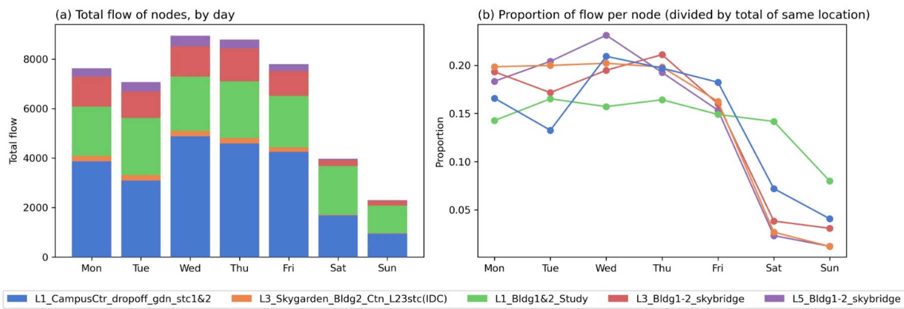

Figure 6: The number of people moving through the five nodes by day of the week: (a) The total flows by day, (b) the proportion of flow per node (divided by the total number of people at the same node).

Figure 6 shows the Level 1 Campus Centre node which had the highest level of human traffic. This finding, combined with those of the network analysis (Figure 4) demonstrates that this node has the top 3 linkages of highest edge betweenness. During the initial response to COVID-19, the SUTD building management access policy mandated compulsory registration for all persons entering the campus buildings at this single Campus Centre node. It was a practical solution for capturing access records of all visitors before they circulated to the higher levels and other spaces in buildings 1,2,3 and 5. However, the centralizing of all building access circulation to a single node rendered the Level 1 campus centre a highly vulnerable node in the entire network during that period. However, an additional registration and access point was subsequently implemented at Level 1 Building 2 study area lift lobby, providing an additional pathway in the network, reducing the human traffic loading on the Level 1 Campus Centre node, and thus reducing its potential as a point of spread and contagion. To this end, increasing the numbers of access pathways whilst assuming the practicality of building access management, is beneficial for the resilience of the circulation network as a whole.

4.0 DISCUSSION AND CONCLUSION

4.1 Spatial network analysis framework and planning and design for resilience

During a pandemic or epidemic situation like COVID-19, one key measure to control it is to split the crowd (e.g., social distancing or safe distancing, work-from-home and split teams for workplaces management measures, and cross-region or cross-border movement restriction) to reduce the chances of spreading the infectious disease. In our study that is based on the emergence of a complex network, we simulated spatial network modifications and analysed links removal in a small university campus. Our findings suggest that for the scale of such an environment, complete zone-separation or isolation measures may not be necessary. Instead, breaking the high edge-betweenness links could increase the spatial separation and reduce physical interactions or close contacts by forcing people to take less frequented detours. Limited entry points concentrate the flow of people in a few locations and therefore maximize exposure to potential virus-carriers. Multiple entry points even out circulation flow and reduce the risk of exposure. They provide alternative circulation routes for users to reach their destinations. From the spatial network point of view, resilience in the system is reinforced with multiple pathways as backup in the case of one pathway being closed.

In our study, the Campus Centre was connected to several high edge-betweenness links. From the view of complex network, to increase the separation between the campus buildings, this node should be closed or its access highly restricted. However, in our case, because of cost, manpower requirement and operational effectiveness, the Campus Centre was used as the main access point---a centralized control measure was set up for the whole university. This set-up forced all users to transit through the Campus Centre---and increased the probability of physical interaction (or close contact) and the traffic at the nearby lift lobbies. In other words, this is not a preferred situation from the view of complex network analysis.

The SUTD Campus was originally designed with multiple entrances, including staircases, escalators and lifts going up to each of its buildings. In addition to the large main Centre next to the drop-off area, the Campus has many other access points. This potentially allows for zone separation between the buildings and as such presents a good example of resilient spatial design. However, there are several weak points in the spatial layout of SUTD---e.g., the canteen is a central unavoidable point of interaction. Time-based shift policies between buildings may be a solution for this problem. Also, access to the higher levels in Building 3 is via a main elevator core and an open staircase. During the COVID-19 pandemic, all the vertical connections from the ground level to buildings other than through the Campus Centre were closed. Access was limited to one controlled location for all the buildings, with contact-tracing registration implemented (this was also the case in many public and restricted access buildings in Singapore, due to manpower and operational access control requirements).

In terms of scale, the SUTD Campus consists of four buildings, which is a common size for a cluster of public space. This urban morphology of several buildings that form a spatially connected environment for public activity is also seen in various public typologies in Singapore. For instance, public transport interchanges with shopping malls (e.g., Tampines Interchange and Jurong East Interchange) or community centres with integrated sport facilities, restaurants, or retail shops (e.g., Kampung Admiralty and Our Tampines Hub). Therefore, a similar analysis framework could be applied to these other types of public spaces at a similar scale for the identification of critical links that could be removed, and for the evaluation of their effectiveness in case of setting up disease control measures.

4.2 Strategies for urban and architectural creative design process

How do we align the spatial design strategy of a campus or urban-architectural space designed to maximize points of interactions in circulatory systems, yet with the goal of disease-control? This analysis has shown that for an adaptive resilient spatial system, it is important for the network analysis framework to take place at an early stage to identify network effects of circulation system, while designing connections between spaces.

Firstly, during the initial conceptual design brief stage, a hierarchy of programme spaces is made based on their size, number of levels, type of connections, ingress and egress points, etc, with their required relational proximities listed. Their relationship to each other is then linked in an initial conceptual spatial layout. This can be done concurrently or preceding the interfacing to existing site programmes, e.g., links such as walkways, bus stops, gardens, other buildings, natural landscape elements and geographical conditions. At this point, one can input these relationships and parameters into a spatial network and identify the links with highest network connectivity---which, when removed, can isolate zones while keeping the spatial network resilient. This means to intentionally plan and design for the flexibility of adapting spatial thresholds by closing off major singular connections between buildings or functional zones while maximizing and retaining multiple alternative linkways, resulting in an evenly distributed flow of people traffic. Thus, designing for continuity of the urban function and experience is facilitated. Additionally, the actual width of these alternate linkways and access points could also be sized by design to accommodate increased flows, and in the context of COVID-19 pandemic, facilitate safe distancing. Next, the layout can be modified by adopting a polycentric or distributed approach to the layout of its spaces, connections, and access points. This further contributes to the resilience of the entire system. Major spatial links of the system can be reduced or separated, whilst multiple clusters that form a system of related functional spaces continue to be accessible, e.g., a cluster of classrooms, faculty offices, cafeteria, vertical access systems, multiple drop-offs, and entrances.

Iterations of multiple variations of this design layout can then be made and improved. One computational approach would be to employ an evolutionary design which scores the overall layout as well as its nodes and linkages by network measure parameters, e.g., network resilience to opening and closing of global and local network links, heterogeneity of connective locations, flexibility of programme repurposing, extent of programme space distribution and redundancies etc. Low scoring local and global nodes and linkages could be identified, adapted or replaced and the results iterated over many generations to evolve and optimize a variety of outcomes for further development and detailing. This design approach would be the subject of a future research paper.

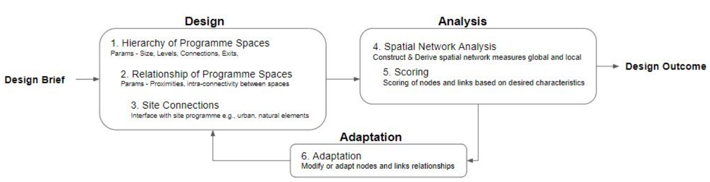

Figure 7: Flowchart of Iterative design process for resilient spatial network.

In existing buildings, time-based spatial zoning strategies can be used without extensive modifications to spatial conditions. When spatial flexibility is not a given, time shift-based policies which buffer and even out people traffic in specific spatial zones could be used. Alternate access control measures or technologies which do not depend on singular point of access could be explored. E.g., people counters or cameras with optical flow techniques can monitor the people traffic at each space; indoor localization (Bluetooth and Wi-Fi) can also help to identify and trace the proximity between groups of people.

4.3 Conclusion

In this paper, we proposed a framework for spatial design and analysis that adapts for resilience in disease control situations. The framework studies the built environment, its spatial network generated from spatial nodes and their links in the design of the urban-architectural environment and examines the layout for major linkages, spatial community clusters and the effect of the reduction of network percolation by link removal. By relating these findings back to the spatial design and building management zoning policies in the case of an existing campus, we discussed and examined its spatial design, access control, and the location and distribution of functional spaces. We looked at external to internal movement, internal circulation, and adequate spacing for multiple minor pathways within a development at the urban-architectural scale. We examined the actual spatial usage of a case study and its key node points. In short, the analytic framework proposed in this paper and the findings of our study suggest an adaptive approach to planning and design that would result in a more resilient built environment.

Analytics help to forecast and optimize urban infrastructural design development and decisions, but they are only as good as their input data and model specifications (Boeing et al. 2021). (1) Our network was generated based on the spatial organization of the SUTD Campus. Its connections to the urban context were not considered, e.g., the entrances from the adjacent public transportation stations, the pedestrian entrances, the vehicle entrance points, the campus parking lots, and the hostel entrance points. By excluding these, some of the nodes' importance levels could be underestimated, especially for those located at the ground floor, due to edge effects. (2) The architectural information of the nodes and links was simplified for the purpose of this study. The details including the areas of classrooms, offices, facilities, etc., and the lengths of the corridors, were not considered in the model calculation, and could be incorporated in future for further precision. (3) The data collection using the people counters was conducted in January 2021---during the Phase-2 recovery period from the COVID-19 lockdown (the 'Circuit Breaker') in Singapore. Therefore, the overall movement traffic was lower than pre-COVID-19. We believe it would be interesting to continue monitoring the movement patterns during the current 'new normal' and the future 'post-COVID' periods to check if the pattern remains similar to our findings.

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