User-Driven Emergent Patterns of Space Use in Vertically Integrated Urban Environments

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ABSTRACT: Public and common spaces in integrated mixed-use buildings in high-density urban environments increasingly take on the form of vertical extensions of public and common spaces on the ground level. Taken together, they can be understood as networks with multiple spatial programs, diverse land use, multi-occupancy, and circulation paths set in complex three-dimensional relationships. This paper argues that studying high-density vertically integrated buildings based on user-generated data can contribute to a better understanding of their socio-spatial performance. It presents aspects of an ongoing research project at the Singapore University of Technology and Design (SUTD) that uses a Complexity Science-based approach to study movement and space use in vertically integrated developments. The case study presented in this paper uses the SUTD Campus, an award-winning urban design and architectural project by Amsterdam, The Netherlands-based UN Studio and Singapore-based DP Architects as a case study. The project consolidates a typically laterally spread-out campus program into a compact and vertically layered interconnected building complex. The paper presents a systematic post-occupancy socio-spatial study using the following methods: (1) qualitative architectural analysis, (2) quantitative spatial network analysis, (3) quantitative data collection, and (4) correlation analysis of actual performance with spatial network patterns. It discusses the use of infrared outdoor people counters, low-energy Bluetooth (BLE) devices, and smartphone sensors to map user movement. The collected data is subsequently analyzed to demonstrate how the public and common spaces within the integrated campus perform. The paper further explores the influence of the campus' spatial layout on user behavior and movement patterns, and the impact on social interactions and user activities over time. The paper finally discusses the potential of this research methodology to inform the future planning and design of vertically integrated mixed-use developments.

KEYWORDS: Spatial performance, Spatial Network Analysis, Complexity Science, Bluetooth localization; mobility patterns

INTRODUCTION

To accommodate growing urban populations in many parts of the world, planners, designers, and architects increasingly experiment with integrated mixed-use buildings as vertical extensions of urban space. Such buildings are often combined with others and feature extensive program networks. They are characterized by public and common circulation paths and spaces located on multiple levels. Vertically integrated buildings can be studied as complex systems. They display properties similar to those that play out in their larger urban context to understand their users' spatial and social interactions systematically.

Just as the city manifests itself as a space of flows (energy, resources etc.) (Kennedy et al., 2011), the same applies to vertically integrated buildings. Generally, a building's spatial configuration forms the network in which these flows take place. Hence a spatial network determines the pace at which processes occur. While buildings and their spaces are typically designed for socio-spatial efficiency, their actual performance is emergent. Complex patterns of emergence are visible in cities as we study social networks, transportation networks, spatial networks, etc. through statistical analysis and other methods used in Complexity Science. (Batty, 2009) With the proliferation of vertically integrated buildings in high-density urban environments, often designed with public and common programs on multiple levels, buildings become vertical extensions of the urban public and common environment they are part of. The interactions of spaces on elevated levels with those on the ground level and their impact on human movement patterns and space use patterns are numerous, varied, and interrelated in complex ways. The study of vertically integrated buildings therefore warrants the use of Complexity Science methods. These encompass spatial and social network analysis using Network Science that understands human mobility as a dynamic process occurring within a complex network.

1.0 CONTEXT AND THESIS

1.1. Performative Scales: City and Building

In Singapore's compact high-density urban environment, urban planners, designers, and architects increasingly experiment with vertically integrated mixed-use buildings. In response to the City State's land scarcity, smaller building footprints with public and common spaces on elevated levels such as sky bridges, parks, terraces, and roof gardens, are combined with residential, civic and commercial programs, resulting in 'vertical cities.' (Schröpfer, 2020).

The SUTD Campus by Amsterdam, The Netherlands-based UNStudio and Singapore-based DP Architects located in the Southeast of Singapore, is one such built experiment of vertical spatial distribution. The project consolidates a typical laterally distributed campus program into an interconnected compact integrated complex of buildings. According to UNStudio, the project's design architect, the buildings' organization is based on a mathematical diagram referring to Knot Theory and UN Studio's Design Models (Schroepfer 2017, 85). In UNStudio's practice, the principles and parameters are developed from one project to another as a chronological lineage of buildings' design development.

Figure 1(L): UN Studio/DP Architects, SUTD Campus, Learning Spine with bridges on Levels 3 and 5 linking buildings, view from the East. (Photograph: Daniel Swee 2017)

Figure 2(R): 'Living Spine' with elevated gardens and bridges view from north. (Photograph: Daniel Swee 2017)

New spatial concepts of buildings can benefit from new methods of analyzing and predicting their post-occupancy performance. Building performance is typically evaluated quantitatively using various environmental, ecological, biodiversity, and economic data. However, addressing spatial performance in the design phase typically relies on the experience of practitioners. This is also the case in the multifaceted systems of vertically integrated buildings. Given the complexity of these buildings, there is a need to develop systematic methods to understand and measure their spatial performance and design effectiveness. The main question we are addressing in this paper is: Is the design of the SUTD Campus meeting its designers' intentions regarding circulation, flow, and collaborative spaces both on the ground and elevated levels, and if not, how could it be designed better?

1.2. Hypothesis and Objective

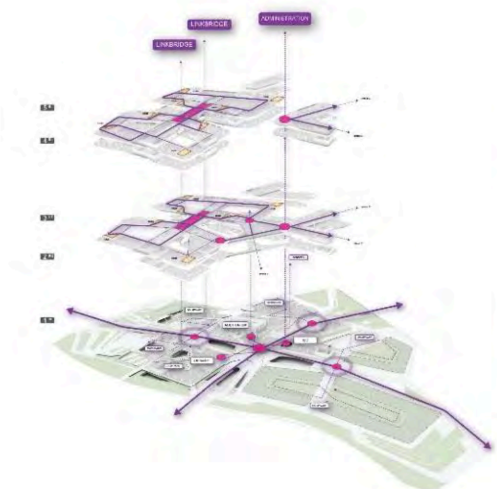
We hypothesize that a Complexity Science-based analysis of the spatial networks of vertically integrated buildings, compared with empirical post-occupancy user data, allows for identifying and quantitatively evaluating emergent space use patterns that become a basis for better future design. To that end, as part of our larger research, we are developing systematic methods that allow for the Complexity Science-based analysis of urban and architectural spaces. These methods include (1) qualitative architectural analysis, (2) quantitative spatial network analysis of patterns of spatial relationships, (3) quantitative data collection of human movement and activity and (4) correlation of actual performance with spatial network patterns. In summary, we evaluate ground and elevated spaces to review the effectiveness of their design.

2.0. METHODOLOGY

Our research has three main phases, (1) the mapping of the design intent and the resulting spatial relationships (architectural analysis) and (2) the collection of actual user data. The resulting data allows for (3) a comparison of design intent and actual space use and, thus, evaluating the building's performance.

2.1 Design Intent Mapping and Architectural Analysis

Our study's design intent mapping and architectural analysis were based on materials provided by the design architect. They included architectural diagrams and drawings that illustrate the intended spatial circulation and flow, collaborative zones, connections between buildings and across the entire campus, and functional lateral and vertical distributions of programmatic spaces. The concepts of Circulation and Interaction (Schroepfer 2017, 79-80) served as the two central conceptual guides - with horizontal, vertical, and diagonal flows (e.g., see Figs. 3 and 4) connecting the various spaces of the project's four main buildings. UNStudio designed two main axes of circulation, the Learning Spine and the Living Spine with a central plaza at the center.



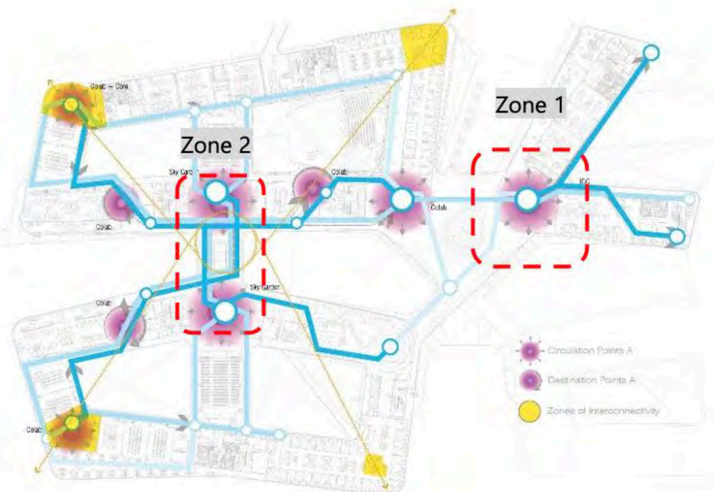


Figure 3(L): Lateral and vertical circulation, Collaborative zones. (Source: UNStudio 2006)

Figure 4(R): Conceptual diagram of nodes of interactivity connected by circulation paths. (Source: UNStudio 2006)

In the context of vertically integrated buildings, the bridge connections, which exist on the ground and elevated levels, were designed to serve as important collaborative zones. They are, therefore, suitable locations for testing our hypothesis. We studied two locations, (1) the main intersection of the circulation axes of the Campus Center at the Ground Level and the Level 2 and 3 Gardens, and (2) the connection between the Buildings 1 and 2 on the Ground Level Plaza and the Level 3 and 5 bridges.

2.2. Spatial Network Mapping

Spatial networks are a type of complex system. The topology of nodes and edges are embedded in space (Barthelemy, 2011). In our study, we extracted the nodes from main program areas and generated edges by connecting each node to other program areas that are spatially accessible via doorways and corridors. The Euclidean distance between the nodes was assigned to their corresponding edges, as is the case for spatial networks. For our study's purposes we consolidated adjacent elevator cores and staircase lobbies as a single node and connected them directly to all other vertically adjacent lobby nodes, thus considering elevator and stair cores as 'vertical streets' with lobbies on each floor as node points.

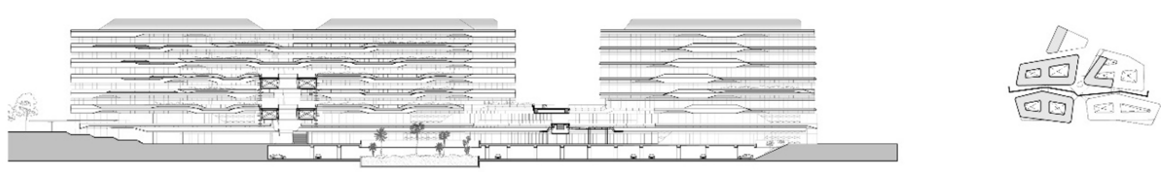


Figure 5: Cross-sections of (i) Block 1 and 2, (ii) Lecture Theatre, (iii) Learning Spine. (Source: UNStudio 2006)

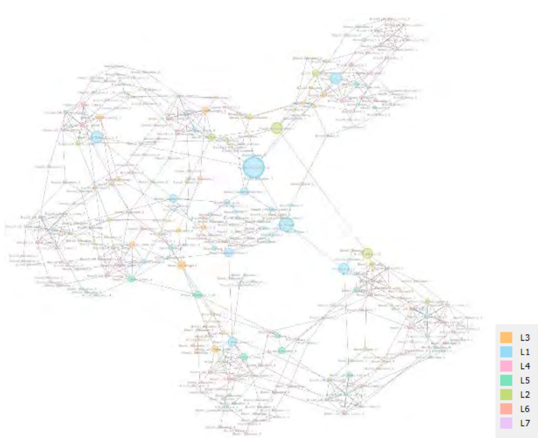
2.3. Spatial Network Analysis: Centrality Measures

Our study's different centrality measures are extracted from the spatial networks by using digital tools including Rhinoceros3D, Grasshopper, Python script, Gephi software and Networkx Python Library. Network centrality measure algorithms used included 'degree', 'closeness', and 'betweenness centrality', all essential measures that assess the local centrality of nodes in a system (A. Barrat et al., 2004)

Degree centrality is a measure of a node's significance in its connectivity, based on the number of its edges. The higher the degree number, the more connected the node is within a network. This measure helps find the most connected spaces or influential individuals within a spatial or social network by ranking them within a network. Determining the degree centrality score allows for the effective planning of active social spaces that act as critical connectors within a development. E.g., the Community Plaza at the SUTD Campus Center forms a high-degree node as it connects the development's vertical spaces with their larger urban context.

The closeness centrality scores of each node are based on its closeness to other nodes in the network. The closeness measure is calculated using the shortest paths between each node and is even across all nodes for a highly connected network. Closeness measures help identify spatial clusters within a development, highlighting the spatial distribution of high degree nodes. Our design intent analysis showed that the collaborative zones of the SUTD Campus are organized along the central circulation axes. They act as bridges to the spatial clusters of the other buildings. Therefore, they are likely to display similar closeness centrality if the spaces' circulation design allows all the program nodes to be highly connected.

Betweenness centrality is one of the critical centrality measures for spatial networks. It characterizes a node's importance by measuring its ability to be part of the shortest paths between all nodes in a network. This measure allows for the identification of key bridges between nodes. In terms of a spatial layout, betweenness centrality helps to understand a node's significance in its connectivity with other nodes. A high centrality measure indicates that the node is part of many shortest routes, thus translating to increased movement and potential interactions. Based on each node's architectural program, e.g. the elevated garden spaces on Level 3, we can infer the effectiveness of such an area within the entire development. Questions such as, "Would we locate the garden space next to a node point which is central and easily accessible by all occupants of the building?" can thus be addressed.



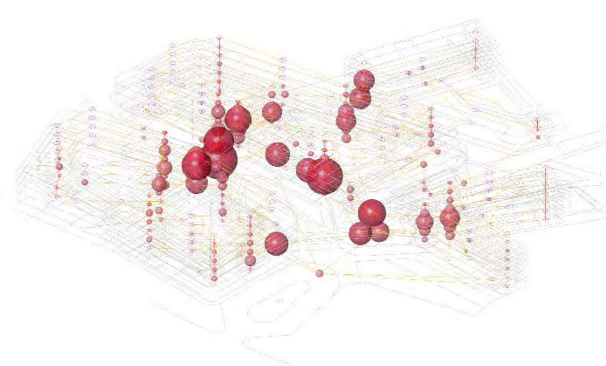


Figure 6(L): Distance-Weighted Betweenness Centrality diagram of SUTD spatial network, visualized by Gephi

Figure 7(R): Distance-Weighted Load Centrality diagram, spatial visualization overlay by Rhino, grasshopper

Comparing and correlating the various centrality measures allows us to identify the significance of spaces regarding their function and location. It further allows us to identify the parameters for designing their size, co-location, and social spaces position within the larger development. Combined with the node attributes, we can further identify the factors influencing a space's effective use.

2.4. Experimental Data Collection: Bi-Directional People Counters

Our mobility mappings in the study consisted of tracking and recording pedestrian movements in public and common spaces in key collaborative zones on ground and elevated SUTD Campus levels. We recorded the frequency and intensity of actual use by employing bi-directional people counters with infrared sensors. People counters are a simple device that allows for measuring the volume and time of human flows. The devices were installed at key access points to the nodes identified during the architectural and spatial network analysis to collect inflow and outflow volumes during different times of the day. The collected data provided the total volume of users circulating through the selected spaces. The variations in space use volumes allowed for identifying space use patterns over the day and provided a measure of actual space use and performance.

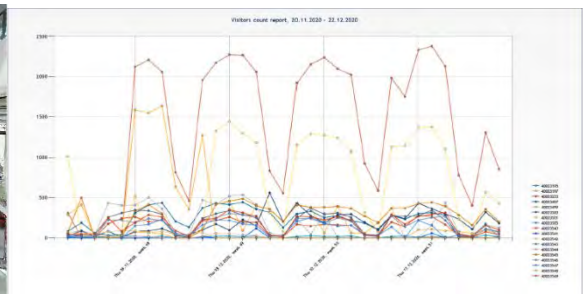


Figure 8(L): Point Cloud image of L1 Campus Centre, visualized by Faro SCENE software

Figure 9(R): Visitor Count Report, Sensmax people counter

3.0. RESULTS

3.1. Correlation of Spatial Network Measures and Actual Usage

The following section presents our comparison between spatial network measures and actual space use in the campus's two selected zones. Zone 1 refers to the L1 Campus Center and L3 Sky Gardens directly above it. Zone 2 refers to the L1 Community Plaza, and the L3 and L5 Sky Bridges directly above it. [*figure 3*]

Table 1: Corresponding nodes on the ground and upper levels: network centrality measures, compared to movement volume, using a fraction of total

Zone	Location	network centrality measures*			fraction within each zone			movement volume per access point	
		degree	close-ness	betweenness	degree	close-ness	between-ness	Fraction within each zone	Weekly average volume per access point
1	*L3 Sky Garden*	0.0185	0.00816	0.131	0.385	0.499	0.576	0.057	494
	L1 Campus Centre	0.0296	0.00818	0.0967	0.615	0.501	0.424	0.943	8212
2	*L5 Sky Bridge*	0.0148	0.00940	0.143	0.286	0.346	0.399	0.122	1848
	L3 Sky Bridge	0.0185	0.00986	0.183	0.357	0.363	0.514	0.417	6295
	L1 Community Plaza	0.0185	0.00794	0.031	0.357	0.292	0.087	0.461	6969

*where ***n*** is the number of nodes in graph ***G***; The degree centrality values are normalized by dividing by the maximum possible degree in a simple graph n-1. Closeness and betweenness centrality are weighted by distance. The closeness centrality is normalized to (***n*** - 1)/(|***G***| - 1) in the connected part of graph containing the node; the betweenness values are normalized by 2/((***n*** - 1)(***n*** - 2)).

3.2. Discussion

Degree centrality: The best connected or influential nodes with the highest numbers of degrees in Zone 1 were the L1 Campus Center and in Zone 2 the L1 Community Plaza and L3 Sky Bridge.

Closeness centrality: All the nodes we selected for our study had similar closeness centrality values. They are located in relatively central and easily accessible areas that connect the various buildings. The result corroborates the architectural design intent and concept of central collaborative zones along the key circulation axes and results in spaces in both zones; the L1 Campus Center, the L1 Community Plaza, the L3 and L5 Sky Bridges and the L3 Sky Gardens are highly connected to the spatial clusters of the various buildings.

Betweenness centrality: As a measure of a node being central to shortest paths between all nodes, the results are significant in the discourse on vertically integrated buildings' effectiveness. They show elevated connections have the shortest paths to all other nodes because the centrally located vertical spaces are privileged as the shortest path between all the other levels.

Actual space use: [refer to results in *Table 1*] In Zone 1, the comparison of network measures to actual space use shows mixed results. The relative volume of movement appears to be heavily skewed towards the L1 Campus Center. The values indicate that the L3 Sky Garden was not used frequently as a bridge between the buildings. The Campus Center is located at the intersection of the Living and Learning Spines of the Campus. It connects Buildings 2 and 3 and includes the main University drop-off point and garden route to the hostels and sports facilities. We can therefore assume that most Campus users would pass through this node. However, we would like to note that due to COVID-19 safety measures, all visitors to the campus were required to register in the Campus Centre during the research period, which most likely skewed the movement volume.

In Zone 2, the high flow on the L3 Sky Bridge corresponds with the closeness and degree centrality we found [*Figure 11*]. The Ground Level presents the highest amount of traffic flow (of the zone subset). The presence of horizontal and vertical connectivity in the elevator and staircase cores improves the elevated connection's connectivity. We recorded substantial actual flow and connectivity on the L3 Sky Bridge and L1 Community Plaza. The data shows that they serve well as collaborative and social zones. The L1 Community Plaza anomaly that displays a low betweenness centrality in the spatial network is inconsistent with the actual flow that amounts to 46.1% of the total traffic in this subset. We believe that this is related to the presence of study tables in the L1 Community Plaza, which increases users' flow and the program's diversity that includes food and retail shops adjacent to the L1 Plaza. The L5 Sky Bridge network measures are proportionally lower, but the actual flow is also much lower. More significant seasonal variations may be related to seasonal reasons, such as exam periods. A more comprehensive study that considers more details, such as timing and study tables, may show better-defined spatiotemporal correlations.

Adding more programs on the L3 Sky Bridge may be warranted, given the correlation of its actual space use with centrality measures. The bridge's function as a connector between the buildings and its proximity to vertical circulation cores aligns with their design intent of 'circulation' and 'flow'.

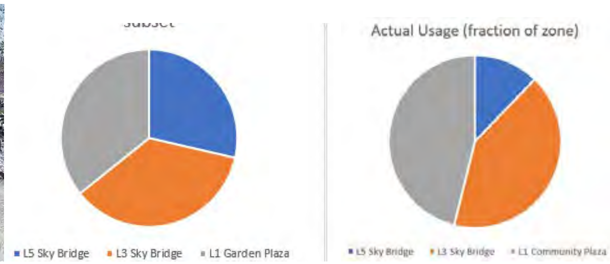


Figure 10: Point Cloud capture of L1 Community plaza, visualized by Faro SCENE software

Figure 11: Pie chart of (L) spatial network measure of degree centrality (fraction of zone) vs (R) actual usage (fraction of zone), Zone 2

Given the design intentions of the architects, our research focused on circulation spaces. However, our research methodology can include other spaces as well and as such inform spatial design in general , e.g., the performance of networks can be improved through the inclusion of additional node attributes, such as visual connectivity or parameters correlated with socio-spatial qualities and macro- and micro-temporal flows can be considered as well.

3.3. Limitations

Our data collection in the larger SUTD Campus is still in progress when we are writing this paper. Once available, the data will allow for a finer granularity and a more detailed comparison of network measures with actual space use and evaluation of the development performance.

As this study was conducted during the COVID-19 pandemic, circulation on the Campus' upper levels was limited and only possible through the Campus Center, which increased actual space use measurements in the latter and other main circulation access points. The consideration of major events and local administrative policies that result in circulation and other space use restrictions would also be valuable to fully capture the performance parameters and suggest how they may affect the entire network's resilience.

Our study provides a snapshot of the performance of the SUTD Campus over four weeks. An extension of the data collection over a more extended period would capture seasonal activities and term breaks and, therefore, allow for a better understanding of longer-term space use patterns. A detailed hourly microflow study that would capture the micro-variations during workdays and weekends would provide finer granularity. We plan to use Machine Learning algorithms to arrive at such a finer granularity in the future.

Lastly, like mobile apps, including popular social media, already capture proprietary movement ostensibly used in activity pattern analysis, the adherence to ethical standards by corporations and governmental bodies for individual liberty and privacy is paramount to any tracking approach. Anonymization and opt-out options were, therefore, crucial in our study and had to be implemented.

3.4. Future Directions: Experimental Tracking with Smartphone App with BLE Beacons

As part of our more extensive research, we are currently developing a low-energy Bluetooth (BLE) tracking and localization method that will be used to track and localize selected study participants. These comprise frequent SUTD space users, including faculty, students, staff, and vendors. The Bluetooth localization consists of three components, (1) stationary low-energy Bluetooth beacons, (2) a mobile app, and (3) a cloud server uses a 'peer-to-environment' sensing system that involves the placement of stationary Bluetooth beacons in the study locations. The smartphone devices allow for the mobile user to receive the data sent by the beacons. The collected data contains information about the transmitting beacon such as unique ID, time, telemetry (temperature, etc.), and the transmitting distance (indicating the stationary beacon's reach from the mobile app). Smartphones constitute the peer component of the system. A custom app installed on smartphones running IOS or Android works in the background and scans for Bluetooth data from the BLE beacons. It stores relevant data temporarily and then transmits the information to the cloud server. The data collected from the participants' Bluetooth devices are plotted on the spatial network to map the participants' movement routines over a continuous period. The experimental data measures deduced from the spatial network analyses are then validated with the real-world data, with the correlations between the designed and actual space use providing the basis for the spatial layout's performance assessment.

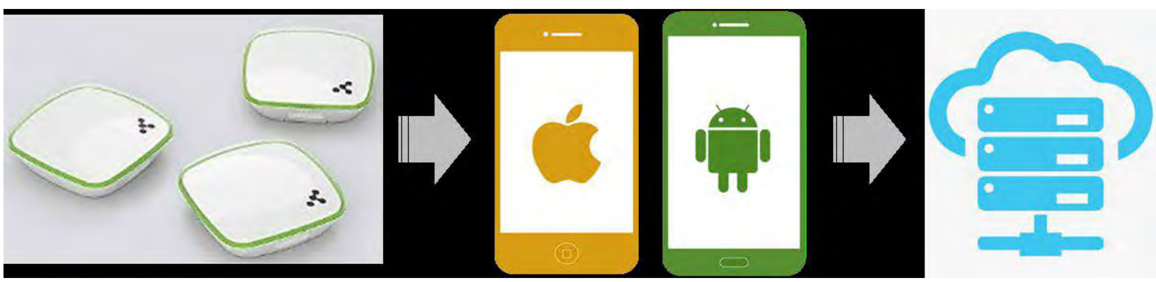


Figure 12: Bluetooth localization and tracking consisting of low-energy Bluetooth beacons, mobile app and cloud server

Also, co-presence networks are discerned from the BLE-localized mobility patterns.

In Complexity Science, when two or more people are close to each other, they are considered to be in co-presence. Co-presence is a necessary but not sufficient condition for interactions. A co-presence network is a social network of friends and strangers that can analyze social relationships as dynamic processes. The participant users form the nodes and the time spent in each other's proximity constitute the edges. Co-presence networks are thus temporal, and their edges appear and disappear. Over time, a co-presence network emerges that displays strong and weak ties. Persistent encounters between users indicate homophily (strong ties), while brief and chance encounters indicate heterophily (weak ties). Stronger ties influence social behavior, while weaker ties complete the connectivity within the network. (Manivannan et al., 2018) When embedded into a building's spatial layout, the temporal co-presence network simulates user interactions patterns and their relative strength over time. The aggregated network can also highlight the connectivity of different social spaces that enable homophily and generate more opportunities for brief chance encounters. These insights can provide important information for the future planning and design of vertically integrated developments.

CONCLUSION

Our study of the SUTD Campus shows that the Complexity Science-based analysis of vertically integrated buildings based on user-generated data can better understand their socio-spatial qualities and performance. The comparison of architectural design intent with quantitative spatial network analyses and actual on-site measurements can provide important insights regarding their spatial effectiveness. These inferences can become the basis for the future planning and design of such buildings, e.g. the location of important social focal points at locations that correlate with high degree centrality, elevated connections at node points with high closeness and between centrality measures, and the design planning of the architectural program that supports the function of the nodes at these locations.

The further extended study of correlation of different network measures with the actual human flow and space use and comprehensive analysis that includes more temporal and co-presence patterns and factors would yield more in-depth insights into buildings' actual performance.

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