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Vertical Cities: Emergent Patterns of Movement and Space Use in Dense Vertically Integrated Urban Built Environments

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In high-density, land-scarce cities like Singapore, the successful translation of ground-level urban qualities and benefits into vertical living is crucial for social, economic, environmental, and ecological sustainability. This research introduces a Network science-based spatial analysis framework to evaluate the connectivity and relationships of vertically integrated urban open spaces. Kampung Admiralty (KA), a unique development integrating housing for the elderly with various facilities, serves as a case study. The methodology combines static spatial network measures and real-world movement data to predict movement flows, accessibility, and connectivity. Lift lobbies and elevated garden connectors emerged as critical paths, effectively distributing pedestrian flows. Landscape spaces played a key role in visual and physical connectivity, offering high recreational and social value. Strategic placement of "social attractors" improved space utilization. The study highlights the importance of spatial design parameters in user-space interactions and provides insights into socio-spatial networks at both ground and elevated levels. It identifies key connectors that facilitate effective planning and design of vertically integrated public space networks, promoting social and spatial effectiveness.

Keywords: Spatial performance; Spatial network analysis; Urban complexity; Bluetooth localization; Spatio-temporal interactions; sDNA; Urban pedestrian network.

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1. Introduction

As cities extend vertically, dense vertical living becomes an important option for sustainable urban development. The past century saw a significant shift toward a compact city model with an increase in vertical organization of urban programs as a new form of sustainable urbanism in dense and land-scarce cities like Hong Kong, New York City, Singapore, and Tokyo. These cities are characterized by intensifications of lateral urban systems on multiple levels, indicating the emergence of a three-dimensional (3D) urban space, where "the horizontal ground plane of a city begins to 'thicken', and growth is through vertical densification in addition to lateral spread" (Cairns 2016). The idea of bringing nature closer to the living spaces with environmental, ecological, and social benefits (Crucitti *et al.* 2006; Newman 2014; Totaforti 2020) by integrating greenery in the vertical dimension contributes significantly to the livability and sustainability of the dense vertical built environments. Integrating the desirable qualities of natural environments with planning and design for density provides the much-needed balance between the latter and livability (Schröpfer 2016, 2020).

Public and common spaces and networks, traditionally located on the ground level, are increasingly complemented by such spaces and networks on elevated levels in the form of sky bridges, sky parks, sky terraces, and roof gardens. Planned in combination with a variety of land uses like residential, civic, institutional, and commercial programs, the vertically integrated mixed-use developments assemble themselves as "vertical cities", where these elevated spaces become elements of larger urban systems. Establishing the vertical and horizontal spatial networks of open spaces and mapping the pedestrian mobility patterns within the networks to generate emerging socio-spatial networks would enable us to understand the vertical expansion of horizontal urbanity. The relationship between the integrated built spaces' configuration and socio-spatial network behavior can provide critical insights for the planning and design of future vertically integrated developments.

In Singapore, the need for comprehensive and integrated urban planning to optimize the limited land resources saw the emergence of new building types with mixed land uses co-located within a single plot of land. These integrated mixed-use buildings take the form of vertical extensions of urban spaces on the ground level, where circulation, land uses, open spaces, ecological networks, and human activities are distributed both laterally and vertically in varying spatial arrangements. The success of a diverse set of design solutions for such integrated mixed-use developments lies in their ability to continue the ground-level urban vibrancy to the elevated networks of vertically integrated social spaces. Accessibility and connectivity are vital to understanding the structure of the spatial networks within the vertical neighborhoods and the occurrence of human activity. While building designs aimed to achieve socio-spatial efficiency, the resulting performance of the user–space interactions is often emergent. In this context, the relationship between the configuration of the integrated built space and its socio-spatial network behavior can provide critical insights for the planning and design of vertically integrated developments.

2. Research Context

2.1. *Urban complexity and user-driven built environments*

Increasingly, cities are studied as complex adaptive systems, drawing on the evolutionary theories of complexity science and ecological sciences to emphasize the bottom–up processes of emergence and adaptability (Batty 2003, 2012; Bettencourt 2013). Urban complexity focuses on the interactivity between the space users and their built environments and provides essential insights into an informed approach to planning, designing, and managing urban built environments. Recent studies leverage advanced digital tools and techniques to develop fascinating explorations into the temporal networks created by human activity patterns within built environments (Alessandretti *et al.* 2018; Barabási 2009; Barthélemy, 2003; Crucitti *et al.* 2006; Manivannan *et al.* 2018; Tekler *et al.* 2020; Torstensson 2010). Yet, these studies are mostly limited to horizontal movements and lateral expansions; little is known about human vertical mobility (Bouffanais and Lim 2019). Therefore, the study of human vertical mobility has recently emerged as essential to understanding the effects of elevated public and common spaces and urban networks on human movement and social behavior patterns. Complex System Studies thus need to be extended to the vertical dimension to systematically analyze and evaluate the character of socio-spatial networks formed as users interact with such vertically integrated built environments.

Just as a city can be understood as a space of flows (e.g., energy, resources, people, etc.), at a smaller scale, a vertically integrated mixed-use building's spatial configuration forms the static network structure with its programmatic distribution of spaces and circulatory paths within which the socio-spatial processes take place. Thus, the spatial network structure influences the dynamics of the process flows, including the temporality of movements, interactions, and occupancy of users. While the static spatial components can be designed for efficiency, their actual performance is an evolutionary process and a product of emergence. The presented research proposes a Network science-based spatial analysis framework that assesses the performance of network connectivity of vertically integrated open spaces and their topological relationships. It uses Kampung Admiralty (KA), a first-of-its-kind "vertical city" building prototype in Singapore, as a case study. KA integrates housing for the elderly with a wide range of social, healthcare, communal, commercial, and retail facilities (Yap 2019). The advent of affordable and efficient technologies like low-energy Bluetooth (BLE) devices combined with smartphone sensors allows tracking and localizing building users within complex multi-level integrated spatial configurations. An analysis of the resulting real-world data produces evidence of (1) how integrated public and common spaces in the building are used, (2) how they influence user behavior and movement patterns, and (3) how they impact social interactions and user activities over time.

2.2. *KA description*

Designed as one of the first integrated community hubs in Singapore, KA is a first-of-its-kind development in Singapore which integrates housing for the elderly with a wide range of social, healthcare, communal, commercial, and retail facilities. The project tested a prototype for a 'vertical city', where the plot became an urban neighborhood planned in the vertical dimension (Figure 1). Awarded "World Building of the Year" in 2018, KA was conceptualized as a "vertical village" that optimized the plot area by vertically intensifying land use and transformed the 0.9-ha site into a dynamic center for the community (WOHA 2018). As described by WOHA, the development's architect, the design uses a "sandwich layered approach" that comprises a community plaza located in the lower layer, a medical center in the middle layer, and a community park with senior apartments in the upper layer of the building (WOHA 2018). The project's community plaza provides a fully public and pedestrianized ground plane to serve as a community 'living room'. The community park on the roof is a more intimately scaled, elevated green space accessible by residents and visitors. Co-location of complementary programs such as childcare and an active aging hub (including senior care) brings together all generations — two 11-storey residential towers consisting of 104 apartments to house elderly singles and couples (Yap 2019).

2.3. *Pedestrian connectivity in vertically integrated neighborhoods*

In the emerging vertical urban environment, people are constantly moving in three dimensions — up, down, and across, in their everyday routines, and vertical mobility has allowed urban planners and designers to reimagine and reconfigure urban spaces. Studying the pedestrian connectivity within the city as a 3D network is imperative to understand how the urban interactions shape the high-density urban environments' spatial integration and influence the urban spaces' socio-

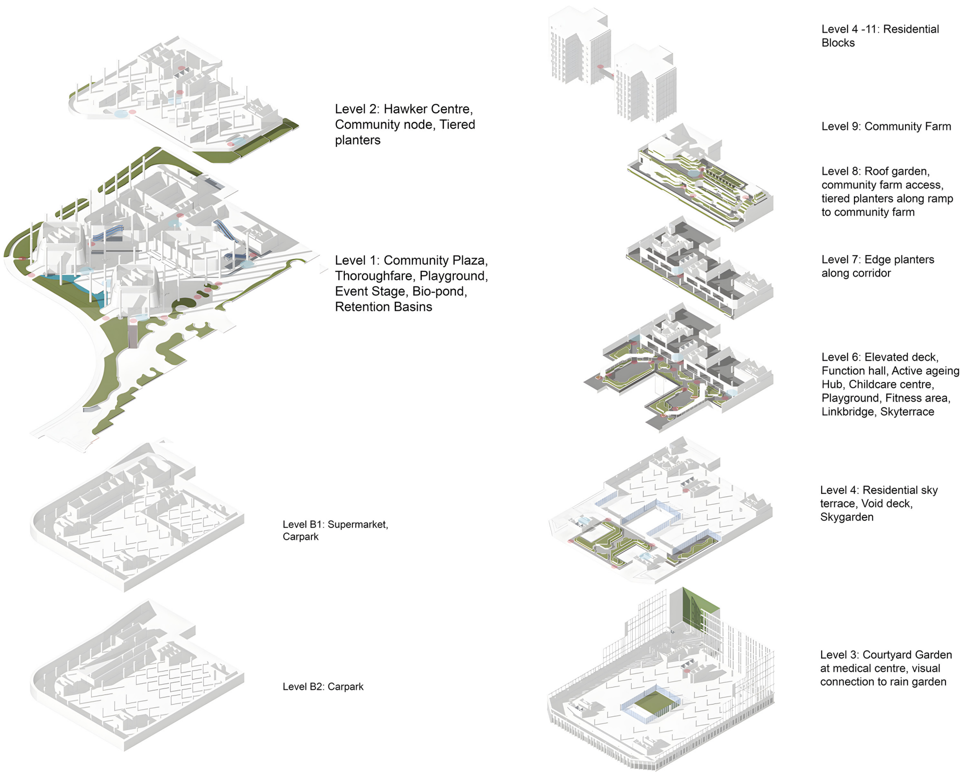


Figure 1. Exploded Axonometric of KA Showing the Vertical Distribution of Public Spaces
Source: SUTD Cities: Urban Science and Design for Density

spatial performance (Sun *et al.* 2021). Understanding the connectivity of vertically integrated built environments requires an accurate capturing of the 3D pedestrian network as a critical consideration for planning and designing future high-density cities.

Urban spatial networks form the basis for mapping, understanding, and analyzing urban spaces and their various multi-layered and interconnected urban systems. A network-based model for spatial network analysis has been used extensively in urban network studies to understand pedestrian behaviors and analyze the impacts of movement flows in different spaces on the overall network performance (Cooper and Chiaradia 2020; Hillier *et al.* 1976; Sevtsuk and Mekonnen 2012). The theory of Space Syntax, one of the most widely applied methods for urban spatial analysis, explains human behavior and social activity as derivatives of spatial configurations. It argues that the configurations of space where the different activities occur influence movement, encounter, and avoidance and generate social relations. Connectivity and accessibility of the networks are measured through various mathematical models using the movement flows through the spatial units. As the most significant proxy for network analysis is movement, circulation systems become the skeleton to analyze the spatial definition. The configuration and programming of spaces with the circulation paths assist in deriving significant measures of how the space performs.

3. Methodology

The methodology maps, analyzes, and produces real-world evidence of how vertically integrated public and common green open spaces in buildings perform spatially and influence users' behaviors and movement patterns within and around the site. Once the relationship between the integrated landscape spaces and their use patterns is established, their performance as effective social spaces can be assessed. Identifying the parameters influencing the socio-spatial use patterns will inform the design of future vertically planned landscape spaces, leading to a more scientific evidence-based approach for planning sustainable, resilient, and adaptive urban landscape spaces.

3.1. *Performance assessment framework*

The proposed framework employs a hybrid approach using static spatial network measures to predict movement flows, accessibility, and connectivity within a network, and overlay real-world movement data to analyze the dynamic network measures and validate the expected static spatial network measures. The validations would provide insights into the critical spatial design parameters influencing the patterns of user–space interactions. The methods include qualitative spatial analysis of the layout, mapping of the spatial network, spatial network analysis for static network measures, quantitative data collection of human movement and activity, spatial network analysis with real-use movement data (dynamic network processes), and validation of actual performance with predicted static spatial network patterns of movement and space use. The study is organized into four stages to derive the patterns of user–space interactions (Figure 2).

Spatial network analysis (static measures). A network structure of nodes and edges was generated based on the built spatial layout. Key network measures were analyzed to understand the designed space's network topology and strengths based on their spatial configurations. This stage involved the qualitative spatial analysis of the landscape spaces, mapping the spatial nodes and edges, and determining the attributes and links for analysis. The vertically integrated pedestrian connectivity was studied using the spatial design network analysis (sDNA) (Cooper 2015;

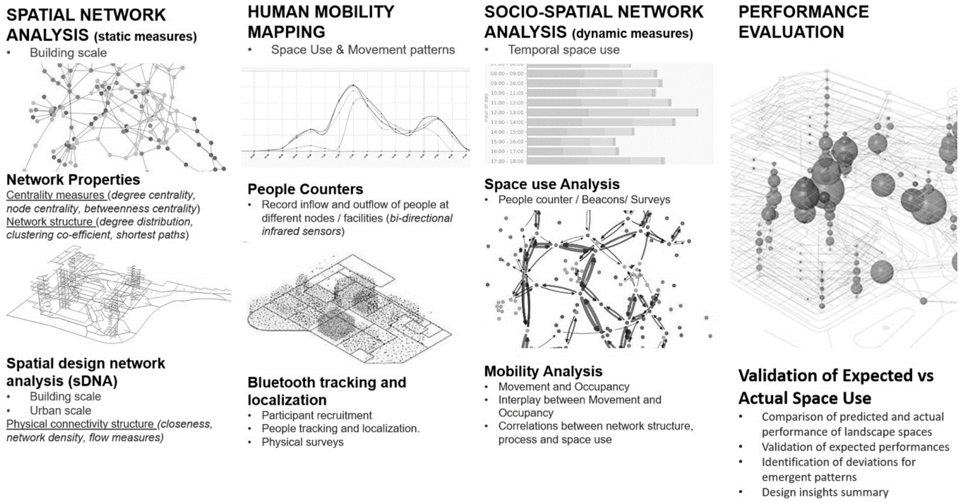


Figure 2. KA Performance Evaluation Framework Structure
Source: SUTD Cities: Urban Science and Design for Density

Cooper and Chiaradia 2020) network link model analysis. A complete 3D pedestrian circulation link model was prepared to analyze the 3D circulation network for expected pedestrian flows and connectivity.

Human mobility mapping. Human mobility is the dynamic process on the static spatial network. This stage consisted of data collection for space use from sensors installed at the site, recruitment of participants to collect data on movement and actual space use at the different spatial nodes, and compilation of physical and observation surveys on site.

Socio-spatial network analysis (dynamic measures). The overlay of real-use data on the static spatial network analyzed social movements and activities as a dynamic process occurring within the embedded spatial structure. It consisted of the analysis of landscape space use data from people counters, analysis of mobility patterns, demonstration of users' movements within the common green open spaces, analysis of occupancy times at various spatial nodes, the interplay between mobility and occupancy, and the relationship between the network structure, the network processes (movement and occupancy), and the landscape space use.

Performance evaluation. As a final step, all the measures derived for the static and dynamic spatial network analyses were populated to the performance assessment frameworks matrix and summarized for the effectiveness of the predicted space use with its actual use.

3.2. *Spatial network measures*

The study of urban networks is rooted in the mathematical graph theory of Network Science, where a network is represented as a graph of nodes and edges, where nodes are points of interest for analysis and edges are the connecting links that help understand the interactivity between the spaces. Nodes have attributes that can be defined using measurable parameters like shape, size, location, function, features, etc. Edges have properties that determine how spaces connect and interact. Connectivity and accessibility of the networks are measured through various mathematical models using the movement flows through the spatial units. These form the basis for deriving different correlations, interactions, and definitions of urban spaces and systems. As the most significant proxy for the network analysis is movement, circulation systems become the skeleton for analyzing spatial definitions.

The socio-spatial networks are analyzed for their centrality measures to quantify the most significant connectors based on their location and accessibility within the spatial network. The critical network measures include “degree”, “closeness”, and “betweenness” centrality (Barrat *et al.* 2004). *Degree centrality* measures a node’s significance in terms of its connectivity, based on the number of links. The higher the degree number, the more connected the node is within a network. Determining the degree centrality score allows for effective planning of the active social spaces to act as critical connectors for the integrated development. *Closeness centrality* scores each node based on its closeness to other nodes in a network using the shortest paths between each node. Closeness measures help identify spatial clusters within building development by highlighting the spatial distribution of high-degree nodes. *Betweenness centrality* characterizes a node’s global 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 critical pathways between nodes. A high centrality measure indicates the node as part of many shortest routes, thus translating to increased movement and potential interactions. Comparing and correlating these various measures allows for identifying spaces’ significance, function, and location. It further helps identify parameters for the planning and design of size, co-location, and configurations of social spaces within larger developments.

4. Spatial Network Analysis

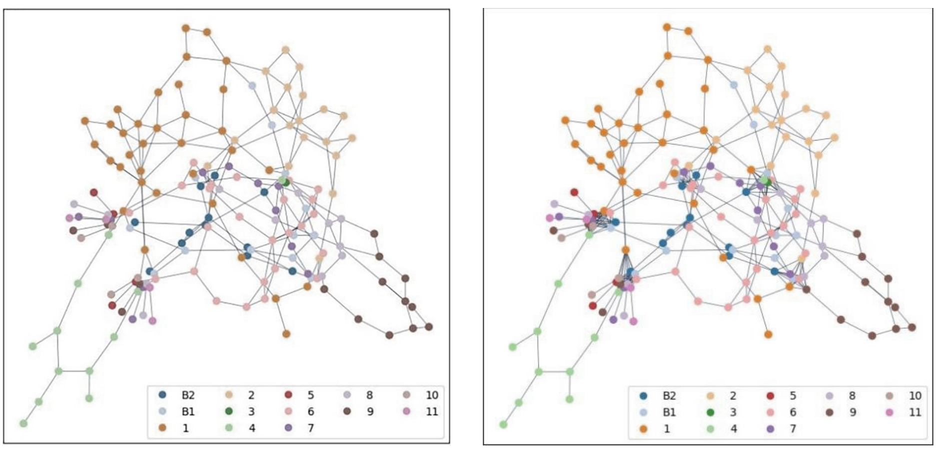
In the analysis of KA, two node attributes were considered for aggregation of the landscape spaces for study, (1) space type and (2) floor level. Space types included residential, commercial, social, F&B programs, health facilities, and vertical streets (lift and stair lobbies). The floor level indicated the location of the nodes and included corridors, staircases, escalators, and ramps connecting the nodes that formed the edges for the analysis. The network analysis study considered the edges as the shortest routing distances connecting adjacent nodes immediately. The routing distance between the centroids of any two nodes is defined as an edge weight. The links were undirected, indicating they were freely accessible with no directional limitations. The lift lobbies were analyzed in the vertical dimension with both adjacent (Network *A*) and all-to-all connectivity (Network *B*) scenarios. The rationale for an all-to-all connectivity between lift lobbies in Network *B* was based on the analogy of considering lifts as bridges or trains, where any location can be reached directly without stops. All homogenous nodes adjacent to each other formed a single node for analysis; thus, edge formations existed only between geographically separated and heterogeneous nodes. Based on the above classifications, the spatial layout of KA translated into a spatial network with 165 nodes and 392 edges.

The global network properties of Networks *A* and *B* are shown in Table 1 and the network structure visualizations are provided in Figure 3. The initial study on the KA connectivity network based on the spatial arrangements revealed preliminary insights. In both cases, the presence of vertical streets in the KA network structure brought out the nonplanar characteristics, with a resemblance closer to airline networks, a distinct departure from the traditional road or rail networks which are represented on a planar surface. The presence of vertical streets gave a prominent 3D aspect to the spatial network. The expected outcomes were the closeness within the network structure, revealing the compact and highly accessible spatial arrangement within the development. Most spaces were easily accessible within a shortest travel distance, indicating a highly walkable spatial arrangement as intended by the architects. The community lift lobby was designed to be a central access point for all the community facilities within KA. The network structure confirmed this configuration. The Level-1 community lift lobby was found to be the barycenter of the network, the most convenient point to reach all other spaces within a 50 m travel distance (Figure 4).

The community facilities were evenly planned at multiple levels to distribute the pedestrian flows within the development. More public and frequented facilities like retail and supermarkets were located at the lower levels, while the hawker center at L2 served as a key connecting node for transit, regular, and resident users. Social facilities like childcare, the active aging hub, function rooms, and the pre-school were located at L6 adjacent to quieter and greenery surroundings. The network structure outcomes were as expected, with L1 spaces emerging as key connectivity

Table 1. KA Global Network Properties of Networks *A* and *B*

Metric	Network *A*	Network *B*
Vertical street connection method	Adjacent connectivity	All-to-all connectivity
Number of nodes	165	165
Number of edges	238	392
Average degree	2.88	4.75
Average shortest path (Unweighted)	7.8 hops	5.3 hops
Average shortest path (Weighted)	105.3 m	104.4 m
Average clustering coefficient C (Topological)	0.10	0.31
Average clustering coefficient C_w (Weighted)	0.03	0.086
C_w/C	0.36	0.27
Graph density	0.017	0.028
Planarity test (Kuratowski theorem)	Nonplanar	Nonplanar
Barycenter (Weighted)	Community lift lobby at Level 1	Community lift lobby at Level 1



(a) (b)

Figure 3. (Color online) Network Visualization. Node Colored by Floor Level. (a) Network *A*: Vertical Connection Type: Adjacent Connectivity and (b) Network *B*: Vertical Connection Type: All-to-all Connectivity

Source: SUTD Cities: Urban Science and Design for Density

nodes followed by L6 garden spaces forming the second connectivity layer for the development.

The garden spaces at KA had distinct spatial arrangements. At L1, the greenery enclosed the development edges to create a garden-like transit setting for the community plaza. The social facilities, like play areas, plaza seating, stage, and water features, were placed subtly within the edges to encourage users along the

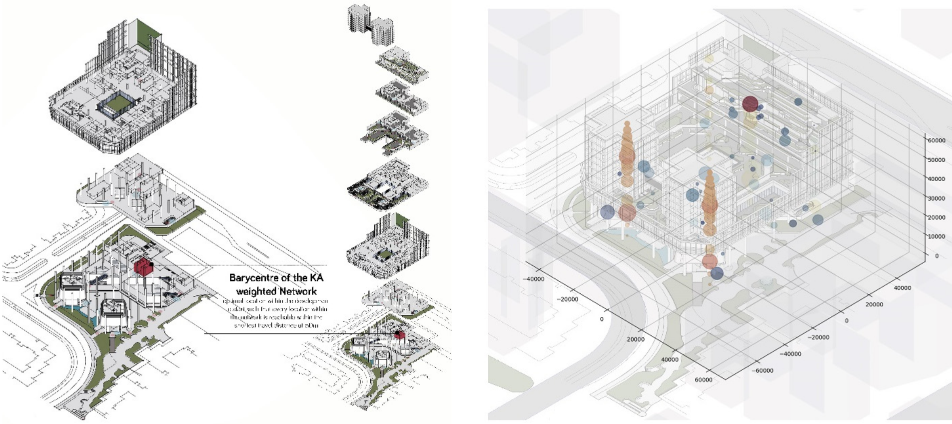


Figure 4. (Color online) (Left) Visualization of Network Measure; The Red Location Indicates the Barycenter of the Weighted Network, the Optimal Location from where Every Other Spatial Node within the Development can be reached within a Minimal Travel Distance of 50 m. (Right) Visualization of Betweenness Centrality indicating the Significance of the Lift Lobbies as Key Connectors
Source: SUTD Cities: Urban Science and Design for Density

movement routes. In contrast, the elevated sky gardens were designed as lush green settings dotted with facilities within, like playground, fitness corner, seating areas, and social corners, encouraging the users to spend time while moving through to various community facilities. The network structure revealed a hierarchy in the garden spaces, with L6 sky gardens forming the most significant node, followed by the roof garden spaces, matching the original design intent for the KA garden spaces.

An interesting insight from the network analysis was the significance of the vertical connections in the overall connectivity of KA, as seen in Figure 4. While the residential lift lobbies were designed primarily to cater to the residents, they also emerged as highly significant vertical connectors to the community facilities, with high values of betweenness, closeness, and degree centrality. In addition, it showed that the residential lobbies were expected to be used almost with the same intensity as the community lobbies.

Figure 5 shows the three networks derived from the spatial structure of KA public spaces for Network *B* generated based on adjacent relationships between the spatial nodes. Most of the link distances were below 50 m, with very few longer than 60 m. As a comparison, a 50 m reachability network was generated, where if a node was able to reach to another node in 50 m, a link was created between the two nodes. For instance, the garden streets (orange nodes, Level 4) at the lower left were not directly reachable by most of the residential streets (green nodes), but the gardens were reachable from those residential streets in 50 m.

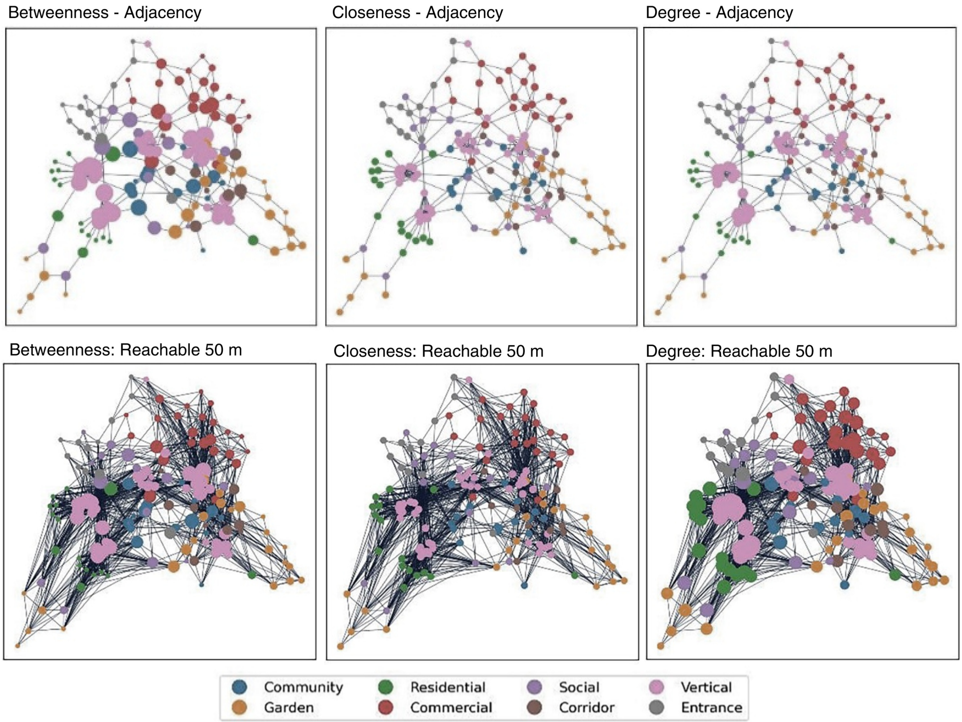


Figure 5. (Top) Weighted Centrality Measures of KA Spatial Network Visualized Using Gephi. Visualization of Betweenness, Closeness, and Degree Centrality for Adjacency and Reachable Networks of the KA Spatial Structure

Source: SUTD Cities: Urban Science and Design for Density

For both, Network *B* adjacency and the reachable network within 50 m, most of the top-ranked nodes for all three measures were lift lobbies, indicating that the lift lobbies had the strongest importance levels while analyzing the network connectivity within the KA. There are two key aspects of the lift lobbies to consider when comparing the relative network connectivity measures as a node, location and type. Location refers to where and at which level the lift lobby is located and type refers to whom or what primary purpose the lift lobby serves. While most top-ranked nodes with the highest scores in degree, closeness, and betweenness centrality were lift lobbies, the differences in location and type of lift lobby nodes were an important distinction for understanding the overall performance of the vertical streets.

Level-1 lift lobbies were the most connected and central for the vertical circulation and ranked 1 for all measures. While the residential lobby had the most connections to all other adjacent nodes and formed part of the shortest paths to many other nodes within KA, the community lift lobbies on Levels 1 and 2 were the most reachable and accessible. Thus, KA users, who were most familiar with the development, such as residents, employees, and regular facility visitors, were most likely to use the residential lift lobbies to move to amenities, while nonregular users and new visitors were most likely to choose the community lift lobbies to move vertically. Similarly, while the Level-6 residential lift lobbies were part of the shortest paths to many other nodes, they were not the easiest to access, based on the reachability network. However, the Level-6 lobbies were the most significant connectors in the development with almost all lobbies forming part of the shortest transit routes. The Level-6 sky gardens thus played a central role in distributing the vertical movement flows through the development.

These differences indicate that while the immediate adjacency of spaces helps understand the overall connectivity within the network, reachable relationships help to capture the structures of accessibility.

4.1. *Spatial design network analysis*

The vertically integrated pedestrian network configuration at KA was studied using a network link model approach. A GIS-based plugin toolkit, sDNA, developed along the principles of Space Syntax was used to derive the various network connectivity measures for analysis. sDNA (Cooper and Chiaradia 2020) works on the premise of defining a complete 3D representation of the network links for the study of movement and behavior patterns in complex vertical environments. The sDNA framework for 3D spatial network analysis uses the network links as the central unit of analysis where every link in the network has defined statistical properties. As a result, it provides a more accurate computation of 3D network measures of accessibility, flows, and geometric efficiency (Cooper 2015; Cooper and Chiaradia 2020). A 3D network link model was generated to connect the different nodes in the physical layout at each level and between various levels to analyze the routes' strength in linking the other nodes within the development (Figure 6). The model enabled the exploration of the link strengths within the connectivity structure.

The network link model was analyzed for the centrality measures, indicating the significance of the links and their connectivity strengths within the network. sDNA analysis uses the origin–destination measure to analyze the accessibility within the link network. It provides a wide range of analysis outputs that measure the connectivity and accessibility within the network like reach, mean distance (inverse of closeness), betweenness, and geometry. This study focused on two key centrality measures — closeness and betweenness.

Closeness measures determine the accessibility of the links in the network within a given radius, thus measuring the "to-movement". It analyzes how close the origin is to all destinations within the network using the Mean Distance (MD)

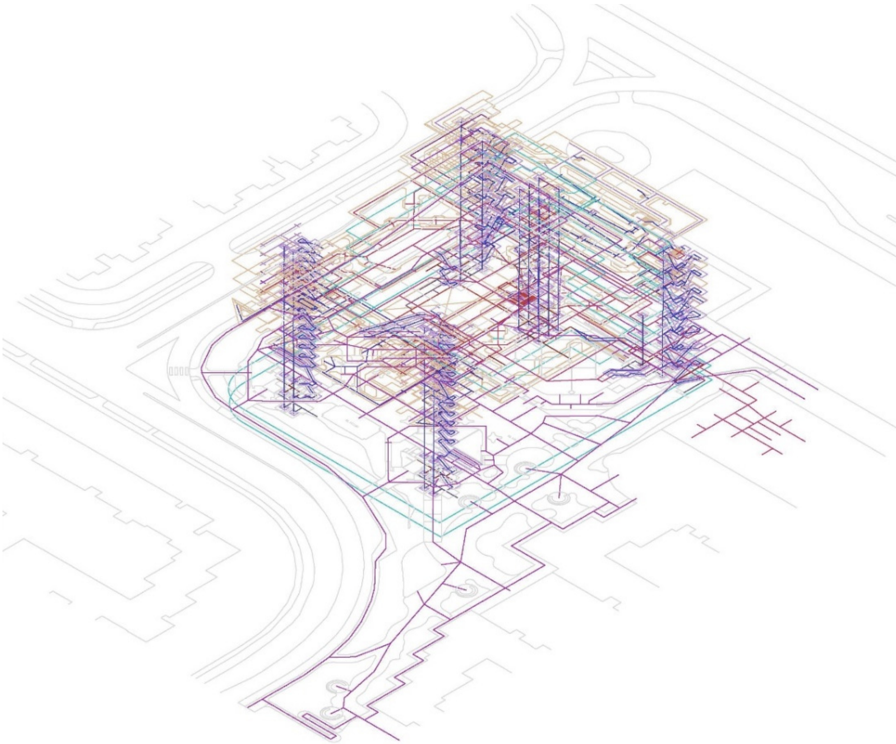


Figure 6. The 3D Model of Network Links of the Public Spaces within KA for sDNA Network Analysis

Source: SUTD Cities: Urban Science and Design for Density

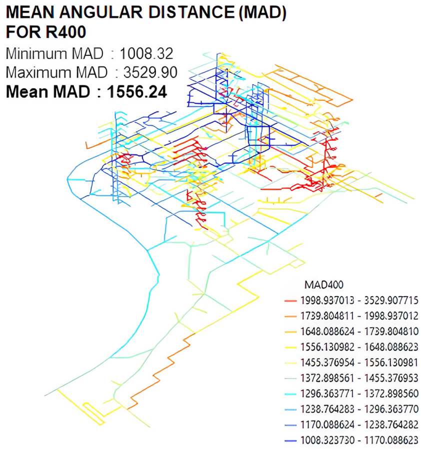
output and Network Quantity Penalized by Distance (NQPD). MED (Mean Euclidean Distance) measures the meter-based length between origin and all reachable places within a given radius. Thus, a lower value of MED indicates closeness. The Network Quantity Penalized by Distance Euclidean (NQPDE) measures the sum of network quantity over distance. A higher value of NQPDE indicates a closer and more accessible network. Betweenness measures assess all possible trips passing through a network link, thus estimating the flow (Bt). It focuses on the shortest path and connections between specific locations and reachable places within a given radius. A higher value of Bt indicates that the links would have an increased flow of "through movement".

Table 2 summarizes the comparative mean values of the sDNA measures for the KA link network. The betweenness and link densities provided valuable insights into the pedestrian flows along specific routes within the development. The overall network configuration showed a high degree of closeness and hence high

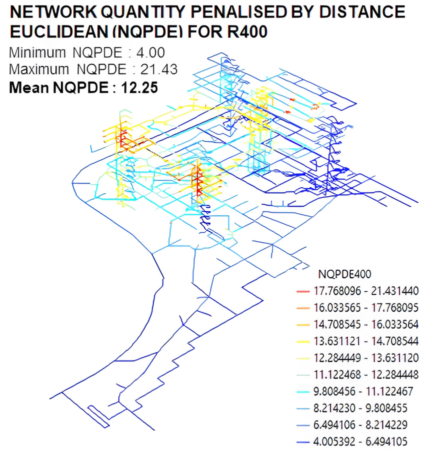
Table 2. Comparison of sDNA Measure (Mean Value) for KA Vertical Network

sDNA Measure		Abbv.	Description	Kampung Admiralty (Vertical Network) R400	Kampung Admiralty (Vertical Network) R800
Individual polyline descriptive measures	Line Connectivity	LConn	Connectivity of each link/ polyline	3.63	
	Line Angular Curvature	LAC	Angularity of individual polyline	40.5	
Centrality measures	Farness	MED	Inverse of closeness; accessibility; mean length between origin and all reachable destinations in a radius	151.4	151.5
		MAD		1,556.25	1,556.72
	Closeness/ Network Quantity Penalized by Distance (Euclidean, Angular)	NQPDE	Sum of network quantity over distance; indicates the closeness/network density	12.25	12.25
		NQPDA		0.726	0.727
	Betweenness	BtE	Flow prediction based on Euclidean or angular shortest path distance	21,597	21,620.22
		BtA		21,730.75	21,753.02
	Mean Crow Flight	MCF	Mean crow flight distance between centers of two links in a radius; indicates severance (opposite of connectivity)	51.93	51.95
	Mean Geodesic Length (Euclidean/Angular)	MGLE	Same as closeness but always outputs in units of length even for non-Euclidean geodesics; shortest route between two points in the network	151.4	151.5
		MGLA		168.98	169.08

accessibility (Figure 7). Regarding closeness density, KA was highly accessible and connected at the elevated levels within the building network, with L6 having the highest values. The MED measures for the KA vertical network indicate that elevated links were shorter between points compared to the ground-level links. Elevated networks in KA were easy to navigate with minimal turns and thus lower MAD values, while routes leading to the lift lobbies and stairs show higher angular navigation [Figure 7(a)]. The higher average value of network link density (NQPDE) indicates increased closeness within the network configuration, translating to higher accessibility and hence potentially improved walkability [Figure 7(b)].



(a)



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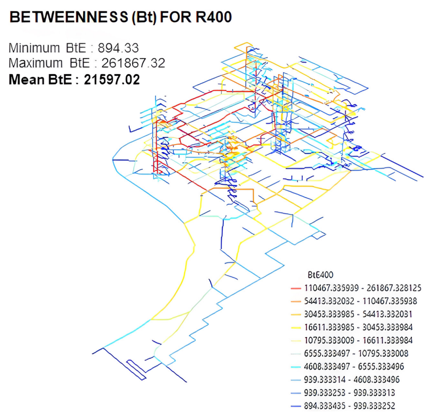

(c)

Figure 7. sDNA Measures Visualization for KA Vertical Pedestrian Connectivity Network
Source: SUTD Cities: Urban Science and Design for Density

The average betweenness values (BtE) for the network links indicated that most links formed part of the shortest paths to reach various destinations [Figure 7(c)]. It suggested that the overall accessibility within the network was high, with specifically lift cores and lobbies creating key links for multiple destinations. The high values for link measures indicated that spaces placed adjacent to or along the links with high flow and walkability potentially encouraged higher volumes of space use. The elevated links at the L6 garden decks displayed highest values for flow, indicating potential routes with high intensity of use.

The spatial network analysis and 3D pedestrian structure analysis presented preliminary insights into the potential design performance of the various public and common spaces within KA. These initial insights were the basis for validating actual space use and movement patterns derived from real-world participant data.

5. Human Mobility Mapping

Human mobility mapping tracked and recorded pedestrian movements, activities, and space use in significant public and common spaces within and around KA. The onsite study recruited a sample group of 73 KA users consisting of residents and nonresidents. Actual use data was collected using a combination of qualitative and quantitative methods. Movement tracking with Bluetooth localization consisted of three components: (1) stationary BLE beacons, (2) a mobile app, and (3) a cloud server (Figure 8).

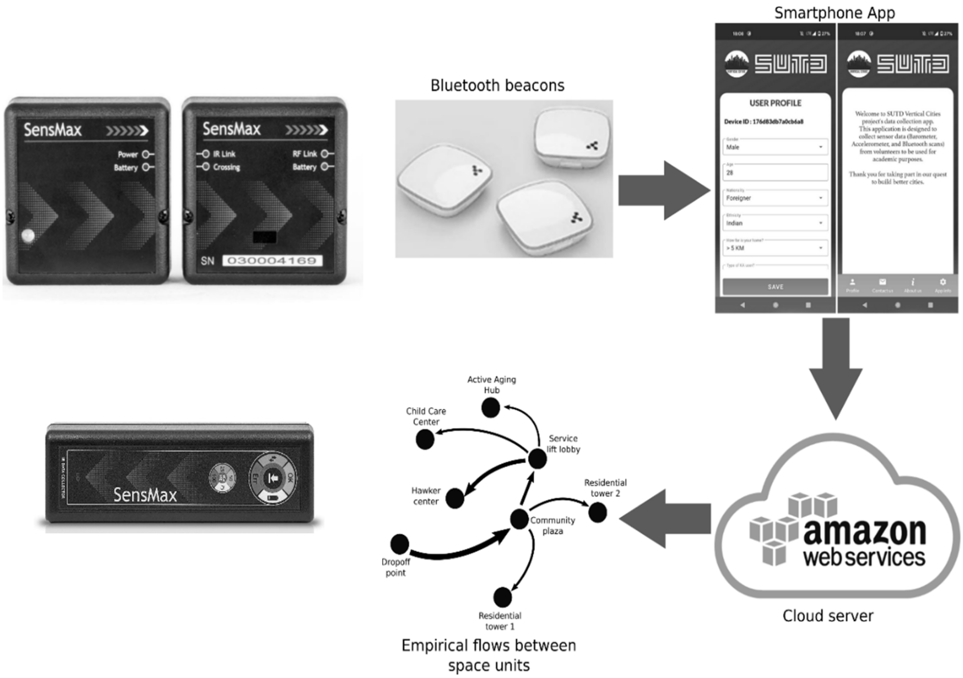

Figure 8. Human Mobility Mapping Ecosystem used at KA. (a) SensMax Outdoor People Counter and Data Collector. (b) The Data Collection Framework: The Beacons Installed at Various Places of Interest; the Participants' Smartphone's App will Scan, Record, and Send the Nearby Beacons Information to the Amazon Cloud Server; The Data from the Amazon Cloud Server is Downloaded and Processed to Represent the Flows of Participants between Space Units

Source: Panel (a): https://sensmax.eu/. SUTD Cities: Urban Science and Design for Density

The tracking method used a "peer-to-environment" sensing system by placing 124 stationary Bluetooth beacons in locations of interest on different floors of KA. A custom app installed on participants' smartphones running iOS or Android worked in the background to scan for Bluetooth data from the BLE beacons. The received data contained 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). The data collected from the participants' Bluetooth devices was plotted on the spatial layout to map the participants' movement routines over two–three weeks. In addition, 14 bi-directional infrared people counters were installed at key nodes identified through spatial network analysis to gather data on the volumes of inflow and outflow during different times of the day and week. The data from the bi-directional counters provided information on the temporal variations in space use volume. BLE beacons and the people counters provided the actual use of the public and common spaces within KA. Finally, participants' survey was conducted to collect qualitative data on movement and space use. The survey was further analyzed to evaluate the user preferences and patterns of space use, level of social interactions, and frequency of landscape space use in KA.

6. Socio-spatial Network Analysis

The various sensor data collected onsite provided a rich source of over 42.6 million data points for analysis (Table 3). The collected data from the people counters, Bluetooth beacons, and participant surveys were overlaid on the static spatial

Table 3. KA Real-use Dataset

Metric	Value (s)
Time period of experiment	28-01-2021–28-02-2021
Number of participants recruited	73
Number of participants with at least one data	68 points
Number of sensor data points	42.6 million
Number of participants with at least one Kontakt	52 beacon data
Number of participants with at least one mobility	51 data
Number of participants with at least one occupancy data	52
Number of accelerometer data	29,117,004
Number of barometer data	12,853,379
Number of Bluetooth data	671,057
Number of Kontakt beacon data	86,826
Number of unique Kontakt beacon data scanned	117 out of 124 beacons placed in KA

network to analyze the temporal user–space interactions at KA. The following subsection describes the results of the socio-spatial network analysis.

6.1. *People counter data analysis*

The people counter data analysis showed distinct and consistent temporal patterns for the garden spaces and community facilities at various levels in KA (Figure 9). Users predominantly used the Level-4 gardens during the daytime, and the number of visitors was lower than at other levels. Level-8 and Level-9 community farms were well frequented by residents, visitors, and facilities users. While Level-9 gardens were used more during the morning and evenings, Level-8 gardens were used well even during the afternoons. Combining well-shaded attractive garden walks with well-defined seating areas effectively encouraged the use of the sky gardens regularly at all times of the day. The community facilities were found to be more active during weekdays than weekends. Levels 1 and 2 served as key connectors with peaks during morning and evening. Levels 6–8 served more as attractors for leisure users, while the lower levels reflected the movement of commuters who were "moving through".

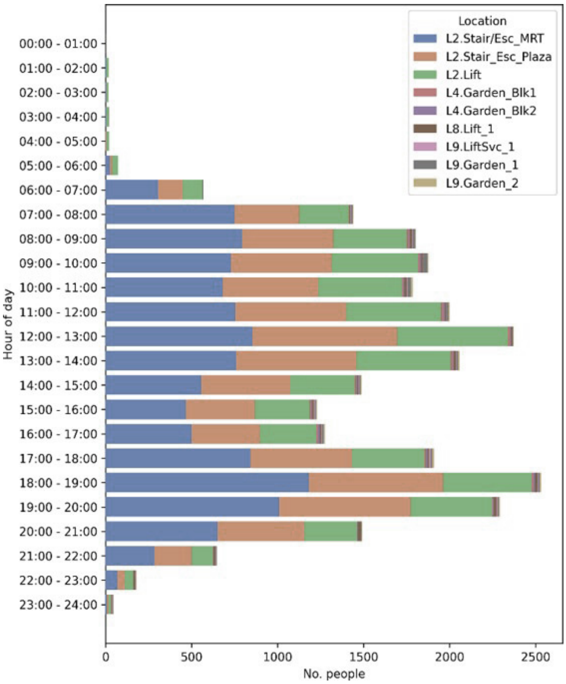

Figure 9. Hourly, Aggregated Use of Community Facilities from People Counter Data
Source: SUTD Cities: Urban Science and Design for Density

6.2. *Bluetooth beacon data analysis*

The beacon data represented the space use patterns of the recruited participant sample. The patterns of space use were also very consistent, indicating active use of open spaces. More importantly, the users (resident and facility users) were regularly meeting in the garden spaces, indicating a healthy familiarity and community bonding.

6.2.1. Space use analysis

The pattern of beacon readings indicated that the use of various common open spaces and facilities in KA had a consistent pattern over the week, with Fridays showing a significant change in the regular routines (Figure 10). It could be interpreted as potentially more activities were scheduled during Friday afternoons, indicating a higher presence of most participants in KA. The visual observations also confirmed that most residents and regular facilities users were in KA premises on Friday afternoons and often met up for lunch after their activities. The patterns of beacon readings also indicated that most participants spent time in the social spaces at KA regularly and at similar areas. It indicated that the users would be regularly meeting each other or familiar with each other, thus indicating active social interactions. The garden spaces at L4, L6, and L9 were well visited,

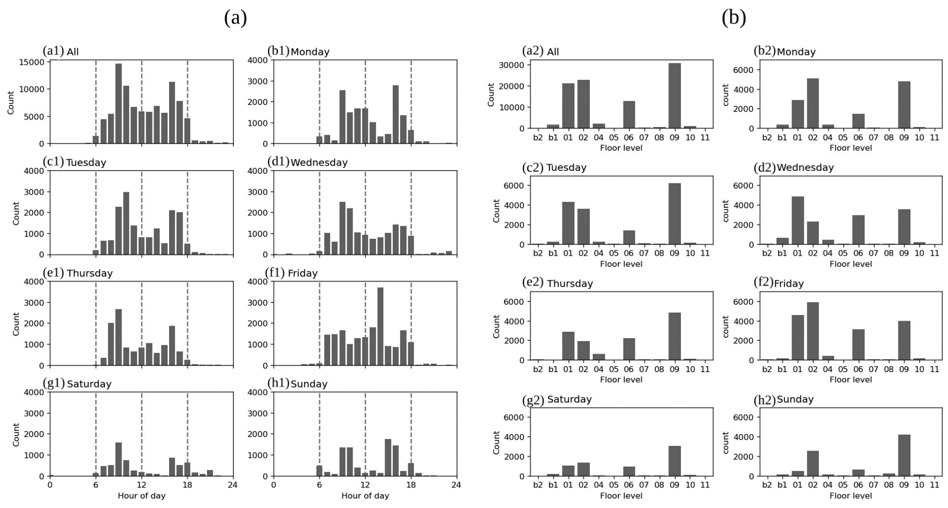

Figure 10. (a) Hourly Aggregated Number of Beacon Readings by Day of Week: (a) All Days and (b)–(h) from Monday to Sunday. (b) Total Number of Beacon Readings by Floor Levels: (a) All Days Aggregated and (b)–(h) Grouped by Day of Week (from Monday to Sunday)

Source: SUTD Cities: Urban Science and Design for Density especially L9. The data may not necessarily indicate that many people visited the L9 gardens. Still, it could be the same small set of participants frequently spending time there, thus resulting in increased beacon readings. The patterns of space use were consistent with the onsite observations, where L2 was busier during the weekdays and relatively less occupied during the weekends.

6.2.2. Participant movement patterns

The beacon data was also used to extract and demonstrate the typical movement and space use patterns of different types of users and understand the preferred destinations and route choices to validate the predictive insights from spatial network analysis measures. Figure 11 shows the movement patterns for an active resident, an employee, a facility user, and a visitor. The comparative results showed the variations and preferences of movement routes and activity spaces. The four participants' movement patterns exhibit starkly different patterns within KA. The active resident moved more on the higher floor facilities than at the lower floor shop levels. This movement pattern was the opposite of the visitor, who frequently visited the shops on the lower floor and seldom went to the facilities on higher floors. On the other hand, the active facility user's movement showed more consistent movement patterns with the active residents, especially between higher and lower commercial floor areas, indicating a stronger socio-spatial link. The facility users and active residents shared common paths and potentially common destinations within KA; thus, residents and nonresidents developed a specific movement pattern that efficiently connected the spaces and people they wanted to interact with. KA was designed to integrate multiple types of land use and community bonding within one building, resulting in different users. It meant that the type of user also affected the movement patterns.

As the pattern of movement within the development is distinctly different for different types of users, efficiently planning the community streets for flexible lateral connectivity at each level and strategically locating the links for vertical connectivity help to generate the active use of public and common spaces.

6.2.3. Analysis of mobility and occupancy

Bluetooth beacon data was analyzed for the network process of mobility and occupancy time of the participant users. Mobility analysis provided insights into the movement patterns of users at the different spatial nodes (Figure 12). The Level-1 plaza recorded the highest movement flows, followed by Levels 6 and 2. Also, the vertical streets (lift lobbies) at all levels recorded the highest movement flows compared to the lateral streets. These were very much in line with the initial predictive measures.

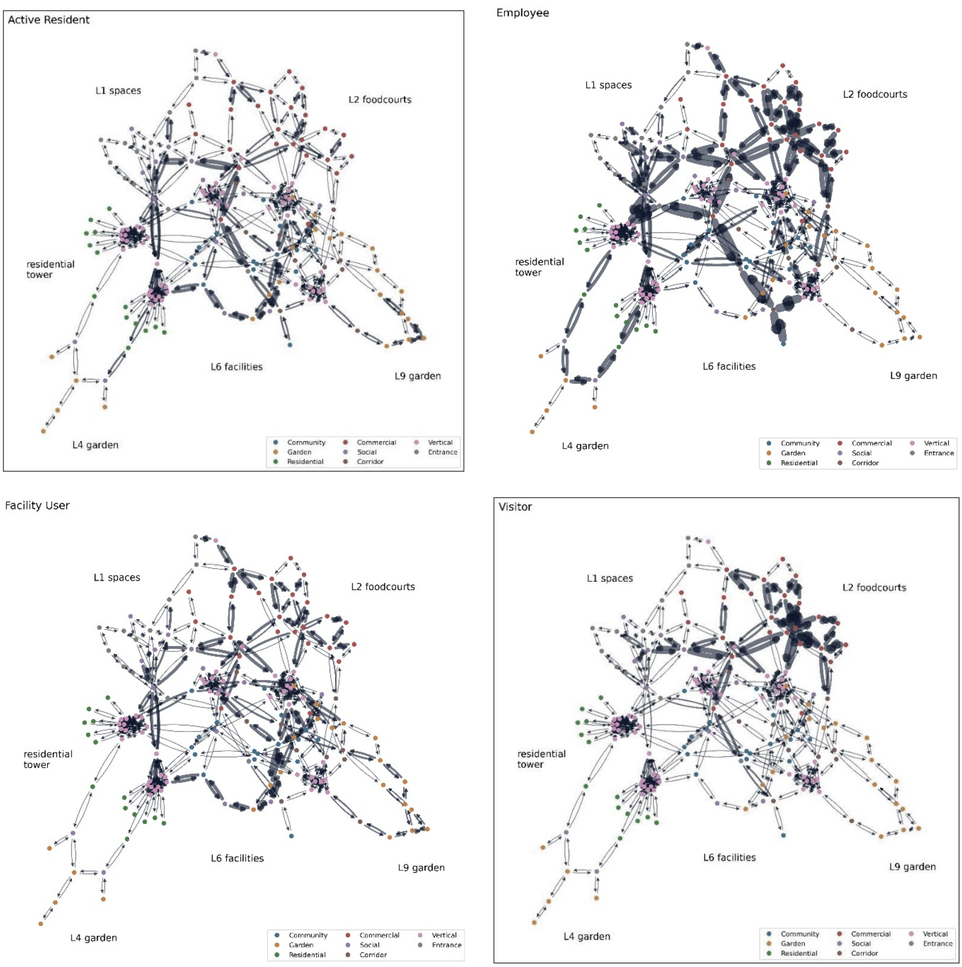

Figure 11. (Top Left) Network Flow of an Active Resident. Edges' Widths indicated the Frequency of the Participant Crossing Between the Two Spaces (i.e., Weight of the Edge). (Top Right) Network Flow of a KA Employee. (Bottom Left) Network Flow of a Facility User. (Bottom Right) Network Flow of a Visitor

Source: SUTD Cities: Urban Science and Design for Density

While all vertical "streets" in KA were well connected, some were part of more travel routes than others due to their topological connectivity within the network. The common spaces with adjacency to commercial and retail areas showed high mobility flows. Strategically locating the key social connectors like hawker centers in the vertical spatial planning to channel the pedestrian flows to elevated locations proved that they served as attractors/destinations for communities and encouraged active space use of facilities along the route.

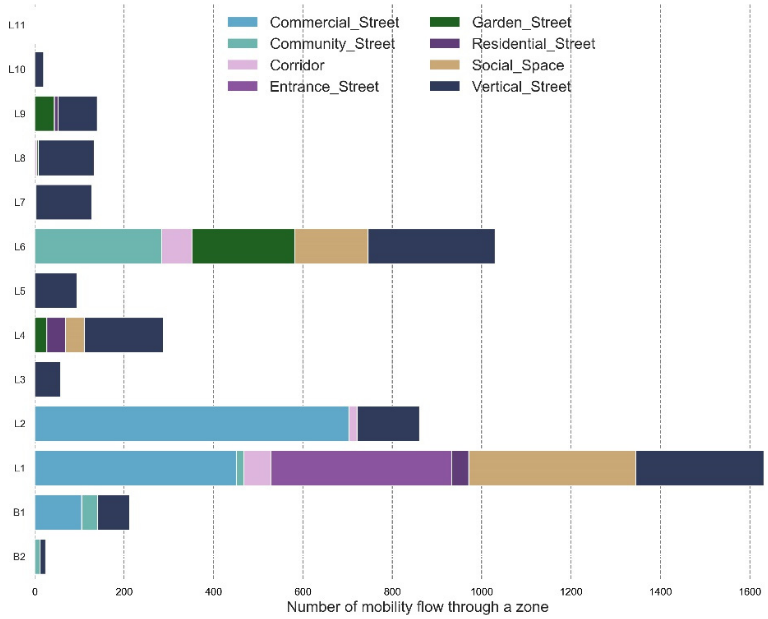

Figure 12. Number of Mobility Inflows through KA Public Spaces per Floor and Location Type
Source: SUTD Cities: Urban Science and Design for Density

The elevated garden connectors in vertical spatial planning effectively distributed the movement flows and channeled the routes to various amenities. Strategically planning the adjacencies to these garden connectors is critical. Access and proximity to KA facilities were crucial for elevated garden streets becoming preferred choices of movement and connectivity. The study validated KA's planning and design for placement of such amenities along the most traversed routes. The real-use data further confirmed the mobility flows at this level and their performance as a critical central connector. In the vertical integration of public spaces, landscape spaces acted as key visual and physical connectivity elements with high recreational and social value.

Another essential characteristic of studying urban human mobility was the occupancy time distribution. Occupancy time is the amount of time an individual spends in the defined space. The occupancy analysis indicated that people spent most occupied time at Level 2 (food court), followed by the community plaza and sky gardens. The garden corridors at community gardens saw more people spending time than the Level-6 or Level-4 corridors. Occupancy time in garden corridors was the longest at Level 9, and users actively spent significant time in the social streets at Levels 1, 4, and 6. While residents' average occupancy time in

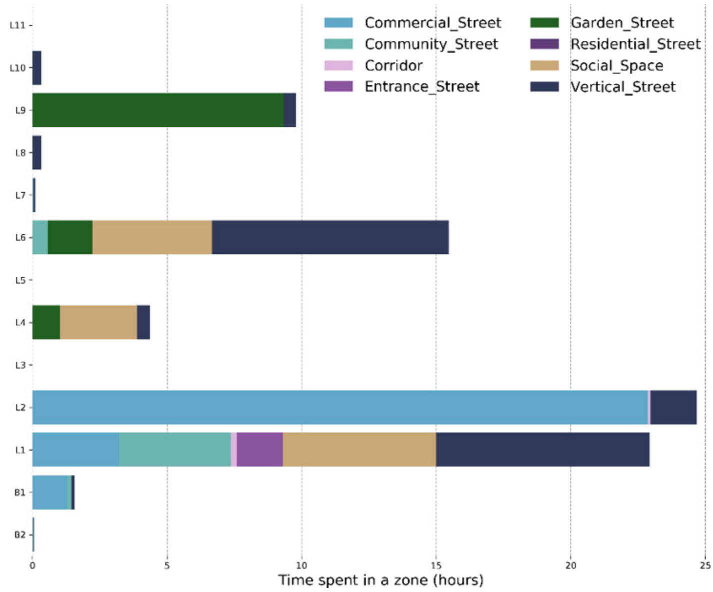

Figure 13. Total Time Spent in KA Public Spaces per Floor and Location Type
Source: SUTD Cities: Urban Science and Design for Density

social spaces was smaller than other groups, some of the residents spent the most extended times of the day in KA's public spaces (Figure 13).

While Level-1 community plaza recorded highest movement flows, the occupancy time was much lower as compared to the hawker center on Level 2 and garden spaces on Level 6. The expected versus actual use analysis shows the opportunity for stronger attraction or anchor points in the community plaza at Level 1 to enhance and strengthen its potential as a vibrant, highly connected, and well-occupied public space.

The correlation analysis between mobility flows and occupancy revealed that many nodes displayed prominence of one function (pathway to move or a place to spend time) more than the other. Figure 14 shows the interplay between mobility flows and occupancy times at nodes grouped by floor level and location type.

Space types and social programs can influence circulation flows significantly. Strategically planning the location of attractive amenities in less well-connected areas within a network can help to better utilize them. The analysis also showed that most social spaces exhibited prominence as either a movement space or an occupied space. Thus, while all social spaces were expected to be well occupied, nodes set away from prime connecting routes performed better as social

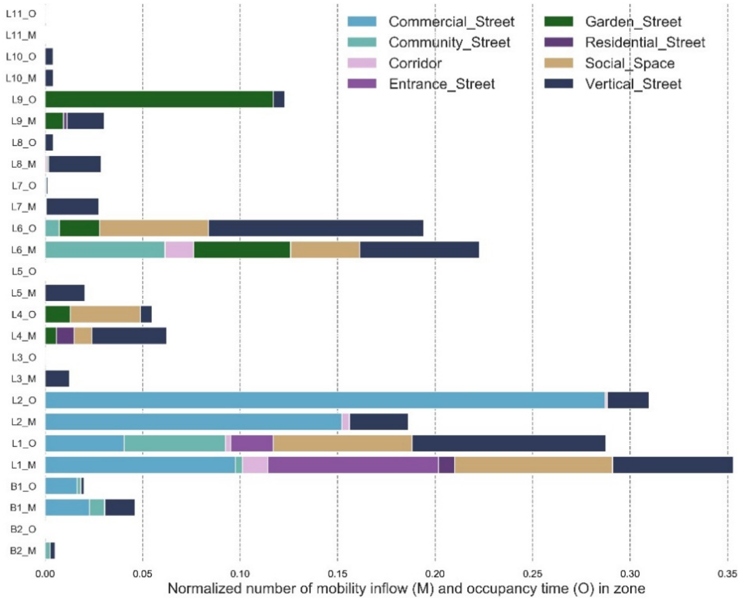

Figure 14. Interplay Between Mobility and Occupancy in KA's Public Spaces per Floor and Location Type

Source: SUTD Cities: Urban Science and Design for Density

destinations. Dotting "social attractors" strategically within the network topology would allow for well-distributed and effective landscape destinations.

6.3. *Visual comparison of sDNA measure with beacon data points distribution*

The beacon points were plotted onto the physical spatial model to visualize the intensity of detected beacon points within the actual embedded space. The graphical representation allowed visual comparisons across different nodes within the architectural space and the timing of activities. A visual comparison between the sDNA measures and the actual beacon count heatmap (Figure 15) compared the network measure of betweenness centrality correlated with the flow of people.

Generally, KA's social spaces, including the community plaza, the food court, the garden, and the playground areas along the L1 thoroughfare, were more used on weekdays and less on weekends, comparable to the high flow measures indicated in the sDNA analysis model. For L6, the sDNA analysis scored lower at the playground and higher at the fitness corner. This corresponds to the beacon activity heatmap. While the links to the fitness corner and playground were symmetrical and connected key community spaces with the residential blocks, the accessibility/

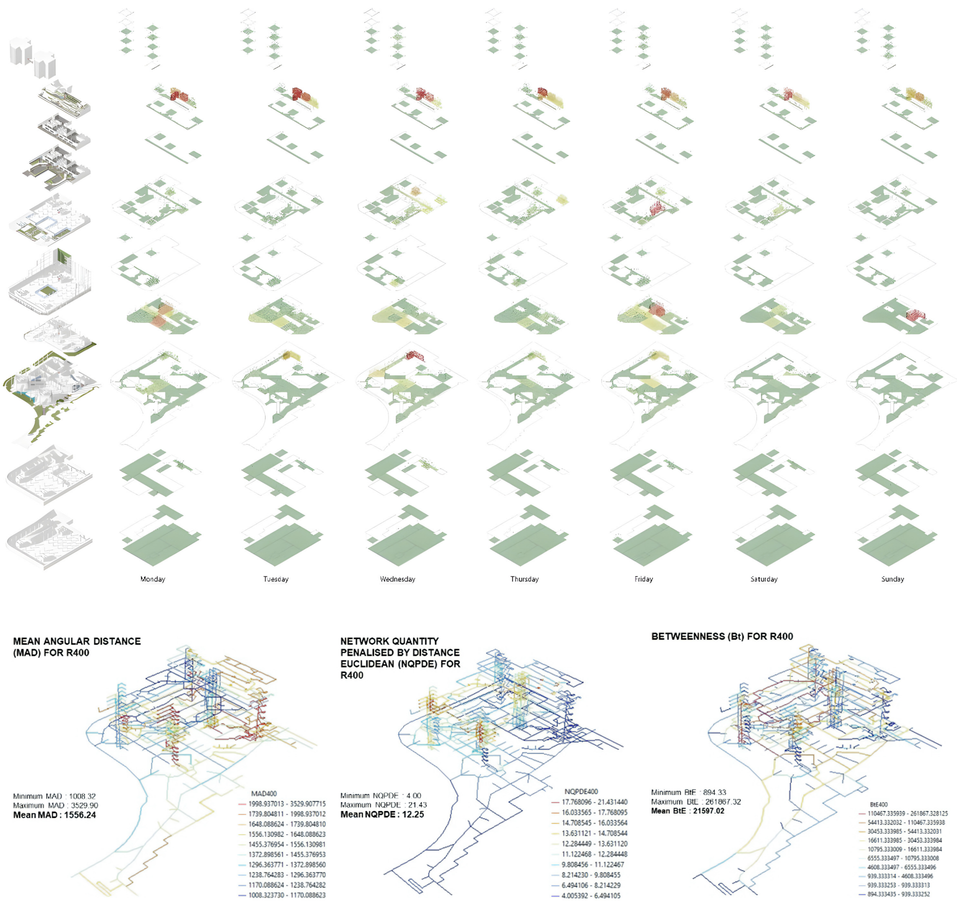

Figure 15. Comparisons Between Visualization of Network Measures on Architectural 3D with the sDNA Pedestrian Flow Measures Visualization; Daily Beacon Activity Heatmap, Aggregated by the Day of the Week: (from Left to Right) from Monday to Sunday

Source: SUTD Cities: Urban Science and Design for Density

boundary definition dictated the difference in sDNA connectivity scores. The playground was enclosed with three-gated access for the safety of the kids. The fitness corner had open access with no gates, thus creating an easy thoroughfare for movements. For L8 and L9, the sDNA diagram showed low betweenness, as the spaces were physically far from the barycenter (community plaza) and the ground plane. However, the actual beacon activity at these locations was significantly high. The beacon and people counter recordings of the community gardens at L8 and L9 and the food court at L2 showed the social nodes were well used despite their low counts of betweenness centrality. It showed that the node typology and the spatial program altered the network's flow.

The KA study was conducted during the COVID-19 pandemic, where social interactions, space use, pedestrian movements, etc. were affected by safe-distancing regulations and requirements. The data would not fully represent how spaces were used before the pandemic when such restrictions on gathering and social interactions were not in place. On the other hand, the study was suitably placed with the status quo being an indicator of the changed urban life as "new normal".

7. Summary and Conclusions

The study conducted on KA employed a Network science-based spatial analysis framework to evaluate the network connectivity and relationships of vertically integrated open spaces. By examining KA's spatial network structure and its relation to mobility and occupancy, the research validated the methodology's potential for predictive planning and design of future vertical cities. This contributes to the development of a systematic approach to assess the performance of public and common green open spaces in vertically integrated urban developments. The study emphasizes the complexity of vertically integrated urban green open space networks, characterized by their nonplanar structure, as evidenced by network structure measures at KA. While the methodology shows promise in validating the actual use of vertically integrated urban spaces, further testing across different integrated building typologies and scales is necessary to establish quantitative and qualitative parameters for broader application. By applying the methodology to multiple case study sites at various scales, a predictive planning and design tool can be developed for vertically integrated urban developments, enhancing our understanding of the intricate correlations between humans and the built environment.

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References

Alessandretti, L, Lehmann S and Baronchelli A (2018). Understanding the interplay between social and spatial behaviour. *EPJ Data Science*, 7: 36, doi: 10.1140/epjds/s13688-018-0164-6.

Barabási, AL (2009). Scale-free networks: A decade and beyond. *Science*, 325(5939): 412–413, doi: 10.1126/science.1173299.

Barrat, A, Barthélemy M, Pastor-Satorras R and Vespignani A (2004). The architecture of complex weighted networks. *Proceedings of the National Academy of Sciences of the United States of America*, 101(11): 3742–3752, doi: 10.1073/pnas.0400087101.

Barthélemy, M (2003). Crossover from scale-free to spatial networks. *Europhysics Letters*, 63(6): 915, doi: 10.1209/epl/i2003-00600-6.

Batty, M (2003). The emergence of cities: Complexity and urban dynamics. *Evolution*, 44: 0–16.

Batty, M (2012). Building a science of cities. *Cities*, 29: S9–S16, doi: 10.1016/j.cities.2011.11.008.

Bettencourt, LMA (2013). The origins of scaling in cities. *Science*, 340(6139): 1438–1441, doi: 10.1126/science.1235823.

Bouffanais, R and Lim SS (2019). The rise of homo verticalis. *Scientific American*, January 16, 2019. https://blogs.scientificamerican.com/observations/the-rise-of-homo-verticalis/ [].

Cairns, S (2016). 3D city, 2D urbanity?*The Singapore Architect*, 04: 91–94.

Cooper, CHV and Chiaradia AJF (2020). sDNA: 3-d spatial network analysis for GIS, CAD, Command Line & Python. *SoftwareX*, 12: 100525, doi: 10.1016/j.softx.2020.100525.

Cooper, CHV (2015). Spatial localization of closeness and betweenness measures: A self-contradictory but useful form of network analysis. *International Journal of Geographical Information Science*, 29(8): 1293–1309, doi: 10.1080/13658816.2015.1018834.

Crucitti, P, Latora V and Porta S (2006). Centrality measures in spatial networks of urban streets. *Physical Review E: Statistical, Nonlinear, and Soft Matter Physics*, 73(3): 036125, doi: 10.1103/PhysRevE.73.036125.

Hillier, B, Leaman A, Stansall P and Bedford M (1976). Space Syntax. *Environment and Planning B: Planning and Design*, 3(2): 147–185, doi: 10.1068/b030147.

Manivannan, A, Yow WQ, Bouffanais R and Barrat A (2018). Are the different layers of a social network conveying the same information?*EPJ Data Science*, 7: 34, doi: 10.1140/epjds/s13688-018-0161-9.

Newman, P (2014). Biophilic urbanism: A case study on Singapore. *Australian Planner*, 51(1): 47–65, doi: 10.1080/07293682.2013.790832.

Schröpfer, T and Menz S (2019). Dense and Green Building Typologies: Design Perspectives. Singapore: Springer, doi: 10.1007/978-981-13-3035-3.

Schröpfer, T (2016). Dense +Green: Innovative Building Types for Sustainable Urban Architecture. Basel: Birkhäuser.

Schröpfer, T (2020). Dense +Green Cities: Architecture as Urban Ecosystem. Basel: Birkhäuser.

Seet, L and Ee D (2020). Co-located Community Hubs. Singapore: Centre for Liveable Cities. https://www.clc.gov.sg/docs/default-source/commentaries/bc-2020-02-community-hubs.pdf.

Sevtsuk, A and Mekonnen M (2012). Urban network analysis: A new toolbox for ArcGIS. *Revue Internationale de Géomatique*, 22(2): 287–305, doi: 10.3166/rig.22.287-305.

Sun, G, Webster C and Zhang X (2021). Connecting the city: A three-dimensional pedestrian network of Hong Kong. *Environment and Planning B: Urban Analytics and City Science*, 48(1): 60–75, doi: 10.1177/2399808319847204.

Tekler, ZD, Low R, Gunay B, Andersen RK and Blessing L (2020). A scalable Bluetooth low energy approach to identify occupancy patterns and profiles in office spaces. *Building and Environment*, 171: 106681, doi: 10.1016/j.buildenv.2020.106681.

Torstensson, D (2010). Indoor positioning system using Bluetooth beacon technology. *MIS Quarterly*, 34(2): 261–279.

Totaforti, S (2020). Emerging biophilic urbanism: The value of the human–nature relationship in the urban space. *Sustainability*, 12(13): 5487, doi: 10.3390/su12135487.

WOHA (2018). Kampung Admiralty/WOHA. *ArchDaily*, October 26, 2018. https://www.archdaily.com/904646/kampung-admiralty-woha [].

Yap, CB (2019). Kampung Admiralty: Building for all ages. *Ethos*, Digital Issue 4, April 29, 2019. https://www.csc.gov.sg/articles/kampung-admiralty-building-for-all-ages [].