Evaluation of Spatial Performance in Vertically Integrated Developments Using a Network Science-Based Approach

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ABSTRACT: This paper proposes a Network Science-based approach to map the spatial use of public and social spaces on the ground and elevated levels and analyse these spaces as networks of socio-spatial nodes in high-density vertical urban environments to provide insights into actual space use. The presented study integrated micro-mobility sensors data with visual observation surveys and spatial maps to (1) identify mobility patterns of users, (2) establish correlations between mobility patterns, spatial networks, and space-use, and (3) analyse the efficacy of spatial arrangements and their use to allow for better-informed future planning and design decisions. The study used Kampung Admiralty (KA), an award-winning integrated mixed-use building designed by WOHA Architects, as a case study. KA is Singapore's first integrated public development that integrates and co-locates a mix of residential, commercial, retail, community facilities, and social amenities, including green open spaces in a vertically distributed spatial arrangement. The study provides important insights into the relationship between the socio-spatial networks at the ground and elevated levels and identifies key connectors that encourage, influence, and enable socially and spatially effective vertical public space networks. It further presents a framework for quantitative analysis that can inform the efficient and effective planning and design of vertically distributed spaces that can support higher population densities, higher environmental sustainability standards, and enhanced liveability.

KEYWORDS: Spatial performance, Spatial Network Analysis, Network Science, Mobility Patterns
PAPER SESSION TRACK: Digital Design and Practices

INTRODUCTION

With cities in many locations becoming denser and built environments scaling new heights, the effective and efficient planning and design of sustainable high-density urban environments are critical to their successful integration into larger urban and natural contexts. In such environments, integrated mixed-use buildings are increasingly becoming vertical extensions of urban spaces on the ground level, where circulation, open spaces, ecological networks, and human activities are stacked vertically in an evolving relationship(Schröpfer 2020). As a result, socio-spatial networks extend and stretch vertically, and their planning and design need to reflect the complex interactions within themselves and with the larger urban network.

In recent times, researchers from many fields, including natural and social sciences, are collectively studying cities as 'Urban Complexity' (Batty 2012; Barthélemy 2003; Bettencourt 2013). The studies provide important insights on an informed approach to planning, designing, and managing urban built environments. Urban complexity focuses on the interactivity between the space users and their built environments (Alessandretti, Lehmann, and Baronchelli 2018; Manivannan et al. 2018). It leverages digital tools and techniques to develop new knowledge that can inform urban development processes. Increasingly, cities are embracing the predictive potential of a science-based approach to address the complex urban challenges of unpredictability and disruptions and plan future urban spaces that can dynamically respond to the evolving social, spatial and environmental needs of its people. However, while extensive research studies focus on horizontal mobility patterns, little is known about human vertical mobility (Bouffanais and Lim 2019). Complex System Studies thus need to be extended to the vertical dimension to systematically analyse and evaluate the character of spatial and social networks formed as users interact with such vertically integrated built environments.

1.0 RESEARCH CONTEXT AND SIGNIFICANCE

1.1 Network Science and the Built Environment

While the definition of the term 'complex system' is still evolving, definite characteristics of Complexity Theory are exhibited by the interactions within the urban systems of cities that help us understand their dynamic activity, growth and evolution (Batty 2012). A city manifests itself as a space that enables flows (energy, resources, people, etc.)

(Kennedy, Pincetl, and Bunje 2011). Similarly, a vertically integrated building also translates as a network of interconnected programmatic spaces and circulatory paths, with nodes and links (also called edges), within the superstructure of the urban spatial network (Barthélemy 2003). Each node has defined spatial attributes like the respective typology of space, location, size, etc. These spatial configurations influence human movements, initiate interactions, and generate socio-spatial networks. Studying these socio-spatial networks can provide important insights into the emergent patterns of pedestrian movement within the built environment and its influence on the effective use of social space. This paper presents a new Network Science-based research approach to a systematic analysis of the effects of vertically integrated built environments on human movement using KA as a case study. KA is a first-of-its-kind public development in Singapore, which integrates housing for the elderly with a wide range of social, healthcare, communal, commercial, and retail facility (Yap 2019). Our study focused on the inter-and intra-building networks at the building scale, defining spaces such as hawker centres, sky gardens, plazas, sky bridges, and lift lobbies as nodes.

1.2 Key Network Measures

Measuring network centrality is a mathematical method of quantifying the importance of nodes in a graph. As the name implies, centrality metrics focus primarily on how central each graph element is in relationship to the surrounding elements (Barthélemy 2003; Barrat et al. 2004). In a spatial network, spaces are assessed through network centrality measure algorithms to identify the most significant connectors based on their location and accessibility within the spatial network. In our study of KA, a node is a programmed space with defined boundaries. The edge of the network is an undirected link formed between directly adjacent spaces. Significant 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 its links. The higher the degree number, the more connected the node is within a network. This measure helps find the spaces with the most connections within a spatial or social network. Determining the degree centrality score allows for the effective planning of active social spaces that act as critical connectors. **Closeness centrality** scores each node based on its closeness to other nodes in a network. The closeness measure uses the shortest paths between each node. Closeness measures help in identifying spatial clusters within building development by highlighting the spatial distribution of high-degree nodes. **Betweenness centrality** characterises a node's global importance by measuring its ability to be part of the shortest paths taken between all nodes in a network. This measure allows for the identification of critical pathways between nodes. A high centrality measure indicates that a node is part of many shortest paths that typically translates into increased human movement and interactions in the built environment—comparing and correlating these various measures allows identifying the significance of spaces in terms of their 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.

2.0 METHODOLOGY

The KA study consisted of three key phases to establish the spatial network for analysis, collect real-world data for mapping user-space interactions and overlay real-world data to analyse the dynamic network processes occurring within the static spatial network.

Phase 1: *Design Intent and Spatial Network Analysis*- KA's architectural design intent and spatial arrangements were studied using the floor plans and architectural drawings. A network structure of nodes and edges was generated based on the built spatial layout and key network measures analysed to understand the designed space's network topology and strengths based on their spatial configurations.

Phase 2: *Human Mobility Mapping -* Human mobility is the dynamic process on the static spatial network. The study used infrared people counters along with low-energy Bluetooth (BLE) beacons combined with a mobile app for tracking and localisation to record user movements, activities, and space use.

Phase 3: *Socio-spatial Network Analysis -* Socio-spatial networks are temporal networks where edges form and disappear over time with actual human movements. The socio-spatial network was generated by overlaying the real-world data collected from BLE beacons and people counters on the static spatial network. It mapped user-space relationships, occupancy, and mobility flows as a dynamic process occurring within the embedded spatial structure.

The collected real-world data, analysed and compared with the spatial network measures, provided insight on user-space relationship and information on (1) the use of public and common spaces in the vertically integrated development, (2) user behaviour and movement in space, and (3) social interactions and activities over time.

2.1 Design intent and Spatial Network Analysis

Awarded 'World Building of the Year' in 2018, KA is Singapore's first integrated public development that brings together a mix of public facilities and services under one roof (Block 2018). As the increasing urban density in Singapore demands creative ways of intensifying land use effectively in the vertical dimension, the elevated and layered urban design and architecture approach to the project transformed the 0.9-ha site into a vertically integrated dynamic mini-neighbourhood for the community. 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 centre 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 pedestrianised 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 programmes such as childcare and an active ageing hub (including senior care) brings together all generations—two 11-storey residential towers consisting of 104 apartments house elderly singles and couples (Block 2018; Yap 2019).

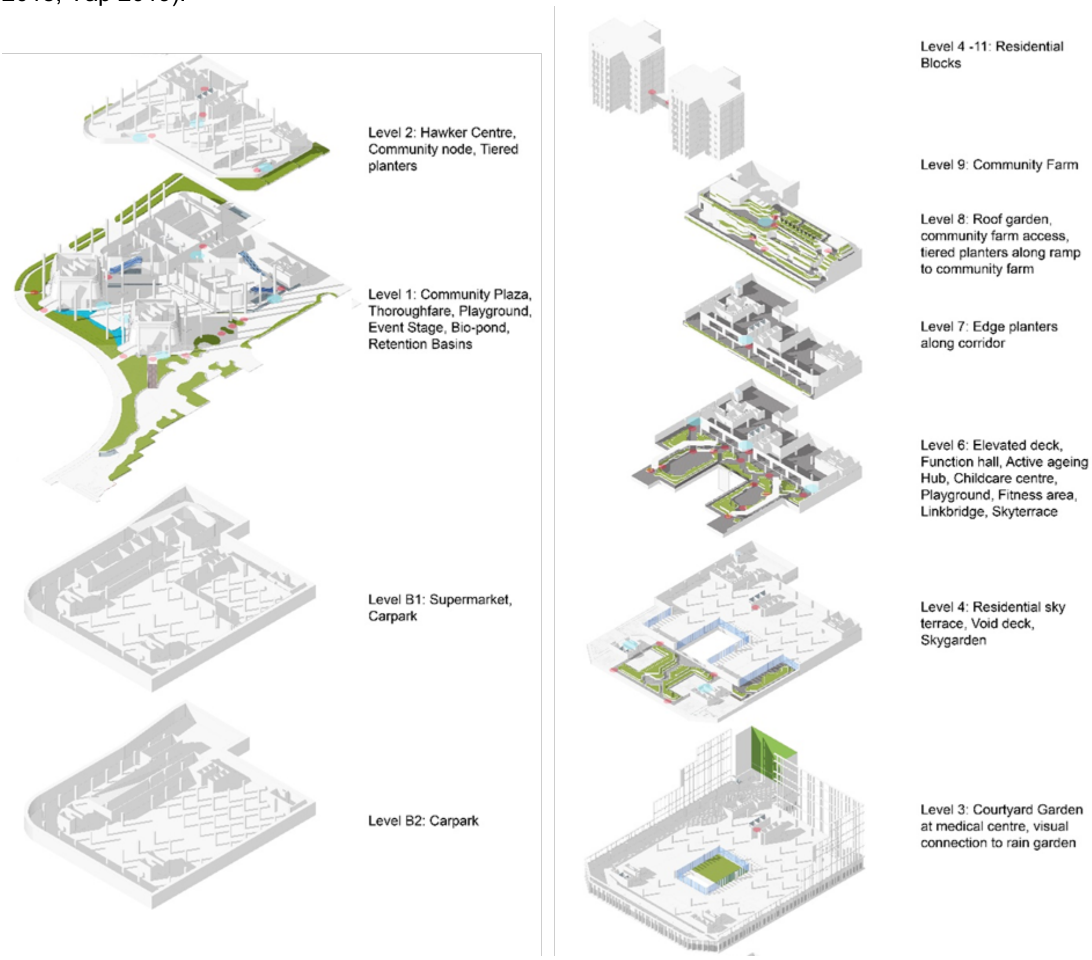
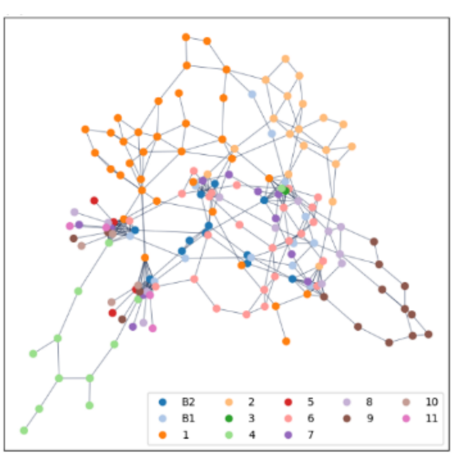


Figure 1: Exploded axonometric of KA showing the vertical distribution of public spaces. (Source: SUTD)

KA's spatial network considered two-node attributes, (1) space type and (2) floor level. Space types included residential, commercial, social, F&B programs, health facilities, and vertical streets (lifts and stairs 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 edges were the shortest routing distances connecting immediately adjacent nodes. In the vertical dimension, the lift and staircase lobbies were considered to have all-to-all connectivity, i.e., each lift lobby was connected to all other lift lobbies if they shared the same lift core. Based on the above classifications, the spatial layout of KA translated into a spatial network with 165 nodes and 392 edges (Figure 2).



Metrics	**Network**
Vertical street connection method	all-to-all connectivity
Number of nodes	165
Number of edges	392
Average degree	4.75
Average shortest path (Unweighted)	5.3 (hops)
Average shortest path (Weighted)	104.4 (metres)
Average clustering co-efficient *C* (Topological)	0.31
Average clustering co-efficient *Cw* (Weighted)	0.086
Cw/C	0.27
Graph density	0.028
Planarity test (Kuratowski theorem)	Non-planar
Barycenter (Weighted)	Community lift lobby at Level 1

Figure 2: KA spatial network visualised by floor level and tabulation of global properties of the spatial network analysis (Source: SUTD)

The analysis of the spatial network structure of KA based on the spatial arrangements revealed some preliminary insights into the development's connectivity network. For a relatively small network with 165 nodes, the unweighted average shortest path was ~5 for the network, exhibiting the characteristics of a small-world network (Barthélemy 2003). The KA network structure resembled a classical air transportation network due to the presence of vertical streets that give the network a prominent non-planarity. With a compact and integrated spatial arrangement, most of the spaces were easily accessible with an average of 104.4 m travel distance. 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 the barycentre of the network, the most convenient point to reach all other spaces within a 50 m travel distance.

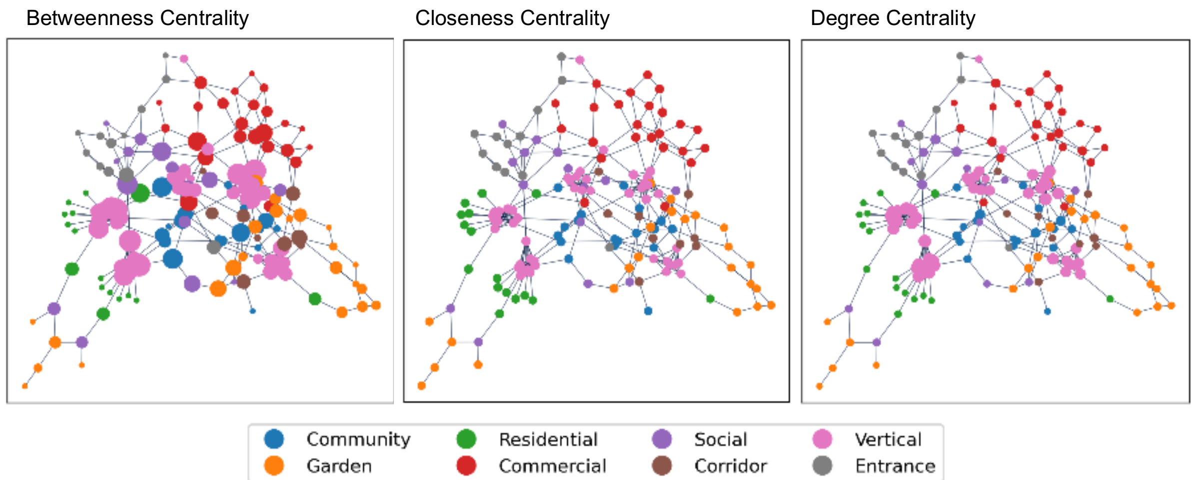


Figure 3: Weighted Centrality Measures of KA Spatial network visualised using Gephi (Source; SUTD)

The community facilities were distributed at multiple levels for heterogenous pedestrian flows within the development. The more public and highly frequented facilities like supermarkets and retail shops were located at the lower levels. At the same time, the hawker centre at Level 2 provided a key connecting node for all users at KA. Social facilities like childcare, Active Ageing Hub, function rooms, pre-school were located at Level 6, adjacent to the sky garden, creating a more exclusive, intimate public space for the users and residents. The network structure outcomes in Figure 3 were as expected, with the Level 1 commercial spaces emerging as key connectivity nodes, followed by Level 2 and Level 6 spaces forming the second layer of connectivity within the development. The green spaces at Level 1 surrounded the development along the edges, creating a garden-like transition to the community plaza. Social activators at Level 1 like the public performance stage, playground, and water features were subtly placed along the edges to engage the users along their movement routes. In contrast, the sky gardens at the elevated levels were designed as lush green spaces featuring amenities like a playground, fitness corner, seating areas, and social corners to encourage users to spend time. The network structure revealed a hierarchy within the elevated garden spaces. The Level 6 sky gardens formed the most significant green node, followed by the roof garden spaces at Level 8, Level 9 and the Level 4 garden space at the residential blocks.

An unexpected result of the network analysis was the significance of the vertical connections in the overall connectivity of KA, as seen in Figure 3. 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.

2.2 Human Mobility Mapping

The on-site study recruited a sample group of 73 KA users to participate in mapping movement tracking. The participants consisted of residents and non-resident users. Actual use data was collected using a combination of qualitative and quantitative methods. Movement tracking with Bluetooth localisation consisted of three components: (1) stationary low-energy Bluetooth beacons, (2) a mobile app, and (3) a cloud server. The tracking method used a 'peer-to-environment' sensing system that involved placing stationary Bluetooth beacons in locations of interest. 124 beacons were installed 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 a continuous period of two to three weeks. In addition, bi-directional people counters using infrared sensors were installed at key nodes identified through spatial network analysis to gather data on the volume of inflow and outflow at the identified spaces 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.

2.3 Socio-spatial Network Analysis

The various sensor data collected on-site provided a rich source of over 42.6 million data points for analysis. The collected data from the people counters, Bluetooth beacons and participant surveys were overlaid on the static spatial network to analyse the temporal user-space interactions at KA. The results were then compared to the measures deduced from the initial spatial network analysis. Finally, the comparisons between the designed and actual use of the spaces provided design insights towards developing strategies for planning more effective vertically distributed social spaces. The following section describes the results of the Socio-spatial Network Analysis.

3.0 RESULTS AND ANALYSIS

3.1 Data from People Counters

The data collected from people counters analysed the use of garden spaces and community facilities at KA.

The hourly aggregated number of people at Level 4, Level 8, and the Level 9 garden areas is shown in Figure 4(L). Users predominantly used the Level 4 gardens during the daytime, and the number of visitors was lower than other levels. This correlated with the design intent as these garden spaces were designed primarily for the residential blocks as green niches within the larger development. Distinctly different use patterns at Level 8 and Level 9 gardens indicated the diverse profile of users. In addition to the residents, frequent visitors and volunteers at the rooftop community farm added to the number of users recorded. Interestingly, while the community gardens were frequented during early mornings and late evenings, Level 8 gardens were visited by users even during the afternoon time. 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 hourly aggregated number of people visiting communal facilities is shown in Figure 4 (R). The most traffic was recorded at vertical connections coming to or leaving from Level 2 (hawker centre). The recorded user flows were more significant after 7 am and 5 pm, with a distinct drop in user volumes between 3 pm and 5 pm. It is because the escalators at Level 2 served additionally as connectors to the centre of KA (Level 1 community plaza) and the main transport gateway (the MRT station adjacent to KA), and the peaks reflected the movement patterns of commuters or people who were “moving through”. On the other hand, the gardens on Level 6 and Level 9 served as attractors, and the patterns indicated the movement patterns of leisure users.

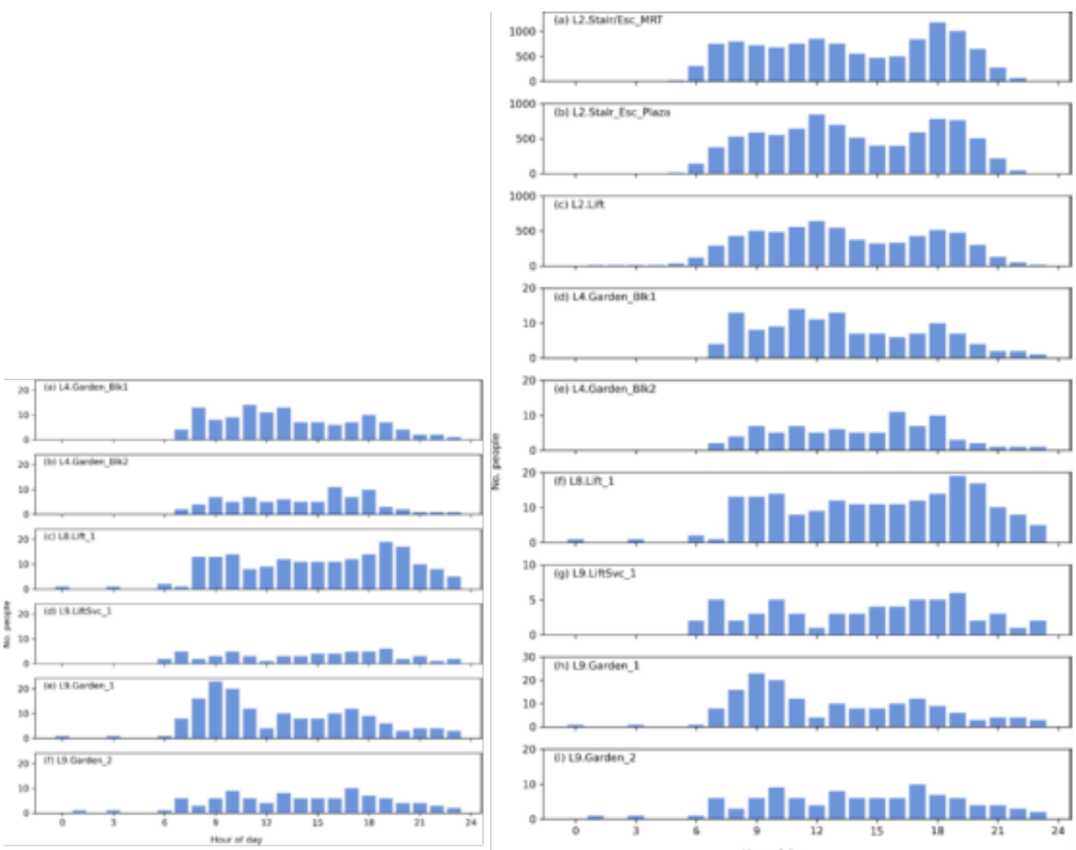


Figure 4: (L) Hourly aggregated use of gardens at different levels (Level 4, Level 8 and Level 9); (R) Hourly aggregated use of community facilities (Source: SUTD)

3.2 Data from Bluetooth Beacons

Bluetooth beacon data was analysed for the network process of mobility and occupancy time of the participant users. The figure below (Figure 5) shows the mobility flows and occupancy times at nodes grouped by floor level and location type. Level 1 registered the highest number of pedestrian flow, followed by Level 6 and Level 2. Among the vertical streets, beacons in Level 1 and Level 6 lobbies recorded the highest numbers in terms of pedestrian flow. At Level 1, mobility was recorded to be similar in magnitude across all the lateral and vertical streets, exhibiting equal flow distribution through different programmes. Another essential characteristic to study urban human mobility was the occupancy time distribution. Occupancy time is defined as the amount of time an individual spends in the defined space. Level 2 saw the highest occupancy time, closely followed by Level 1, Level 4, Level 6 and Level 9. Users in KA spent most time in the commercial streets followed by social spaces and garden corridors. Interestingly, all vertical streets in KA recorded high occupancy time, indicating that vertical mobility was significant and programs were well distributed across all levels within the development. Occupancy time in garden corridors was the longest at Level 9 and users actively spent significant time in the social streets at Level 1, Level 4 and Level 6.

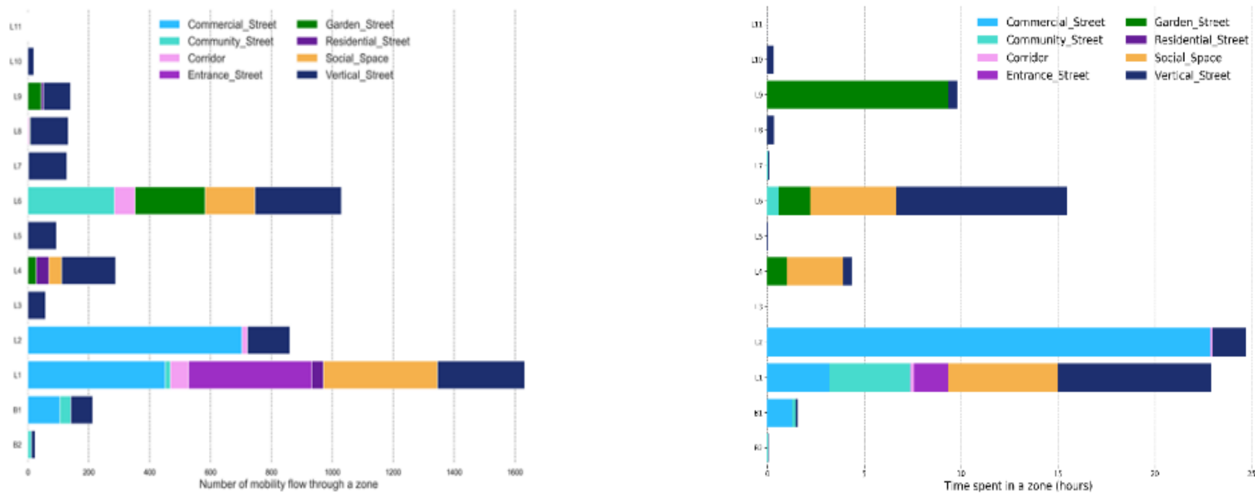


Figure 5: (L) Number of mobility inflow through KA public spaces per floor and location type (R) Time spent at KA public spaces per floor and location type (Source: SUTD)

The correlation 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 6 shows this interplay by floor level and location type. Both Level 1 and Level 2 showed significant mobility traffic and occupancy, with participants being more mobile at Level 1 and spending more time at Level 2. This can be attributed to the food court at Level 2, with ample seating, allowing for higher occupancy. The garden corridors at Level 6 were used primarily as mobility paths, while the Level 9 garden corridors leading to the community gardens saw more prolonged occupation.

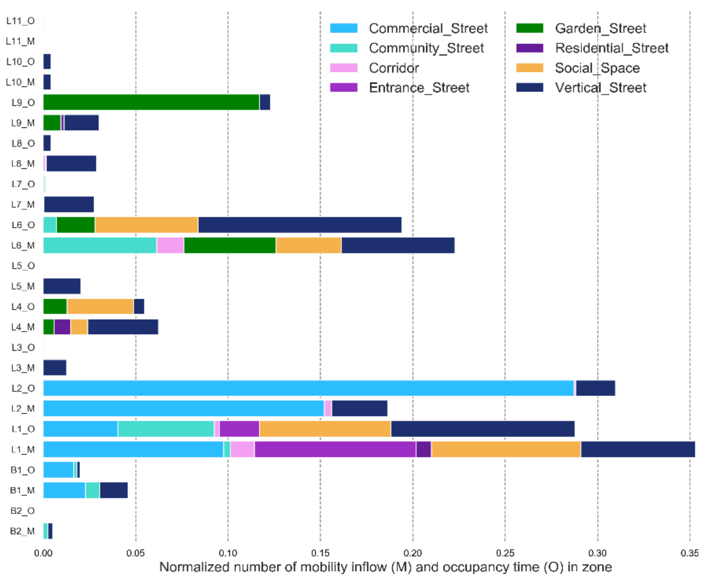


Figure 6: Interplay between mobility and occupancy in KA's public spaces per floor and location type.

3.3 Visualisation of Participant Flows

The BLE sensor data collected was graphically visualised (Figure 7), allowing for comparisons across nodes. In addition, the activities were visualised as daily aggregates to show socio-temporal networks and how they evolve.

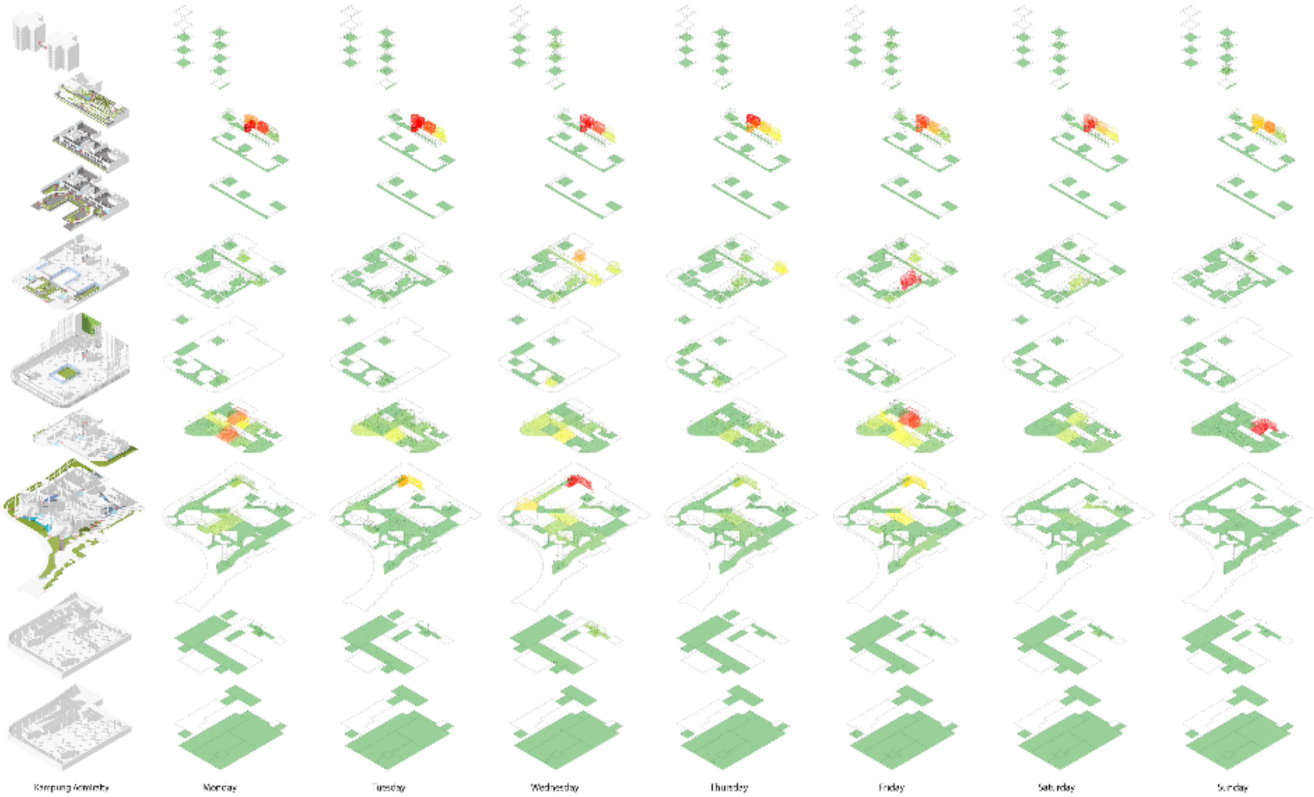


Figure 7: Beacon count at KA mapped on exploded axonometric (Source: SUTD)

4.0 DISCUSSION

The comparison between the actual space use with the centrality measures provides important insight into how socio-spatial temporal networks in KA differed and evolved compared to the theoretical model.

Vertical circulation spaces such as the residential and community lift lobbies served as the most critical paths in KA that connect amenities across levels. 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 in KA showed high mobility flows. Some commercial streets on L1 and L2 had higher betweenness values, indicating that they act as key connectors within the overall spatial network. KA's L1 community plaza, planned and designed as a central community node, served as a key social space with a high pedestrian flow and activity volume. It showed a high level of connectivity to lift lobbies, amenities within KA and the surrounding neighbourhood. The real-use sensor data collected on-site showed high visitor counts for all the nodes at this location, thus indicating high values of mobility flow. Interestingly, the analysis on the occupancy time in the community plaza showed that people tended to move through it rather than occupy it. The study demonstrated the opportunity for stronger attraction or anchor points in the Community plaza to enhance its potential as a vibrant, well-connected and well-occupied public space. Elevated garden connectors in such vertically integrated developments are effective in distributing and channelling the pedestrian flows. Strategically planning the adjacencies to these garden connectors is critical as access and proximity to KA facilities were key to encouraging elevated garden streets to become a preferred choice 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 its performance as a key central connector. In the vertical integration of public spaces, landscape spaces form key visual and physical connectivity elements with high recreational and social value in KA. These garden amenities form defined destinations with a strong identity or green pathways with activity niches along key connecting routes.

Space types and social programmes can influence circulation flows significantly. Strategically planning the location of attractive amenities in less well-connected areas within a network would help better utilise those parts of development. Dotting these 'social attractors' strategically within the network topology would allow for well-distributed effective landscape destinations. The analysis also revealed 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 destinations. The mobility flows in KA were influenced by how the different spatial nodes were arranged within the development, their immediate adjacencies, and the travel distance between the different facilities. At the same time, the same network parameters may not drive the time spent by the users at the various spatial nodes. The analytical process showed a valid methodology to derive correlations between the topology, space, and network properties using the collected participant data. It also helped validate the expected versus actual space use of the vertically integrated public and common open spaces.

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'.

CONCLUSION

The presented study explored a Network Science-based approach to the spatial performance analysis of KA and examined its spatial network structure and relationship with network processes such as mobility and occupancy based on real-world data. The results of the study validated our approach to developing (a) a reliable method to convert floor structure and programme to a weighted spatial network, (b) testing hardware and software required to collect user data, (c) developing models to convert sensor data to user-activity info, (d) providing fundamental analyses of the spatial network with tools available in Urban and Network Science, (e) providing a method to visualise network metrics for urban planners and designers, (f) analysing human-tracking data based on user- demographics, and finally (g) designing a method to analyse the relationship between topology, geography, and real-world pedestrian flows in urban built environments. The real-world data collection methods to track users in our study included (a) people counters to understand mobility flows, (b) beacon, mobile app, and cloud infrastructure to track occupancy time and mobility flows, (c) site observation and (d) user surveys. The study demonstrated how these collected data sets could help successfully understand user mobility and occupancy patterns over time. Classifying built spaces as relationships with attributes and applying various network measures to quantitative analytical models can complement current spatial planning and design practices and result in more informed decisions. The methodology explored in our study holds great promise in the validation of actual use of the vertically integrated urban landscape spaces with its predicted and intended use. However, to explore its full potential as a predictive design tool, the methodology needs to be tested more aggressively on different integrated building typologies at multiple scales to establish quantitative and qualitative planning and design parameters for wider application. Applying these research methods and tools to multiple case study sites at a building and urban district scale will potentially provide the necessary data to develop a predictive planning and design tool for vertically integrated urban developments and provide us with a better understanding of the complex correlations between humans and the built environment across multiple city scales.

ACKNOWLEDGMENTS

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