EXPLORING SPATIAL PATTERNS IN SUSTAINABLE INTEGRATED DISTRICTS: A METHODOLOGY FOR EARLY-PHASE URBAN NETWORK ANALYSIS

Anjanaa Devi Srikanth
Srilalitha Gopalakrishnan

Future Cities Laboratory Global
Singapore-ETH Centre, CREATE Tower,
Singapore 049374, SINGAPORE
anjanaa_devi@mymail.sutd.edu.sg
srilalitha.gopalakrishnan@sec.ethz.ch

Chirag Hablani
Thomas Schroepfer

Singapore University of Technology and Design
8 Somapah Road, Singapore 487372, SINGAPORE

{chirag_hablani,thomas.schroepfer}@sutd.edu.sg

ABSTRACT

This paper presents a new methodology for early-phase analysis of large urban spatial networks. The study uses Social Network Analysis (SNA) based on Graph Theory to understand pedestrian connectivity in urban districts. It compares two SNA methods that capture pedestrian movement patterns differently. The presented study illustrates the comparative analysis of the methods using the case of one-north, a planning subzone in Singapore. The results provide important insights on the connectivity of one-north and enable the selection of smaller sub-sites for the next stage of the analysis. Furthermore, the research summarizes that both methods can be applied independently or combined in different scenarios based on the specific urban context. The combination of methods forms a novel hybrid approach to analyze pedestrian movement in integrated urban environments.

Keywords: sustainable integrated districts, spatial network analysis, network science, urban design.

1 INTRODUCTION

High-density cities such as Singapore are increasingly turning towards an integrated approach to study and advance their urban built environment and to improve livability. A city can be understood as a complex system (Balmaceda and Fuentes 2016; Batty 2013; Bettencourt 2021), which "consists of a large number of connected agents that, as a whole, exhibits a coordinated behavior without any centralized control" (Boccara 2010). The concept of networks, which can visualize the organization of many entities and usually display hierarchy and cluster aggregations, fits the characterization of cities as systems (Batty 2013) and therefore allows us to study them.

SNA is a widely used method to study networks based on Graph Theory (Harary 1967). SNA is also used to study spatially embedded networks such as transportation networks, due to similar properties found across the networks (Cheng et al. 2015; Wasserman and Faust 1994). From the perspective of urban planning and design, urban form has been associated and rigorously studied with way-finding after the development of Space Syntax Theory, which indicates that the configuration of spaces is the dominant influence on movement (Hillier and Hanson 1984; Hillier et al. 1993). Advancement in the field of Spatial Network Analysis has led to the development of tools which are used in research and practice worldwide (Cooper and Chiaradia 2020; Feng and Zhang 2017; Sevtsuk and Mekonnen 2012). However, they are not a part of everyday urban planning and design research due to a lack of domain expertise and their often time-consuming processes. Furthermore, it is a rigorous undertaking to analyze the whole city or significant parts of it in order to observe spatial patterns and connectivity. This paper seeks to explore spatial patterns and develop insights that direct further detailed Spatial Network Analysis methods.

The design of Sustainable Integrated Districts (SIDs) drives the environmental and social benefits of sustainability in cities in response to trends of development and livability. SIDs aim to realize the potential of urban innovations and systems solutions, such as the integration of district cooling and the adoption of electric vehicle charging stations, at the district scale to test their performance before scaling up to the larger scale of the city. Existing literature on SIDs focuses on sustainability (Bibri 2021; CLC 2014) but it can be argued that the development of SIDs incorporates socio-economic aspects like diversity, vibrancy, and vitality as well. The planning approach to inculcating these aspects often integrates multi-level mixed-use programs. The integrated three-dimensional public realm in SIDs redefines the analysis of walkability. The vertical dimension of the urban network adds more publicly accessible connections that require a novel way to understand interactions and flows. Since these flows and interactions are inherently dynamic and evolving, SIDs can be understood as complex systems. Due to the fractal-like nature of cities (Batty and Longley 1994), SIDs can be studied as indicative cases within larger experimental studies of cities. In our study, we use one example of an SID, the case of one-north, a planning subzone in Singapore. one-north serves as a testbed for integrated urban planning and systems solutions in Singapore.

This paper discusses a new methodology for deriving quick and reliable insights into large urban spatial networks, and understanding movement in the vertical dimension of spatial networks. The methodology involves a Network Science-based approach to assess the formation of spatial groups or clusters and determine their significance in the urban network. Using a comparative analysis of two SNA methods, Origin-Destination (OD) Matrix and Immediate Neighbor (IN) Adjacency, the paper discusses their applicability and combination in urban scenarios. It addresses the knowledge gap in understanding pedestrian connectivity in large urban spatial networks and deriving key insights that allow for a viable scope of Spatial Network Analysis research.

1.1 One-North

one-north is a vibrant research and business park in Singapore that serves as a hub for research, innovation, and test-bedding. Developed by JTC corporation, the 200-hectare development houses key growth sectors such as biomedical sciences, info-communications technology and media, and startups, supported by capabilities in science and engineering. Located in the Queenstown planning zone, one-north is strategically placed near educational and research institutes including the National University of Singapore, INSEAD, the Singapore Institute of Technology, and the Singapore Science Park. The district has easy access to social and recreational hubs like Holland Village and Commonwealth Avenue. The precinct is split into the following developments (as shown in Figure 1): Biopolis, Fusionopolis, Mediapolis, Vista, LaunchPad @ one-north, Nepal Hill, Rochester Park, Wessex, and Pixel.

The 200-hectare masterplan for one-north was developed by Zaha Hadid Architects (ZHA) in 2003. ZHA's idea was to 'fold' the building masses over the existing hills and valleys as though they were a flexible layer draped over the terrain. The 'bent' urban grid and pedestrian connections cut the site in a crisscross manner, creating blocks of varying sizes, with a concoction of parks, green spaces, streets and pedestrian thoroughfares for a highly vibrant streetscape.

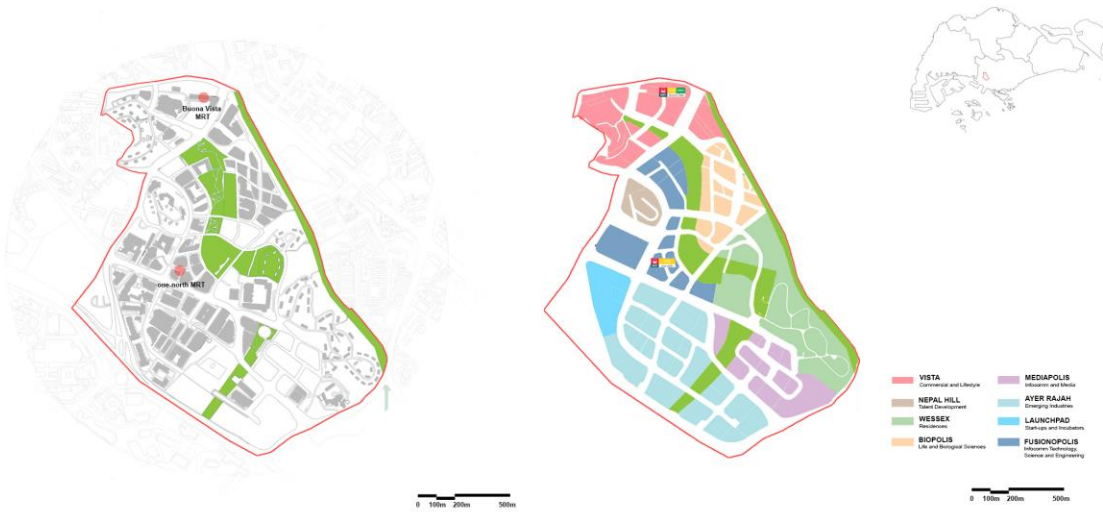

Figure 1: one-north masterplan: Building footprint and developments.

The aim was to create a new architectural typology to differentiate Singapore and encourage the setting up of R&D capabilities among local enterprises. one-north is envisioned as an SID, comprising a community of schools, businesses, and research centers, with everything that researchers would need to work, live, play and learn.

2 RESEARCH METHODOLOGY

2.1 Overview

The approach followed in our study can be described by the concept of Graph Theory (Harary 1967; Pachayappan and Venkatesakumar 2018; Wasserman and Faust 1994) which identifies the basic entities to be analyzed as nodes or vertices and the relationships between the entities as edges connecting them. The network of nodes and edges is called a graph. In our study, the nodes are defined as the spatial elements in one-north, e.g., buildings, public spaces, walkable areas, etc. Since the aim of the study is to analyze pedestrian movement amongst these spaces, the edges are defined as the distances between these nodes that are measured along the pedestrian footpath network.

Graph theory uses certain metrics such as Betweenness Centrality and Closeness Centrality to guide the comparison and study of relationships between the nodes. These measures provide us with insights into connectivity and how important nodes are within the network. Additional parameters can be related to the nodes and edges, like weights, directions of flows, etc. to improve the interpretability of the measures (Harary 1967; Harary and Robinson 1985; Pachayappan and Venkatesakumar 2018). Graph theory is extensively used and well-documented in social network analyses. There are many tools to visualize social networks like Gephi, Pajek, Cytoscape, Graphviz, etc. Due to its open-source nature, ease of use, and wide distribution among social analysts, we chose Gephi as the central platform for our study.

2.1.1 Gephi

Gephi is open-source software for visualization and exploration of graphs and networks. The software is used to visualize the topology of the spatial network and analyze the network measures. The representation of the network on the software is carried out by means of tables relating to nodes and edges (Cherven 2015).

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. Gephi allows the computation of important centrality indices like Degree, Closeness Centrality and Betweenness Centrality (Zhang and Yu Luo, 2017).

Degree is a centrality measure that counts the number of links incident upon a node. Degree centrality measures a node's significance in terms of its connectivity. 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, measuring the 'movement potential' of a node. Closeness measures help in identifying spatial clusters within building development by highlighting the spatial distribution of high-degree nodes.

Betweenness centrality characterizes a node's 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 public spaces.

2.2 Research framework

The study uses the following research framework:

- Graph generation and evaluation: The first phase of the research includes the definition of nodes and edges to reflect the one-north urban environment and capture all the spatial elements relevant to the scope of the study. Two methods are assessed to study their effects on pedestrian patterns in the site. The generation of the nodes and edges is conducted in QGIS, an open-source Geographic Information Systems (GIS) software. The edges are measured along the pedestrian footpath network, an OpenStreetMap dataset.
- Comparative analysis of the methods/results: The results in both methods are analyzed based on real-world observations and compared to determine which method is better suited to gain insights for further research at one-north. The methods are also analyzed to understand their general applicability in different urban networks.

2.3 Weightage of Nodes

We weight the spatial nodes based on their 'publicness' as urban attractors, in order to better reflect real-world walking patterns in the graph. Each node is assigned a score in accordance with the number and accessibility (spatial and temporal) of public outlets, as described in Figure 2 and Table 1. In the case of a commercial building, the public outlets comprise the retail outlets in the building. In the case of distinct public spaces and monofunctional facilities, the access to the space is calculated as the public outlet of the node. The weightage of the nodes is critical in the graph generation to avoid skewed results in the evaluation.

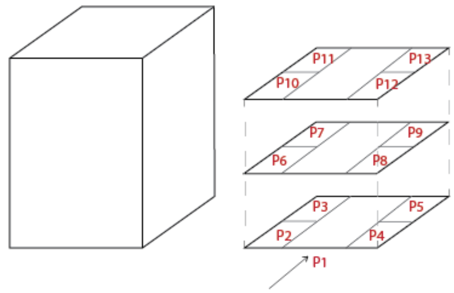

Figure 2: Node composition of public outlets (Px).

Table 1: Description of weightage of nodes.

Factor	Score Range	Description
Spatial Accessibility	0-1	The public outlets are scored based on the level they are accessed at. Outlets on the most public level (level 1) are scored 1, and scored lower as their level progresses (above ground and underground).
Temporal Accessibility	0-1	The public outlets are scored based on their average opening hours per day. Score 1 denotes 24-hr public access and is progressively lower as the time of access reduces.
Number of outlets	Sum	The nodes with a higher number of public outlets (like mixed-use buildings, malls, etc.) are stronger urban attractors than nodes with minimal outlets (like 24-hour public car parks, road intersections, etc.)

2.4 Method 1: Origin-Destination (OD) Matrix

OD Matrices are ubiquitous in network analyses and are critical in transportation planning. In the study, we used the OD Matrix method to analyze pedestrian connectivity in one-north. The OD graph is generated by drawing connections from each node to every other node in one-north, as shown in Figure 3. We considered the following as nodes (as shown in Figure 4): buildings with some public access, distinct retail spaces, parks, distinct public social spaces like decks, playgrounds, fitness stations, etc., distinct public facilities like car parks, cycle parks, etc., and individual MRT exits. The edges are all the shortest possible connections along the existing pedestrian network between all the nodes. The distances were generated using the QNEAT3 OD Matrix function in QGIS (Raffler 2018). We evaluated connections that fall within 400 m or a 5-min walk.

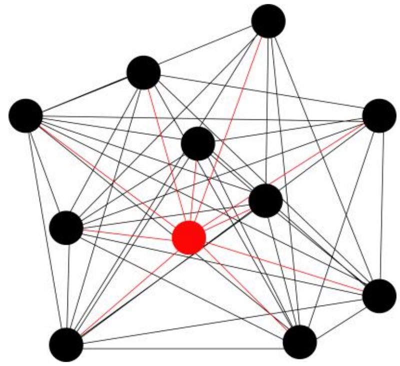

Figure 3: Typical OD Graph.

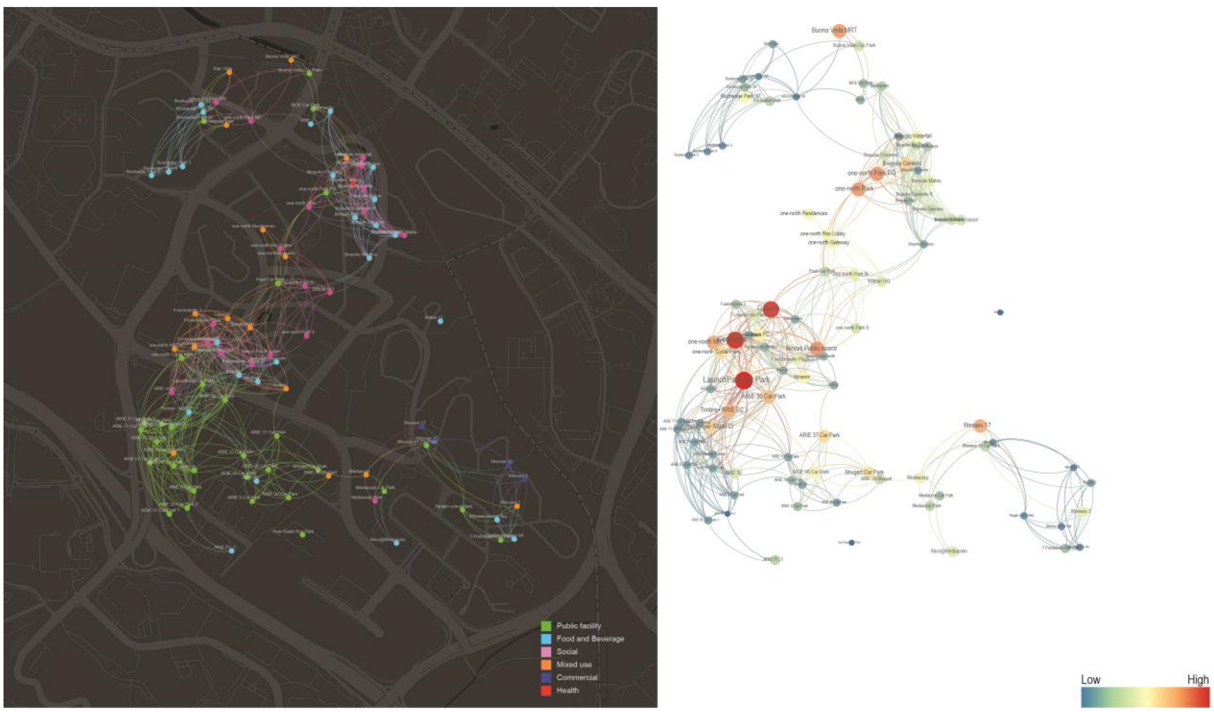

Figure 4: OD graph of one-north and Closeness Centrality.

2.5 Method 2: Immediate Neighbor (IN) Adjacency

When studying the vertical dimension of urban networks, an OD graph does not capture the pedestrian connectivity correctly, e.g., in a multi-level shopping street where nodes are defined as pedestrian transitory spaces, a level 1-walkway cannot connect with a level 3-walkway directly but must connect to the nearest elevator/ staircase, which then connects to the next level, and so on. The IN-Adjacency method is developed by the authors to better analyze pedestrian connections in the vertical built environment. In the IN-Adjacency method, the graph is generated by drawing connections between each node and its immediate neighbor, as shown in Figure 5. In one-north, we considered the following as nodes: buildings with some public access, distinct retail spaces, parks, distinct public social spaces, distinct public facilities, and individual MRT exits. In order to connect the graph and spatially represent one-north, we also considered the road intersections to be nodes (as shown in Figure 6). The edges were the shortest possible connections mapped along the existing pedestrian network between nodes. We evaluated connections that fall within 400 m or a 5-min walking distance.

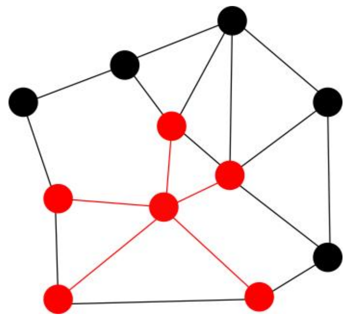

Figure 5: Typical IN Graph.

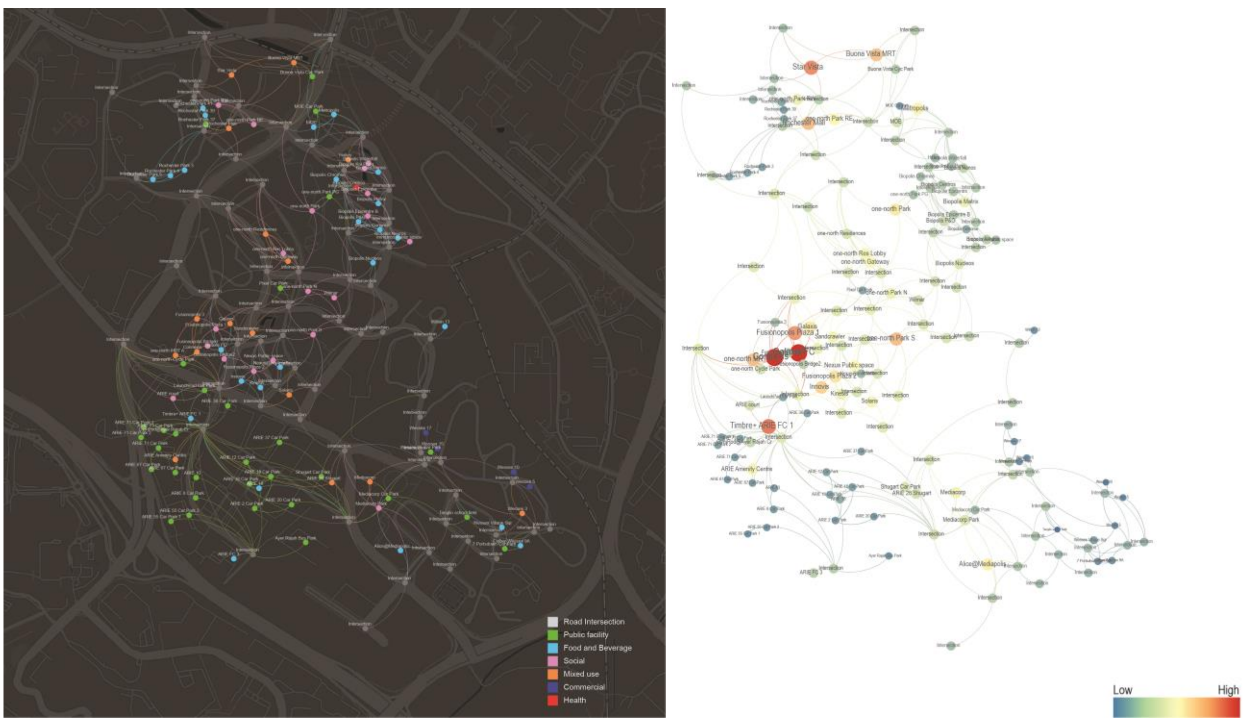

Figure 6: IN graph of one-north and Closeness Centrality.

3 COMPARATIVE ANALYSIS OF THE METHODS

The results in both methods helped us determine which approach is better suited for the aim of the study, based on our observations of pedestrian flows in one-north. Predictably, the degree of most nodes within a 400 m-radius is significantly higher in the OD Matrix method than the IN-Adjacency method. This indicates that the OD graph captures more 5-min pedestrian connections than the IN graph. The betweenness values vary significantly in both methods. In the IN-Adjacency method, the reduced choice of connections between nodes means that the road intersections automatically become crSitical connectors within the network. This implies that the road intersections should have the highest interactions in one-north, which is not what we observed in one-north (we do not capture multi-modal flows in the graph.) After discounting the road intersections, the nodes Connexis, Galaxis Food Court, one-north Park South and Fusionopolis Plaza—

buildings and spaces that are observed to have typically high interactions—are shown as key connectors in the IN graph but not in the OD graph. The OD graph captures certain public car parks, Mediacorp and one-north Park as key connectors in the network, which partially reflects our observations. In terms of closeness centrality, the OD graph displays higher closeness values for most nodes than the IN Graph. The difference in values is because the OD graph allows for more flexibility in individual walking decisions between spaces, which reflects pedestrian behavior more efficiently in one-north than the IN-adjacency method. This shows that the OD Matrix method is better suited overall for the study of one-north.

The study shows that the OD Matrix method is suitable for analyzing pedestrian movement across the scales of the built environment. However, the novel IN-adjacency method is more applicable in scenarios where the vertical dimension is a key means of connection. In the architectural scale, the ease of use of the IN-adjacency method allows architects and researchers to develop quick insights on connectivity within a multi-level building. The methods can be combined to form a hybrid approach to analyze pedestrian movement in integrated urban environments, like districts where vertical connectivity is a significant spatial aspect of the spatial network.

4 DISCUSSION

Both the generated graphs show the aggregation of similar clusters. We observed two dense mixed-use clusters at Fusionopolis and Biopolis, which we defined as sub-sites for further detailed spatial network analyses. We also selected a third mixed-use, loosely aggregated cluster at Mediapolis for comparative analyses with the other sub-sites.

The research in this paper is part of a larger ongoing study of urban vibrancy at one-north. It helps us to define our overall study area and to identify sub-sites of manageable scales for further detailed spatial network analyses. The next step in our larger study of one-north will be to develop an integrated multi-level pedestrian model of the sub-sites to predict pedestrian movement flows and spatial occupancies.

Since our SNA study defines buildings and bound spaces as nodes (rather than the spatial network analysis approach of studying axes of movement across space), it can be argued that it does not capture intricate spatial properties of buildings. However, the scalability of both methods ensures that a building can be broken down into smaller nodes, if the scope of the study requires it. This will allow urban planners and designers to use the methodology quickly and test different scenarios.

A frequent problem in studying networks is the possibility of missing significant connections due to arbitrary network boundaries. To address this, the methodology presented in this paper provides a quick and viable solution to analyze significant connections that helps us to inform the studies of smaller sub-sites. Further, our methodology can be used to extend the network to the larger urban context to identify critical connections. One limitation of our approach is that the dimension of verticality is not accounted for in the software used, in terms of the topography of the study site. This may lead to unforeseen results in the next stage of study.

5 SUMMARY

In this paper, we illustrated and compared two methods of SNA to study pedestrian connectivity in urban districts. The advantage of the OD Matrix method is that it captures potential pedestrian movement patterns thoroughly across the scales of the built environment. However, it is not as efficient as the IN-adjacency method in capturing the movement potential of the vertical built environment. Both methods can thus be applied in different scenarios based on the scale and complexity of the urban context. The weightage of the nodes is a critical component of the methodology. Since the weightage of the nodes allows for a comparative basis of centrality indices, the methods can be combined in future research as a hybrid approach to analyze pedestrian movement in integrated urban environments.

The insights gained from our study are important for the definition of key sub-sites. In our future research, the networks within the sub-sites will be analyzed in more detail using Spatial Design Network Analysis (sDNA), an open-source GIS-compatible Spatial Network Analysis tool. The scale of the sub-sites is feasible for mapping pedestrian movement using micro-mobility sensors, which can validate the Spatial Network Analysis results. In this way, our methodology serves as an important early-phase analysis preluding the adoption of Spatial Network Analysis tools to efficiently study urban districts.

REFERENCES

Balmaceda, B. and M. Fuentes. 2016. "Cities and Methods from Complexity Science." *Journal of Systems Science and Complexity* vol. 29 (5), pp. 1177-1186.

Barrat, A., M. Barthélemy, R. Pastor-Satorras, and A. Vespignani. 2004. “The Architecture of Complex Weighted Networks.” *Proceedings of the National Academy of Sciences* vol. 101 (11), pp. 3747–3752.

Barthélemy, M. "Crossover from Scale-Free to Spatial Networks. 2003." *Europhysics Letters* (EPL) vol. 63 (6), pp. 915-921.

Batty, M. 2013. *The New Science of Cities*. Cambridge: MIT Press.

Batty, M. and P. Longley. 1994. *Fractal Cities - a Geometry of Form and Function*. London: Academic Press.

Bettencourt, L. M. A. 2021. *Introduction to Urban Science: Evidence and Theory of Cities as Complex Systems*. Cambridge, Massachusetts: The MIT Press.

Bibri, S. E. 2021. "Data-Driven Smart Eco-Cities and Sustainable Integrated Districts: A best-Evidence Synthesis Approach to an Extensive Literature Review." *European Journal of Futures Research* 9(1), pp. 1-43.

Boccara, N. 2010. *Modeling Complex Systems*. Springer Science & Business Media.

Cheng, Y. Y., R. K. W. Lee, E. P. Lim, and F. Zhu. 2015. "Measuring Centralities for Transportation Networks Beyond Structures." Chap. Chapter 2 In *Applications of Social Media and Social Network Analysis*. Lecture Notes in Social Networks, 23-39.

Cherven, K. 2015. *Mastering Gephi Network Visualization*. Packt Publishing Ltd.

CLC, Centre for Livable Cities Singapore. 2014. Livable & Sustainable Cities: A Framework.

Cooper, C. H. and A. J. Chiaradia. 2020. "sDNA: 3-D Spatial Network Analysis for Gis, Cad, Command Line & Python." SoftwareX 12. https://doi.org/10.1016/j.softx.2020.100525.

Feng, C. H. E. N. and W. Zhang. 2017. "Grasshopper Reach Analysis Toolkit: Interactive Parametric Syntactic Analysis." In *Proceedings of the 11th Space Syntax Symposium, Lisbon*.

Harary, F. 1967. "Graphs and Matrices." *SIAM Review 9(1), pp. 83-90*. http://www.jstor.org.library.sutd.edu.sg:2048/stable/2027411 Accessed: July 2, 2022.

Harary, F. and R. W. Robinson. 1985. "The Diameter of a Graph and Its Complement." *The American Mathematical Monthly 92(3)*, pp. 211-12. http://www.jstor.org.library.sutd.edu.sg:2048/stable/2322878.

Hillier, B., A. Penn, J. Hanson, T. Grajewski, and J. Xu. 1993. "Natural Movement: Or Configuration and Attraction in Urban Pedestrian Movement." *Environment and Planning B: Planning and Design* 20(1), pp. 29-66.

Hillier, B. and J. Hanson. 1989. *The Social Logic of Space*. Cambridge University Press.

Pachayappan, M. and R. Venkatesakumar. 2018. "A Graph Theory Based Systematic Literature Network Analysis." *Theoretical Economics Letters* 08(5), pp. 960-980.

Raffler, C. 2018. QNEAT3 - QGIS Network Analysis Toolbox 3. https://root676.github.io/. Accessed Dec. 27, 2021.

Sevtsuk, A. and M. Mekonnen. 2012. "Urban Network Analysis. A New Toolbox for Arcgis." *Revue internationale de géomatique* 22(2), pp. 287-305.

Wasserman, S. and K. Faust. 1994. Social Network Analysis: Methods and Applications. *Structural Analysis in the Social Sciences*; 8. Cambridge: Cambridge University Press..

Zhang, J. and Y. Luo. 2017, “Degree Centrality, Betweenness Centrality, and Closeness Centrality in Social Network.” *Proceedings of the 2017 2nd International Conference on Modelling, Simulation and Applied Mathematics* (MSAM2017).

AUTHOR BIOGRAPHIES

ANJANAA DEVI SRIKANTH is a Ph.D. researcher at Future Cities Lab Global, Singapore-ETH Centre, and a Ph.D. student at the Singapore University of Technology and Design. She holds a Master’s degree in Urban Design from the National University of Singapore. Her research interests lie in Spatial Network Analysis and Complexity Theory in urban design. Her email address is anjanaa_devi@mymail.sutd.edu.sg.

CHIRAG HABLANI is a researcher at the Singapore University of Technology and Design. He holds a Bachelor’s degree in Architecture from National University of Singapore. His research interests include AI tools in architecture and urban design and LIDAR point cloud analysis. His email address is chirag_hablani@sutd.edu.sg .

SRILALITHA GOPALAKRISHNAN received her doctoral degree in Architecture and Sustainable Design from the Singapore University of Technology and Design. She is a landscape architect with over 15 years of professional experience and diverse projects across Singapore, Malaysia, China, Hong Kong, and India. She is the President of Singapore Institute of Landscape Architects. Her email address is srilalitha.gopalakrishnan@sec.ethz.ch.

THOMAS SCHROEPFER is Full Professor of Architecture and Sustainable Design at the Singapore University of Technology and Design where he leads the Cities: Urban Science and Design for Density research thrust. He received his doctoral and master’s degree with distinction from Harvard University. His email address is thomas.schroepfer@sutd.edu.sg.