# CONFIGURATIONS OF SPATIAL RESILIENCE: IMPACT OF CONNECTIVITY ON SPATIAL RESILIENCE

Darren **Nel**[1], Gerhard **Bruyns**[1], Christopher D. **Higgins**[2], Akkelies **van Nes**[3]

*[1]School of Design, The Hong Kong Polytechnic University, [2]Dept. of Land Surveying and Geo-Informatics & Dept. of Building and Real Estate, The Hong Kong Polytechnic University, [3]TU Delft & Western Norway University of Applied Sciences*
*Mailing address*
*E-mail of corresponding author: darren.nel@connect.polyu.hk*

## ABSTRACT

*Urban resilience is more than just about a city's ability to resist and 'bounce-back' after a disruption. Rather, resilience is also about a city's ability to respond to and adapt to changing circumstances. Recent developments in urban resilience theory requires that a space be considered at multiple scales when assessing urban resilience. Yet, most assessments of urban resilience have either neglected spatial elements of cities or have only considered a single scale. In response to this oversite, there is a small but growing body of literature which has begun to explore the spatial elements of resilience. Within this context, connectivity is often identified as an important determinant of both resilience and urban design. Connectivity facilitates adaption by creating more opportunities for potential interaction and, though a diverse array of connections, can enable the city to reorganise itself into different configurations should the need arise. While the overall connectivity of the network is important, the configuration of the network is perhaps even more important for spatial questions of resilience. Drawing on the ideas of configurational analysis, we explore the properties of connectivity in terms of access, flow and efficiency as well as how they are measured spatially. Through the case study of Hong Kong, SAR, we then present a method which combines the properties of connectivity with each other and at multiple scales and through multiple modes of transport. Through our approach, we are able to identify areas with varying strengths of connectivity at various scales, and which there for have varying adaptive capacity.*

*Keywords: Spatial resilience, urban design, urban form resilience, urban morphology, urban resilience.*

## 1. INTRODUCTION

The contemporary understanding of urban resilience regards resilience as being more than just about a city's ability to resist a specific threat and 'bounce-back' after a disruption, i.e. sometimes called specific resilience (Folke et al., 2010). Rather, within the social-ecological or evolutionary resilience perspective, urban resilience also considers a city's ability to respond to and adapt to changing circumstances (Coaffee & Lee, 2016). This ability to respond, adapt and transform to unknown and unplanned threats is often referred to as general resilience (Elmqvist, Barnett, & Wilkinson, 2014; Walker & Salt, 2012). Carpenter et al. (2012, p. 3250) define general resilience as a systems "capacity to absorb shocks of all kinds, including novel and unforeseen ones". General urban resilience shifts the emphasis of resilience away from planning *only* for specific, predefined threats or risks (i.e. typhoon, earthquake, etc.), but to rather also focus on the ability of a city to persist through periods of rapid and gradual change by enhancing the capacity to adapt. Additionally, within the general resilience view, change can be regarded as a precondition for the persistence of a city as without change a city would stagnate and die (Elmqvist et al., 2014, p. 21). However, current assessments of the resilience of cities (such as those by the 100 Resilient cities initiative (100 Resilient Cities, 2016)) have largely been focused on studying aspects of specific resilience, while failing to take into account aspects of general resilience (Peres, Landman, & du Plessis, 2016; Walker & Salt, 2012).

In addition to the addition of general resilience, spatial considerations have begun to make their way into urban resilience discourse, i.e. through the New Urban Agenda from the UN Habitat (2016), which have begun to emphasis spatial resilience. Despite the emphasis and importance of spatial aspects of cities on resilience (Marcus & Colding, 2014), the existing urban resilience assessments of resilience have largely neglected any spatial assessments of resilience (Garcia & Vale, 2017). When any spatial elements have been included the assessments have either only considered a single scale, typically using highly aggregated data, or have focused on aspects of specific resilience, i.e. disaster risk reduction. Examples of such assessments can be seen Gebremichael et al (2014); DiGregorio et al. (2018); Sim and Dongming (2017) and The City of Hague and AECOM (2018). This lack of a spatial understanding of urban resilience is significant because "For designers wanting to measure resilience in the built environment the available frameworks are not useful for achieving concrete results" (Garcia & Vale, 2017, p. 164). This makes intervening within any city in any in terms of its spatial design a difficult prospect. This lack of clear analytic guidance means that new approaches to spatial resilience must be developed.

Recent research into urban spatial resilience (see Feliciotti, Romice, & Porta, 2017; Garcia & Vale, 2017; Marcus & Colding, 2014; Nel, Bruyns, & Higgins, 2018; Nel & Landman, 2015; Sharifi, 2018) has identified connectivity, alongside diversity and redundancy among others, as an important determinant of both resilience and urban design. Within this paper we present, through a case study of Hong Kong, a multi-scale spatial analysis method for studying connectivity in relation to urban resilience. We focus specifically on three properties of connectively (access, flow, route directness). The aim of the method for the identification of areas which are most and least connected at specific or all spatial scales. This allows for the identification of areas which are most and least vulnerable and disconnected at all scales. The paper will first discuss to role of connectivity in building spatial resilience. This will be followed by a discussion of how connectivity can be measured in terms of access, flow and efficiency. We then present the case study and method which is followed by a discussion of the results as well some suggestions for future studies.

## 2. CONNECTIVITY AND SPATIAL RESILIENCE

Cities are often described as a set of complex interrelated networks which allow new locations to emerge (Batty, 2013; Serge Salat, 2017). Thus, the importance of connectivity to the city cannot be overstated, as without good connectivity urban areas could not function (Marshall, 2005; Reggiani, Nijkamp, & Lanzi, 2015). This is because connectivity, or rather the networks of the city, supplies access across the city to urban function and determines how goods flow and people interact (Hillier, 2007). As a result, connectivity might be considered to be the binding element of the city.

A well-connected urban area is able to improve the overall general resilience of a city by facilitating the adaptive capacity of the city. Good connectivity dose this by providing more opportunities for potential interaction and, though a diverse array of connections, wich can enable the city to reorganise itself into different configurations should the need arise (Salat & Bourdic, 2012; Sharifi, 2018). Reorganisation, through redundant connections, allows the system to reconfigure, by re-routing resources through alternative paths, while continuing to function should a link or section of the network fail. Conversely, the lack of connectivity is often the cause of failure of functions after a perturbation (Ahern, 2011), as areas with low levels of connectivity are likely to have several points of failure and are thus more the area which are most vulnerable to disruption (Boeing, 2017a). It should also be cautioned that too much connectivity is also not desirable as it results in inefficient networks (Feliciotti, Romice, & Porta, 2016).

While connectivity in general is considered vital for urban resilience, often it is the structure of the network itself, as well as the distribution of elements and strength of the connections between locations which are more important for the continued functioning of the city (Feliciotti et al., 2017; Salat & Bourdic, 2012). The argument for this is that by changing the overall structure of the network it is possible to change the ease at which areas are reached, the flow of goods and interaction the interaction between elements. Much in the way that a highway bypass can have a dramatic impact on how a city or small town functions (Collins & Weisbrod, 2000; Funderburg, Nixon, Boarnet, & Ferguson, 2010).

Of interest to this paper is the connectivity of the urban movement network, specifically streets and public transport. We focus on these two elements, specifically streets, because “Streets and road networks are the backbones of cities. They are fundamental for emergence of cities and guide their growth and evolution” (Sharifi, 2018, p. 171). And as streets are the longest lived elements of the urban fabric, remining largely unchanged for decades and even centuries, they can be considered to be a relatively permanent part of the urban fabric (Carmona, Heath, Oc, & Tiesdell, 2003). Meaning that any intervention within the street or mobility network is likely to have an impact for years to come.

Research which involves studying urban form and movement patterns is conducted through a configurational analysis of the urban fabric (Hillier, 2007; Sevtsuk, 2010; van Nes, 2002). The configurational approach to urban morphology is concerned with how the arrangement of spatial elements are linked together to form a global patterns and how these patterns impact movement in in the city (Hillier, Penn, Hanson, Grajewski, & Xu, 1993, p. 29). Within configurational studies, there are several ways to study connectivity. This paper focuses specifically on three properties of connectively, namely: access, flow and efficiency. Each of these properties is strongly linked to aspects of urban design (Porta et al., 2010) and, more recently, being used to study urban resilience (Nel et al., 2018; Sharifi, 2018). The selected properties are often measured through centrality measures of networks. Centrality measures, derived from graph theory (Kropf, 2017, p. 17; Marshall, 2005, p. 108), allow for the assessment the relative importance of a location within a network. However, not all locations are important at all scales (Sharifi, 2018). Therefore, when centrality assessments are performed at various scales, i.e. using varied radii, it allows locations which are important at one or multiple scales to be identified (Sevtsuk, 2010). Through this process, we hypothesis that it is possible to identify areas which are vulnerable and disconnected at all scales and are therefore less able to easily respond and adapt - i.e. less resilient.

## 3. ACCESS, FLOW AND EFFICIENCY

In the previous section access, flow and efficiency were identified as three properties of connectivity which can be used to question spatial aspects of urban resilience. Each of these properties will be discussed briefly as well as how they can be used to study resilience.

***Access*** is a common concept found within urban planning and design and can be defined as the ease with which one can travel between origins and destinations of value, is as result of joint effect of the transportation network as well as the spatial distribution of activates (Páez, Scott, & Morency, 2012, p. 141). Access is greatly influenced by the urban form of an area and the quality of its public transport, with any changes to the configuration of the network (removing a road) potentially having a large impact on the overall access of an area (Verma, Verma, Rahul, Khurana, & Rai, 2019). Accessibility analysis allows for the identification of areas which are relatively disconnected from the network and are therefore able to reach less opportunities or require higher costs (time or money) to reach the same number of opportunities. Less accessible areas are also less likely to be able to adapt easily simply because there are less opportunities available to them. Furthermore, areas with lower access are more likely to be disconnected should there be a disruption to the network, making them more vulnerable overall.

Access can be studied in several ways, the most common of which are the cumulative opportunities and gravity-based measures (Páez et al., 2012). Cumulative opportunities measurements simply sum the total number of opportunities (can be weighted) reachable within a defined cost (i.e. time or distance). Gravity-based measure (Table 1, Equation 1) on the other hand also include a spatial impedance factor, through a distance decay function, which takes into account the effort required to reach that opportunity. Additionally, gravity measures also consider the attractiveness of a location based on its weight (Sevtsuk, 2014). Overall, gravity type measures are able to indicate the attractiveness of a location as well as the effort required to reach other locations into a single value (Sevtsuk, 2010).

*Table 1: List of connectivity metrics*

| Metric | Formula | Equation # |
|---|---|---|
| Gravity | $C_G{}^r[i] = \sum_{\substack{\forall j \in G-\{i\};\\ d[i,j] \le r}} \frac{W[j]}{\varepsilon^{\beta . d[i,j]}}$ | 1 |
| Betweenness Centrality | $C_B{}^r[i] = \sum_{\substack{\forall j \in G-\{i\};\\ d[i,j] \le r}} \frac{n_{jk}[j]}{n_{jk}} \cdot W[j]$ | 2 |
| Straightness centrality | $C_S{}^r[i] = \sum_{\substack{\forall j \in G-\{i\};\\ d[i,j] \le r}} \frac{\delta_{[i,j]}}{d_{[i,j]}} \cdot W[j]$ | 3 |
| i: location as the origin; j: destination location; G: network; r: network radius; d[i, j]: shortest network distance between locations i and j; δ[i, j]: Euclidian distance between locations i and j; njk[i]: number of routes that pass through location i between j and k in radius r; from location i; njk: number of paths between locations j and k; Beta(β): decay parameter for units; W[j]: weight of location j. Source: modified from Sevtsuk and Mekonnen (2012) | | |

***Flow*** type metrics estimate the potential through movement along a path or at an intersection (Rodrigue, Comtois, & Slack, 2013). A common means to measure potential flow is through betweenness centrality, which indicates the number of shortest paths which pass along a location. Betweenness centrality (Table 1, Equation 2) can be used to indicates the ease at which a location can be accessed while on route to another location (Rodrigue et al., 2013). Locations with high betweenness centrality values tend to have high numbers of traffic, both vehicle and pedestrian (B Hillier et al., 1993; Rodrigue et al., 2013). As areas with high betweenness have the most through traffic they also tend to be the areas with high number of business and retail (Porta et al., 2009). As shown by van Nes (2002), changes in the betweenness centrality, i.e. by altering the network by building new roads, can have an impact on where retail and business tend to locate. This might indicate that area with higher betweenness values are more likely to persist, through adaption, as there is more energy (in the form of movement) in these areas. While streets with high betweenness create areas of high value, these streets are also vital for the continued functioning of the city, as they tend to carry large volumes of traffic (Rodrigue et al., 2013), and any disruptions along these streets might have serious ramifications to the functioning of the city (Boeing, 2017a; Sharifi, 2018).

Network ***Efficiency*** considers how much extra cost is needed to reach a location (Crucitti, Latora, & Porta, 2006). Areas which have efficient networks are able to provide more cost effective interactions between locations, thereby improving the adaptive capacity of the area as people and information are able to move easier within the area (Sharifi, 2018, p. 175). Porta et al. (2010, p. 116) argue that “the efficiency of networks at the global level increases with the increase of their efficiency at the local level”. Therefor, to improve the overall efficiency of the entire city it is vital that the local area be well designed.

While there are many ways to study network efficiency (see Barthélemy, 2011; Porta, Crucitti, & Latora, 2006a; Rodrigue et al., 2013), our concern is predominantly with the street configuration, as such we use the straightness centrality metric (Table 1, Equation 3). Straightness centrality (Porta, Crucitti, & Latora, 2006b) works on the assumption that paths between locations which are more direct (i.e. have fewer deviations and more closely reflect a straight line) require less energy and are thus more efficient (Barthélemy, 2011). Straightness centrality indicates how closely a path between origins and destinations resembles a straight line, with values closer to one indicating locations which have more efficient urban configurations (Sevtsuk & Mekonnen, 2012).

## 4. STUDY AREA AND METHODOLOGY

To test how these metrics can be used we conducted a case study of the city of Hong Kong S.A.R (Figure 1). Hong Kong was selected as a case study as the city has a mixture of different urban forms across the territory as well as having a well-developed public transportation system. While Hong Kong is used as the case study, the method presented below is transferable into other areas and, while useful, it is not reliant on a public transport network. The sections to follow will describe the method, results and the conclusions of the study as well as the potential implications for urban design to facilitate the creation of more spatially resilient cities.

Configurational morphological studies typically only focus on the street network (i.e. space syntax), were they tend to limit their analysis to links and nodes of the network, while also ignoring information provided by buildings (Kang, 2019). In contrast, our approach makes use of a multi-modal transportation network (currently limited to walking and rail network) as well as incorporating buildings as our unit of analysis. We do this as the building is typically the smallest unit of analysis within urban morphology studies (Kropf, 2017). Furthermore, by using buildings as the unit of analysis we are able to incorporate additional information into the analysis, i.e. building volume or land use (Sevtsuk & Mekonnen, 2012) as using weights in the analysis has a strong impact on the results of accessibility analysis (Kang, 2019).

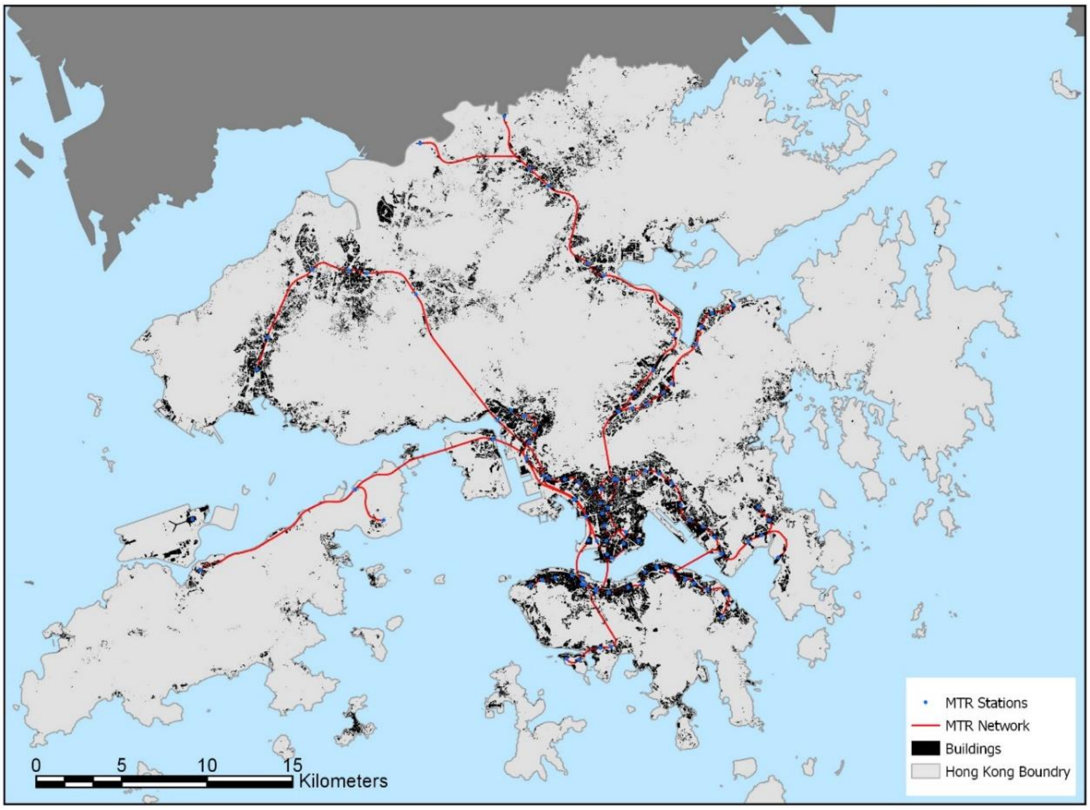


*Figure 1: Hong Kong with the MTR network and the spatial distribution of buildings.*

We have weighted our analysis by building volume which was derived from building data created by the Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University. Our spatial network is based on an OpenStreetMaps pedestrian network which was obtained and prepared using OSMnx (Boeing, 2017b). An assumed walk speed of 5 Km/h was selected for travel times along the pedestrian network (Tobler, 1993). In terms of the public transport, this study was limited to only using the train network (MTR). Mean travel times between stations were estimated based off information obtained from the MTR corporation website (MTR, 2019). The pedestrian and train network were combined and prepared in in ArcGIS using the Network Analyst extension.

The calculations of betweenness centrality, straightness centrality and gravity where done using the Urban Network Analyst tool developed by Sevtsuk & Mekonnen (2012). Using several metrics network together is not something new. For example, Porta et al (2010) use several different metrics, in their multi-centrality approach. However, where Porta et al. (2010) use closeness centrality as a measure of access, our approach uses gravity metrics, which include both a weight and a distance decay function, the latter of which is controlled by the Beta (β) function.

For the Gravity metric, Handy & Niemeier (1997), suggest that a β value of 0.1813 should be used for gravity measures which use travel time for walking trips. However, we selected a β of 0.22 as our analysis includes travel by train and as shown by Higgins (forthcoming), this β value, while more constrained compared to the value suggested by Handy & Niemeier (1997), is not overly strong or lenient. Additionally, as the aim of the study is to conduct a multi-scale assessment, several scales are needed. The flowing scales of analysis were selected using travel time or the equivalent distance in metres[1] of 10, 20 and 30 minutes or the equivalent distance in metres of 800, 1600, 2400 respectively.

The multi-scale connectivity assessment was done using the workflow shown in Figure 2. First, each of the metrics; access (gravity metric), flow (betweenness centrality) and efficiency (straightness metric); were calculated for a single scale (i.e. 10 min). The results of each metric were then normalised from 0-1, where 1 is represents areas with the highest scores for each metric. The three normalised scores where then combined into a single *Mixed Connectivity Index* (MCI) with, the following weights Gravity = 40%, Betweenness = 20% and Straightness = 40%, with the highest possible score being 1. These weights were selected as betweenness centrality tends to favour some areas over others. Through several tests the selected weights

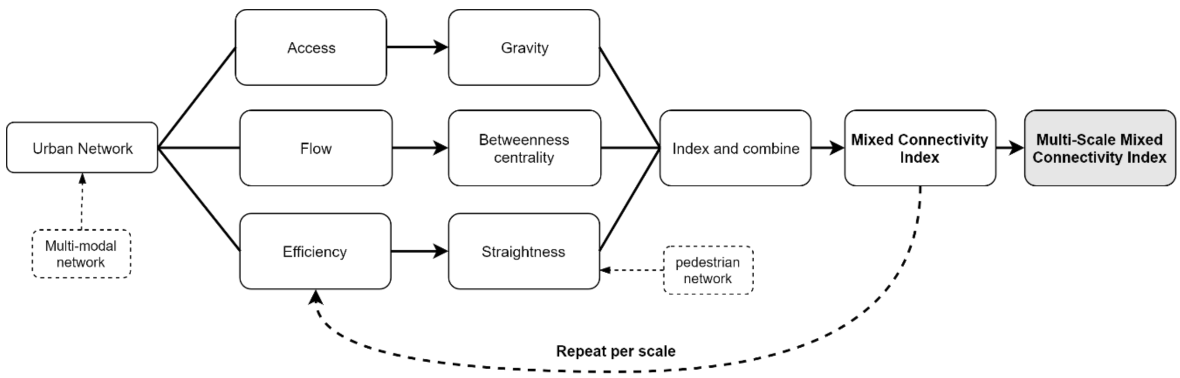


*Figure 2: Workflow of the Multi-scale Mixed Connectivity Index*

[1] Meters are needed for the calculation of straightness centrality as it compares the difference between route length and the Euclidian distance between two locations

were deemed as the best compromise between metrics and how they contribute to spatial resilience.

This process was then repeated for each scale, resulting in three separate MCI. The MCI's where then combined with and equal weight per scale, into a single *Multi-scale Mixed Connectivity Index* (Ms-MCI) to give an overall connectivity score for the entire study area. The results of the analysis are discussed in detail in the next section.

## 5. RESULTS AND DISCUSSION

The descriptive statistics of results of the analysis have been presented in Table 2. The analysis was done using 213,326 buildings for the territory of Hong Kong. The table shows the descriptive statistics of the metrics used and it includes a description of the raw analysis as well as the normalised values. The table also shows the statistics of the Mixed Connectivity Index (MCI) for each scale as well as the statistics for the Multi-scale Mixed Connectivity Index (Ms-MCI).

*Table 2: Descriptive Statistics of Connectivity Analysis*

| **Variable** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|
| Gravity 10 | 937,705.53 | 1,850,531.79 | 0 | 20,353,549.43 |
| Betweenness 10 | 103,621,614.07 | 564,551,359.86 | 0 | 22,511,428,340.60 |
| Straightness 10 | 1,886,584.07 | 3,341,162.12 | 0 | 22,853,345.77 |
| Gravity 20 | 1,622,695.86 | 3,230,043.07 | 0 | 28,833,154.33 |
| Betweenness 20 | 1,222,350,600.89 | 11,890,094,956.23 | 0 | 447,311,099,346.00 |
| Straightness 20 | 6,284,701.25 | 10,070,629.27 | 0 | 51,042,733.00 |
| Gravity 30 | 1,816,679.61 | 3,563,811.81 | 0 | 29,967,183.55 |
| Betweenness 30 | 5,282,977,451.89 | 56,261,173,861.03 | 0 | 2,019,046,216,630.00 |
| Straightness 30 | 11,867,060.51 | 18,328,681.53 | 0 | 75,985,499.68 |
| Gravity Norm 10 | 0.0461 | 0.0909 | 0 | 1.0000 |
| Betweenness Norm10 | 0.0046 | 0.0251 | 0 | 1.0000 |
| Straightness Norm10 | 0.0826 | 0.1462 | 0 | 1.0000 |
| Gravity Norm20 | 0.0563 | 0.1120 | 0 | 1.0000 |
| Betweenness Norm20 | 0.0027 | 0.0266 | 0 | 1.0000 |
| Straightness Norm20 | 0.1231 | 0.1973 | 0 | 1.0000 |
| Gravity Norm30 | 0.0606 | 0.1189 | 0 | 1.0000 |
| Betweenness Norm30 | 0.0026 | 0.0279 | 0 | 1.0000 |
| Straightness Norm30 | 0.1562 | 0.2412 | 0 | 1.0000 |
| MCI 10 | 0.0524 | 0.0929 | 0 | 0.7258 |
| MCI 20 | 0.0723 | 0.1192 | 0 | 0.7759 |
| MCI 30 | 0.0872 | 0.1380 | 0 | 0.7896 |
| Ms-MCI | 0.0706 | 0.1150 | 0 | 0.7317 |
| **Nbr. of observations** | | | | **213,326** |

In addition to the descriptive statistics, the results of the analysis have also been mapped and are shown in Figure 3 and Figure 4. From Figure 3 we can see how as the scale of analysis becomes larger (i.e. going from 10 to 30 min travel time) that some area become more prominent. This fact emphasises the importance of the MTR lines on the connectivity score as the areas which have the highest scores on all scales also tend to be close to an MTR stations. However, as can be seen in the Kowloon and Hung Hom stations (two large building stations on the South West and South East of Kowloon), this is not true for all stations. As both Kowloon and specifically Hung Hom station only begin to show any significant importance on the higher scales. This would indicate that they likely play a role as metropolitan level connectors and are not as well used for local trips. Building on this idea, the results indicate that the areas which dominate on all scales are also areas which correspond to areas which have finer urban blocks and are thus more walkable. This is supported by the straightness centrality maps which are a good indicator of walkability (Sevtsuk & Mekonnen, 2012), and which emphasis areas which are more able to provide more direct routes between places.

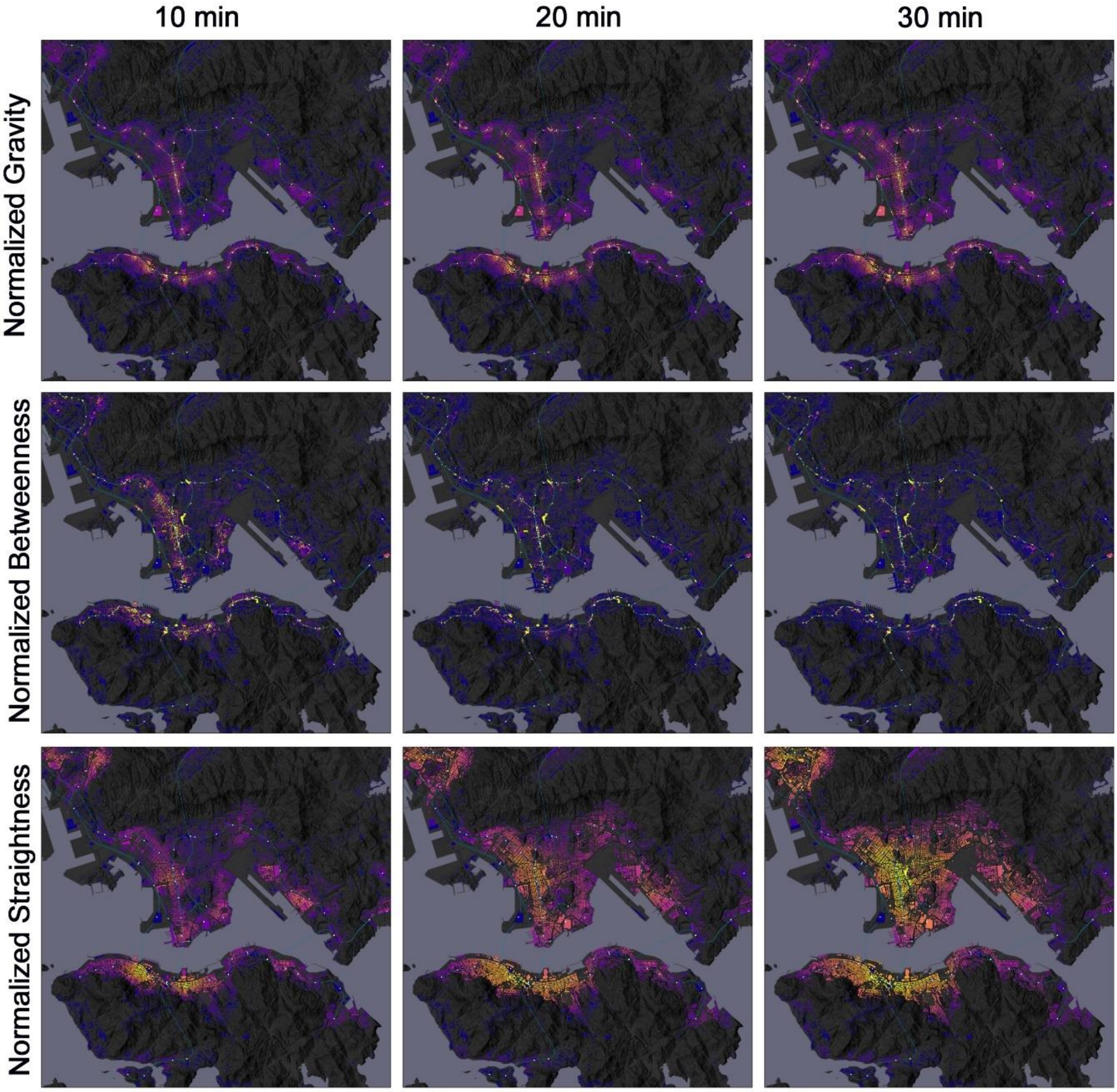


*Figure 3: Sample of the results for Hong Kong Island and Kowloon in Hong Kong. Normalised results of the selected metrics (Gravity, top row), Betweenness (middle row) and Straightness (bottom row) for each of the selected scales of 10 (left column), 20 (middle column) and 20 minutes (right column). Warmer colour indicates higher score.*

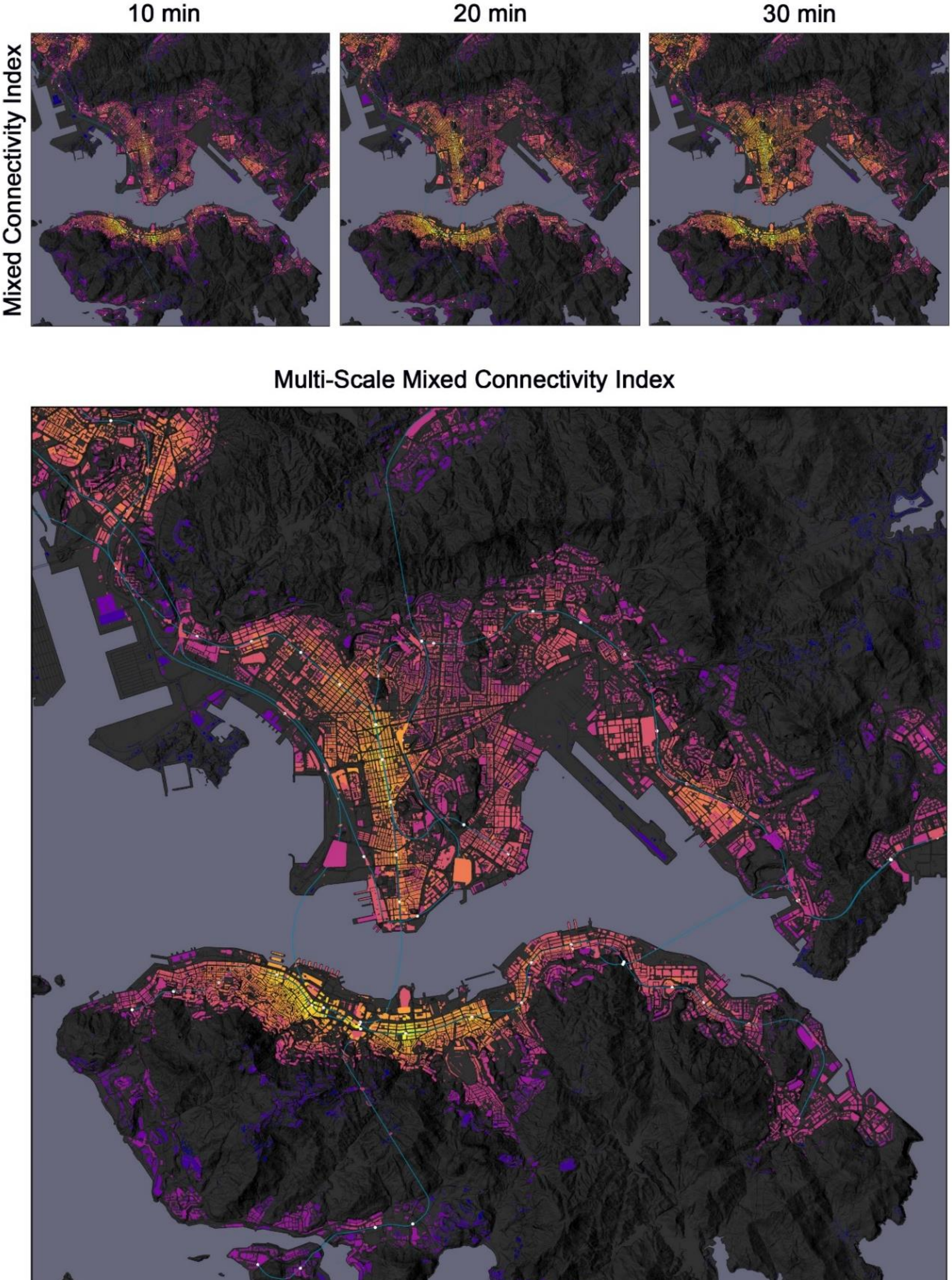


*Figure 4: Sample of the results for Hong Kong Island and Kowloon in Hong Kong. (Top row) The Mixed Connectivity Index per scale. (Bottom) Final Multi-scale Mixed Connectivity Index for Hong Kong. Warmer colour indicates higher score.*

most connected on all scales. The most prominent of these areas are Mong Kok, Central and Wan Chai. When looking at the urban form of these areas we can see that these areas are characterised by finer scale urban blocks and building which are generally higher density. This emphasises the relationship between urban form and built density, where more built volume is accessible with smaller blocks. For example, in the New Towns (i.e. Tuen Mun and Yunlong) of Hong Kong, the buildings are generally much larger than those in in Central and Mon Kok. Yet despite this, The New Towns mentioned still score lower on the connectivity index, even on the local 10 min scale (See Figure 5). It can be argued that this is a result of the larger buildings and blocks requiring that pedestrians have to travel further to reach the same built volume when compared to areas like Mong Kok. Interesting to note is that the areas which have the highest connectivity scores also tend to be the oldest areas of Hong Kong and were originally built on the shop house type built form which is dependent on pedestrian movement (see Shelton, Karakiewicz, & Kvan (2010))

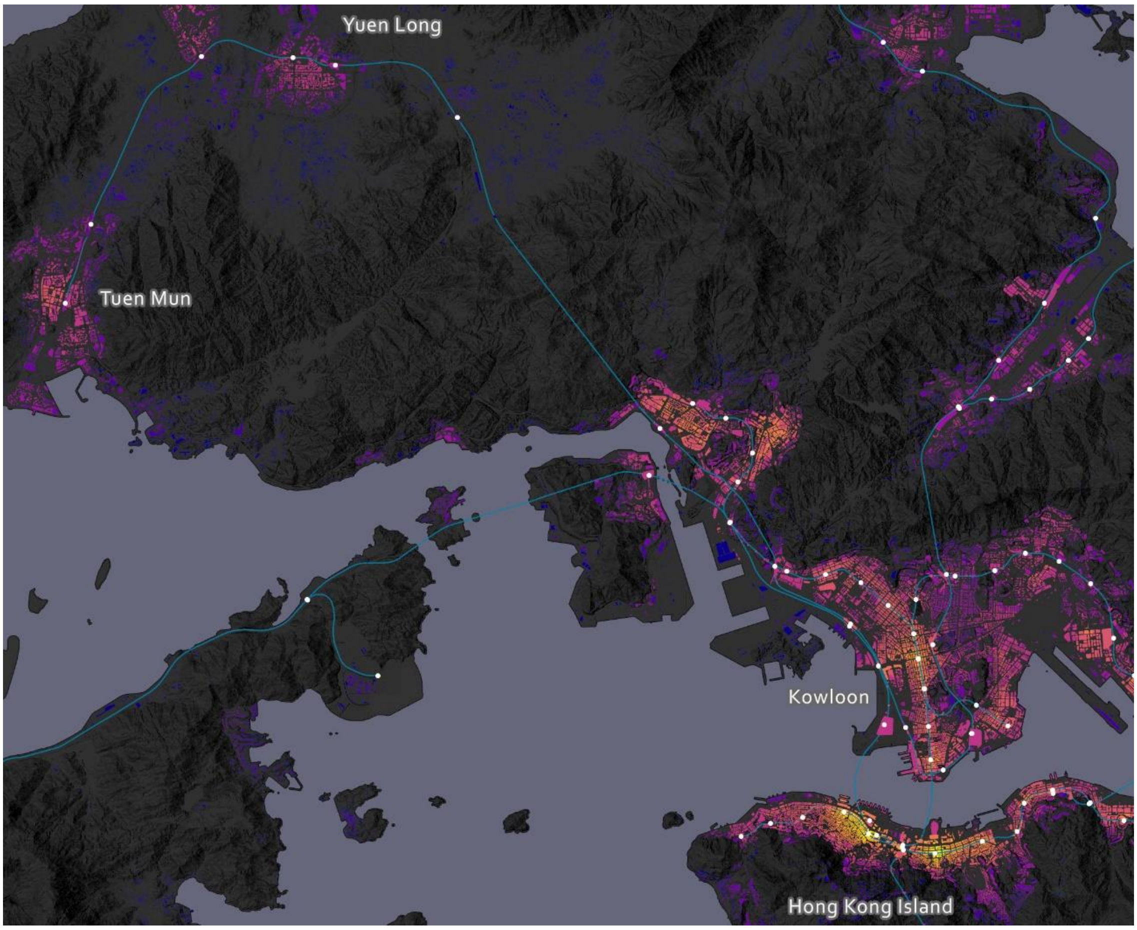


*Figure 5: Comparison of the Mixed Connectivity Index at 10 min travel time for different areas of Hong Kong*

## 6. CONCLUSION

Urban movement networks are vital for the resilience and continuation of our cities. As such it is vial that we understand how they function and change. The characteristics of urban network, how it is configured and the strength of the connections, are significant determinants of the ability of a city to adapt and transform (Sharifi, 2018). Once built, streets in particular have a very long lifespan and are difficult and costly to change, therefore the argument can be made that the design of streets have a large long term impact on the resilience of cities (ibid).

Despite the importance of streets on the resilience of cities, there is currently little research which has explored their importance through practical analysis and specifically within the general resilience debate. This paper has begun to explore some of the methods which can be used to understand a single aspect of spatial resilience, connectivity. While still in the early stages of development, the method aims to combine multiple metrics with multiple scales to form a single connectivity indicator. To test the method a case study of Hong Kong was presented. The initial results show that our approach is able to identify areas which have high and low access to built volume. With higher access to built volume citizens are able to access more amenities (Higgins, Nel, & Bruyns, 2018), provided that there is sufficient diversity. Better access to urban amenities would mean that citizens are able to potentially access a higher diversity of resources, therefore allowing them to respond faster and with less effort, should the need arise. Furthermore, areas which are better connected are likely to be less vulnerable to disruptions, provided that they have a multitude of transport modes and routes.

The results of the study also tend to suggest that while access to the MTR network greatly facilitates connectivity on the larger scales, the form of the street network is just as important as streets with larger buildings and bigger blocks tended to have lower connectivity scores and seen easily through the analysis of the straightness metric. Some of the limitations of this study is that only the MTR network was used, future studies should include all forms of transport such as bus and ferries to provide a clearer picture of cities actual movement network. Furthermore, deeper statistical and longitudinal studies are needed to confirm the validity of the method.

## 7. REFERENCES

[1]. 100 Resilient Cities. (2016). 100 Resilient Cities. Retrieved 5 October 2016, from www.100resilientcities.org

[2]. Ahern, J. (2011). From fail-safe to safe-to-fail: Sustainability and resilience in the new urban world. *Landscape and Urban Planning at 100*, *100*(4), 341–343. https://doi.org/10.1016/j.landurbplan.2011.02.021

[3]. Barthélemy, M. (2011). Spatial networks. *Physics Reports*, *499*(1), 1–101. https://doi.org/10/bv242z

[4]. Batty, M. (2013). *The new science of cities*. Cambridge, Massachusetts: Cambridge, Massachusetts : MIT Press.

[5]. Boeing, G. (2017a). *Methods and Measures for Analyzing Complex Street Networks and Urban Form* (PhD thesis). University of California, Berkeley, Berkeley.

[6]. Boeing, G. (2017b). OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. *Computers, Environment and Urban Systems*, *65*, 126–139.

[7]. Carmona, M., Heath, T., Oc, T., & Tiesdell, S. (Eds.). (2003). *Public Places, Urban Spaces: The Dimensions of Urban Design*. Architectural Press. Retrieved from https://books.google.co.za/books?id=6ElPAAAAMAAJ

[8]. Carpenter, S. R., Arrow, K. J., Barrett, S., Biggs, R., Brock, W. A., Crépin, A.-S., Engström, G., Folke, C., Hughes, T. P., Kautsky, N., Li, C.-Z., McCarney, G., Meng, K., Mäler, K.-G.,

Polasky, S., Scheffer, M., Shogren, J., Sterner, T., Vincent, J. R., Walker, B., Xepapadeas, A., & Zeeuw, A. D. (2012). General Resilience to Cope with Extreme Events. *Sustainability*, *4*(12), 3248–3259. https://doi.org/10/f2zm4r

[9]. Coaffee, J., & Lee, P. (2016). *Urban resilience: Planning for risk, crisis and uncertainty*. Palgrave.

[10]. Collins, M., & Weisbrod, G. (2000). Economic Impact of Freeway Bypass Routes in Medium Size Cities. *Excerpt from Economic Impact of I-73 Alignments on Roanoke*.

[11]. Crucitti, P., Latora, V., & Porta, S. (2006). Centrality in networks of urban streets. *Chaos: An Interdisciplinary Journal of Nonlinear Science*, *16*(1), 015113. https://doi.org/10/bmq73k

[12]. DiGregorio, M., Thanh, N. T., & Trung, L. Q. (2018). *The Vietnam City Resilience Index*. Asia Foundation & The Rockefeller Foundation.

[13]. Elmqvist, T., Barnett, G., & Wilkinson, C. (2014). Exploring urban sustainability and resilience. In L. Pearson, P. Newton, & P. Roberts (Eds.), *Resilient Sustainable Cities* (pp. 19–28). New York: Routledge.

[14]. Feliciotti, A., Romice, O., & Porta, S. (2016). Design for Change: Five Proxies for Resilience in the Urban Form. *Open House International*, *41*(4), 23–30.

[15]. Feliciotti, A., Romice, O., & Porta, S. (2017). Urban regeneration, masterplans and resilience: the case of the Gorbals in Glasgow. *Urban Morphology*, *21*(1), 61–79.

[16]. Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. *Ecology and Society*, *15*(4).

[17]. Funderburg, R. G., Nixon, H., Boarnet, M. G., & Ferguson, G. (2010). New highways and land use change: Results from a quasi-experimental research design. *Transportation Research Part A: Policy and Practice*, *44*(2), 76–98. https://doi.org/10/b7k6dj

[18]. Garcia, E. J., & Vale, B. (2017). *Unravelling Sustainability and Resilience in the Built Environment*. Routledge. https://doi.org/10.4324/9781315629087

[19]. Gebremichael, D., Gebremichael, A., Worku, A., Abshare, M., Habtemariam, Y., Balcha, G., & Gebremichael, D. (2014). *Building urban resilience: Assessing urban and peri-urban agriculture in Addis Ababa, Ethiopia* (No. DEW/1781/NA). Nairobi, Kenya: UNEP.

[20]. Handy, S. L., & Niemeier, D. A. (1997). Measuring Accessibility: An Exploration of Issues and Alternatives. *Environment and Planning A: Economy and Space*, *29*(7), 1175–1194. https://doi.org/10/fsjkcf

[21]. Higgins, C. D. (forthcoming). Accessibility Toolbox for R and ArcGIS. *Transport Findings*.

[22]. Higgins, C. D., Nel, D., & Bruyns, G. (2018). Slope, Layers, and Walkability: Estimating the Link Between Pedestrian Accessibility and Land Values in the Morphology of High Density Cities. In I. Kukina, I. Fedchenko, & I. Chui (Eds.), *Urban Form and Social Context: from traditions to newest demands* (p. 214). Krasnoyarsk: Sib. Feder. University. Retrieved from http://conf.sfu-kras.ru/en/isuf2018

[23]. Hillier, B, Penn, A., Hanson, J., Grajewski, T., & Xu, J. (1993). Natural Movement: Or, Configuration and Attraction in Urban Pedestrian Movement. *Environment and Planning B: Planning and Design*, *20*(1), 29–66. https://doi.org/10/ffq6mm

[24]. Hillier, Bill. (2007). *Space is the Machine: A Configurational Theory of Architecture* (2nd ed.). Cambridge: Cambridge : Cambridge University Press. Retrieved from http://spaceisthemachine.com/

[25]. Kang, C.-D. (2019). Effects of spatial access to neighborhood land-use density on housing prices: Evidence from a multilevel hedonic analysis in Seoul, South Korea. *Environment and Planning B: Urban Analytics and City Science*, *46*(4), 603–625. https://doi.org/10/gddtg7

[26]. Kropf, K. (2017). *Handbook of Urban Morphology*. West Sussex: Wiley.

[27]. Marcus, L., & Colding, J. (2014). Toward an integrated theory of spatial morphology and resilient urban systems. *Ecology and Society*, *19*(4). https://doi.org/10.5751/ES-06939-190455

[28]. Marshall, S. (2005). *Streets and Patterns*. New York: Taylor & Francis. Retrieved from http://books.google.co.za/books?id=DyRr_3G6abQC

[29]. MTR. (2019, March 5). Train Trip Planner. Retrieved 3 May 2019, from http://www.mtr.com.hk/en/customer/jp/index.php

[30]. Nel, D., Bruyns, G., & Higgins, C. D. (2018). Urban Design, Connectivity and its Role in Building Urban Spatial Resilience. In I. Kukina, I. Fedchenko, & I. Chui (Eds.), *Urban Form and Social Context: from traditions to newest demands* (p. 214). Krasnoyarsk: Sib. Feder. University. Retrieved from http://conf.sfu-kras.ru/en/isuf2018

[31]. Nel, D., & Landman, K. (2015). Gating in South Africa: A gated community is a tree; a city is not. In Bagaeen & Uduku (Eds.), *Beyond Gated Communities* (pp. 203–226). London: Routledge. Retrieved from http://www.routledge.com/books/details/9780415748254/

[32]. Páez, A., Scott, D. M., & Morency, C. (2012). Measuring accessibility: positive and normative implementations of various accessibility indicators. *Journal of Transport Geography*, *25*, 141–153. https://doi.org/10/f4f4c5

[33]. Peres, E., Landman, K., & du Plessis, C. (2016). Unpacking a sustainable and resilient future for Tshwane. Presented at the Urban Transitions Global Summit, Shanghai, China: Procedia Engineering (under review).

[34]. Porta, S., Crucitti, P., & Latora, V. (2006a). The network analysis of urban streets: A dual approach. *Physica A: Statistical Mechanics and Its Applications*, *369*(2), 853–866. https://doi.org/10/dcxwhm

[35]. Porta, S., Crucitti, P., & Latora, V. (2006b). The Network Analysis of Urban Streets: A Primal Approach. *Environment and Planning B: Planning and Design*, *33*(5), 705–725. https://doi.org/10/fdncrn

[36]. Porta, S., Latora, V., & Strano, E. (2010). Networks in Urban Design. Six Years of Research in Multiple Centrality Assessment. In E. Estrada, M. Fox, D. J. Higham, & G.-L. Oppo (Eds.),

*Network Science: Complexity in Nature and Technology* (pp. 107–129). London: Springer London. https://doi.org/10.1007/978-1-84996-396-1_6

[37]. Porta, S., Strano, E., Iacoviello, V., Messora, R., Latora, V., Cardillo, A., Wang, F., & Scellato, S. (2009). Street Centrality and Densities of Retail and Services in Bologna, Italy. *Environment and Planning B: Planning and Design*, *36*(3), 450–465. https://doi.org/10/bfkx9v

[38]. Reggiani, A., Nijkamp, P., & Lanzi, D. (2015). Transport resilience and vulnerability: The role of connectivity. *Transportation Research Part A: Policy and Practice*, *81*, 4–15. https://doi.org/10/f7vsrh

[39]. Rodrigue, J.-P., Comtois, C., & Slack, B. (2013). *The Geography of Transport Systems* (3rd ed.). London, UNITED KINGDOM: Routledge. Retrieved from http://ebookcentral.proquest.com/lib/polyu-ebooks/detail.action?docID=1319001

[40]. Salat, S, & Bourdic, L. (2012). Urban Complexity, Efficiency and Resilience. In Z. Morvaj (Ed.), *Energy Efficiency - a Bridge to Low Carbon Economy* (pp. 25–44). Online: InTech. Retrieved from ww.intechopen.com/books/energy-efficiency-a-bridge-to-low-carbon-economy/urban-complexityefficiency-and-resilience

[41]. Salat, Serge. (2017). A systemic approach of urban resilience: power laws and urban growth patterns. *International Journal of Urban Sustainable Development*, *9*(2), 107–135. https://doi.org/10.1080/19463138.2016.1277227

[42]. Sevtsuk, A. (2010). *Path and place: a study of urban geometry and retail activity in Cambridge and Somerville, MA* (Thesis). Massachusetts Institute of Technology. Retrieved from http://dspace.mit.edu/handle/1721.1/62034

[43]. Sevtsuk, A. (2014). Analysis and Planning of Urban Networks. In R. Alhajj & J. Rokne (Eds.), *Encyclopedia of Social Network Analysis and Mining* (pp. 25–37). New York, NY: Springer New York. https://doi.org/10.1007/978-1-4614-6170-8_43

[44]. Sevtsuk, A., & Mekonnen, M. (2012). Urban network analysis. *Revue Internationale de Géomatique–n*, *287*, 305.

[45]. Sharifi, A. (2018). Resilient urban forms: A review of literature on streets and street networks. *Building and Environment*. https://doi.org/10/gd8gr2

[46]. Shelton, B., Karakiewicz, J., & Kvan, T. (2010). *The making of Hong Kong: from vertical to volumetric*. Routledge.

[47]. Sim, T., & Dongming, W. (2017). *Making Hong Kong a Resilient City: Preliminary Report*. Hong Kong: Hong Kong Polytechnic University. Retrieved from https://fhss.polyu.edu.hk/ext/makingHKresilientcity.pdf

[48]. The Hague, & AECOM. (2018). *The Hague 100 Resilient Cities: Preliminary Resilience Assessment*. City of The Hague, Netherlands. Retrieved from https://www.100resilientcities.org/cities/the-hague/

[49]. Tobler, W. (1993). *Three presentations on geographical analysis and modeling*. NCGIA.

[50]. UN Habitat. (2016). *Adopted Draft of the New Urban Agenda*. Quito, Ecuador. Retrieved from https://habitat3.org/the-new-urban-agenda

[51]. van Nes, A. (2002). *Road building and urban change: The effect of ring roads on the dispersal of shop and retail in Western European towns and cities* (PhD thesis). Agricultural University of Norway, Department of Land Use and Landscape Planning, Oslo.

[52]. Verma, A., Verma, M., Rahul, T. M., Khurana, S., & Rai, A. (2019). Measuring accessibility of various facilities by walking in world's largest mass religious gathering – Kumbh Mela. *Sustainable Cities and Society*, *45*, 79–86. https://doi.org/10/gfkwhm

[53]. Walker, B., & Salt, D. (2012). *Resilience thinking: sustaining ecosystems and people in a changing world*. Island Press.