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URBAN DESIGN, CONNECTIVITY AND ITS ROLE IN BUILDING URBAN SPATIAL RESILIENCE

Abstract: *Cities are increasingly being regarded as complex dynamic systems, coupled with the growing uncertainties for urban areas brought about by factors like global climate change, socio- political instability and limited resources. The necessity for cities to be adaptive and responsive to these concerns, while chasing the goals of sustainability has left many urban practitioners in a difficult position. Where they do not have the tools or conceptual frameworks available which place the factors of change and time as the central themes in how they plan cities. In response to this, resilience is becoming a prevailing framework, as the notion of adaptive change across spatial scales is a core characteristic of resilient urban systems. This has led many cities to pursue the development of resilient city strategies. Yet, many of these strategies often disregard the role that urban form plays in building resilience. To compound matters, resilience is an emergent property of a complex adaptive system. As such, it cannot be measured directly, it can only be indirectly inferred through a series of proxies. Connectivity is one of the few proxies related to resilience that is also commonly associated with urban morphology, design and regeneration. As part of a larger study, we look at the new field of urban spatial resilience by linking urban morphology to resilience through the notion of connectivity. We discuss how connectivity enables resilience through redundancy and hierarchic efficiency. We then discuss a few existing measures of connectivity which can be used to begin to engage with the morphologies of urban spatial resilience and how they can be used to gain insights into the resilience of the urban environment. The paper concludes by making some suggestions for interventions. However, any intervention into the urban form of a city should be undertaken incrementally to allow the city to adjust to changes while also allowing for experimentation within city spaces without disrupting the larger network.*

Keywords: *urban resilience, proxies, connectivity, urban morphology, urban design.*

Introduction

Cities are increasingly being regarded as complex dynamic systems, which are progressively facing growing uncertainties and becoming more vulnerable to factors like global climate change, economic fluctuations, socio-political instability and limited resources (Coaffee and Lee, 2016). These challenges are further compounded when considering that the world is expected to become more urbanised in the future, nearly tripling the current global urban area by 2030 (UN Habitat, 2016).

While looking back at the performance of urban areas built in the past 80 years, many urban professionals have begun to critique previous, modernist based, methods of city building (cf. Jacobs (1961); Nel and Landman (2015); Salat (2011)). Scholars have argued that these urban forms are unable to manage the increasing uncertainty and changing needs of the 21st century city (Feliciotti et al., 2015). These growing concerns have necessitated that cities become more adaptive and responsive to these challenges, while at the same time urban areas should still strive to attain the moving goals of sustainability.

The complexities of the issues facing urban areas in the future have left many urban practitioners somewhat baffled on how to proceed. This is because we currently do not have the

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tools or conceptual frameworks available which place the factors of *change* and *time* and *uncertainty* as the central themes in how cities are planned and designed (Feliciotti et al., 2016). For many academics and practitioners, urban resilience has become a prevailing framework to engage with these complex challenges (Coaffee, 2013). Thus, the acknowledgement of the need for urban resilience is a recognition that the future is going to be significantly different from what we have experienced in the past (Coaffee and Lee, 2016).

As part of a larger study, this paper seeks to begin to address some of these concerns by engaging with the spatial considerations of urban resilience through the lens of connectivity. To follow will be a brief outline of urban resilience and why it must be engaged spatially. This will be followed by a discussion of how connectivity builds resilience and how we might begin to capture resilience with spatial measures of connectivity. The paper will conclude with some possible implications for urban design and planning.

Urban resilience

Broadly speaking, urban resilience can be defined as the ability of a city to not just withstand and recover from disturbances, but to also learn from, adapt to and transform to changing circumstances while maintaining the functioning of the city at all scales (Barnes and Nel, 2017; Peres et al., 2016). This definition draws on the boarder evolutionary resilience approach, which shifts the focus of resilience from a static characteristic of a system (i.e. to resist a shock) to one that is more focused on resilience as a process of adaptation and transformation (Peres, 2016). Furthermore, the concepts and metaphors contained within resilience thinking place emphasis on uncertainty and bring new ideas that “break open sterile analyses and rigidly conservative interventions, so that we can see them afresh” (Porter and Davoudi, 2012, p. 329).

While there is a small but growing body of research into urban spatial resilience (cf. Baron and Donath (2016); Feliciotti et al. (2016, 2015); Landman and Nel (2017, 2013); Marcus and Colding (2014); Nel and Landman (2015); Olazabal et al. (2018)), there is still limited knowledge on how the spatial aspects of urban resilience manifest. As such, there is an urgent need for urban resilience to be questioned in terms of its morphological properties to identify the potential impact of urban form on the adaptive and responsive capacity of cities at all scales.

One of the difficulties of studying resilience is that it is an emergent property of a complex adaptive system (Folke, 2006). Meaning that the general resilience of a system cannot be directly observed, measured or created (Peres, 2016). Rather, it can only be inferred (for measurement purposes) or facilitated (to enable or create resilience) through a series of Surrogates (Carpenter et al., 2005) or Proxies (Feliciotti et al., 2016). Thus, for cities to be resilient we must encourage the properties and characteristics of complex systems that build adaptive capacity, thereby facilitating resilience to emerge (Peres, 2016; Salat and Bourdic, 2011).

Of the many different proxies that have been found to enable resilience, connectivity is one of the few that is frequently associated with urban morphology and design (Feliciotti et al., 2016). Additionally, connectivity is often strongly associated with the presence of other proxies that build resilience, such as diversity (cf. Feliciotti et al (2016); Porta et al. (2011)).

Connectivity and urban resilience

Cities are often described as complex networks from which locations emerge. These locations are created through the interactions within these networks (Batty, 2013; Salat, 2017). Thus, we are able to use the science of networks to study cities because it allows us to identify the hidden order beneath the structure of the city and plan with the complexity of the city (Porta et al., 2005).

The way that goods and information flow across a network is governed by the connectivity of the network and is often dependent on the structure of the connections, i.e. how the parts are connected, how many connections there are and the strength of these connections (Neal, 2013).

Connectivity can be defined as a measure of the minimum number network components (nodes or edges) which must be removed from a connected network to disconnect that network. Essentially, connectivity is a measure of the resilience of the network as “complex networks with high connectivity provide more routing choices to agents and are more robust against failure" (Boeing, 2017a, p. 73). Connectivity is required for building resilience in many ways, highlighted below are a few of the ways connectivity facilitates resilience. The focus of the discussion will be on how connectivity builds resilience through redundancy and hierarchic efficiency.

In terms of resilience, connectivity is a crucial parameter, as the lack of connectivity is often the cause of failure of particular functions after a perturbation (Ahern, 2011). Areas with low levels of connectivity can have several points of failure, thus leaving the system vulnerable. This can often be seen in "urban design through permeability and choke points: if circulation is forced through single points of failure, traffic jams ensue and circulation networks can fail" (Boeing, 2017a, p. 74). A multiplicity of connections not only protects a city from random failures through enhanced redundancy, which maintains functional connectivity after a disturbance, it also builds the capacity of the city to adapt and evolve 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 (Coaffee and Lee, 2016; Jacobs, 1961; Salat, 2011). However, over-connectedness is also not desirable as it leads to inefficiency, i.e. too many roads to maintain as well as using lots of space (Feliciotti et al., 2016).

Redundancy

Increased connectivity builds redundancy into the network. Redundancy can roughly be defined as a "diverse number of elements that can fulfil the same or similar functions" (Nel et al., 2018, p. 4). In the case of city movement network redundancy can be regarded as having a well-connected network with multiple alternative pathways should a path become blocked. Additionally, redundancy can be built into the city network by having multiple movement options in the form of multiple modes of transportation, the benefits of which are well documented (cf. Bertolini and Le Clercq (2003); Gallotti and Barthelemy (2014)).

A good metaphor of how redundancy allows the network to reorganise, thus building resilience, can be seen in the example of two leaves, shown in Figure 1. The Lemon leaf, which has a semi lattice structure, shows how nutrients can be redirected to all parts of the leaf even when the main artery is cut off, thus allowing the leaf to continue functioning. While in the ginkgo leaf, which does not have any network redundancy, the sections that have been cut off from the network die out as they are unable to receive any nutrients (Monroe, 2010). In the same way as the leaf, complex street networks with multiple connections, build resilience capacity through redundant circuitry, allowing the city to continue functioning even when parts of the network have been cut off (Ahern, 2011; Masucci and Molinero, 2016; Salat and Bourdic, 2012).

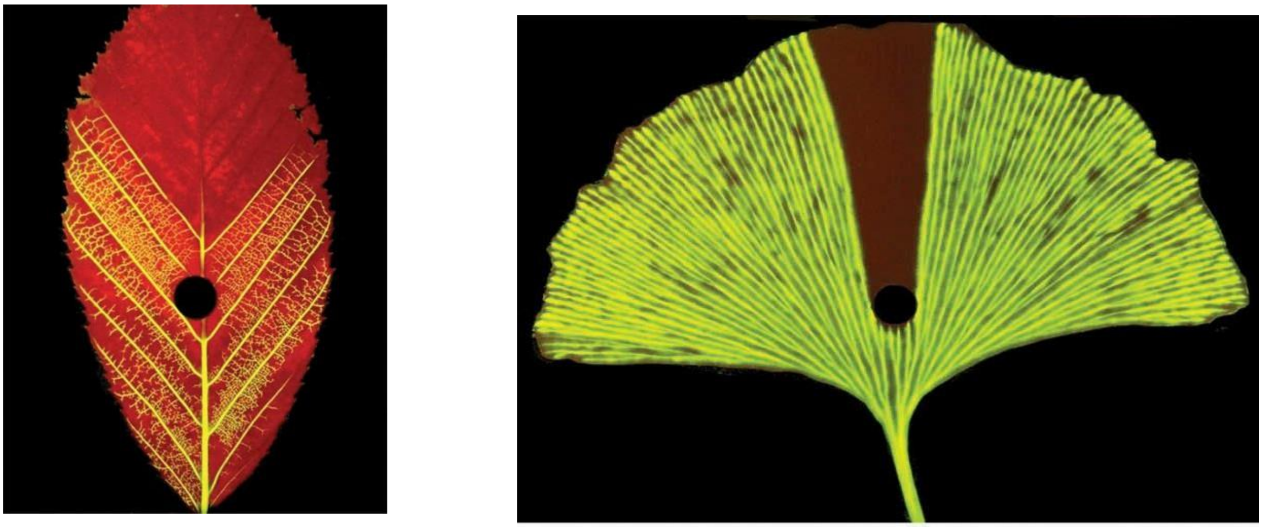

Figure 1. Lemon leaf (left) shows how nutrients can still be supplied to the leaf even when the main artery is cut off, while in the ginkgo leaf (right), the sections which have been cut off die out.
Image Source: E. Katifori, Rockefeller University

Hierarchic efficiency

While redundancy is essential for resilience, efficiency is also required. Efficiency refers to the optimisation of processes for maximum output. However, efficiency becomes problematic when it is used to address short term goals, typically on a single scale, and is attained at the expense of redundancy (Novotny et al., 2010) and diversity (Anderies, 2014). Worth noting, within "complex systems there is no optimal state and, due to scale interdependency, maximization of one element or process has unpredictable non-linear repercussions on others" (Feliciotti et al., 2016, p. 4). However, complex networks are very efficient hierarchic systems, while at the same time they also have sufficient amounts of redundancy and modularity, which facilitates resilience of the system (Batty, 2013; Salat, 2017, 2011).

The combination of efficiency and redundancy is created though the natural hierarchic organisation found within complex networks. This hierarchic nature corresponds to a scale free structure, which appears regardless of the network structure and internal dynamics. The scale free structure is a direct result of self-organisation within the network (Forgaci and Van Timmeren, 2014; Salat, 2017; Salat and Bourdic, 2012).

Additionally, the scale free structure implies a nested hierarchy, which is created though modularity, while also meaning that no one single scale can describe the entire network (Batty, 2013; Salat and Bourdic, 2012, 2011).

Simon (1962), by using the parable of the watchmakers, most eloquently illustrates how nested hierarchies are not only necessary for complex systems to function, they also facilitate a high degree of efficiency and redundancy through modularity. Batty (2013) further illustrates how hierarchies are a fundamental part of cities but also contribute to efficiency with cities. While Jiang (2009) shows how traffic patterns tend to follow a hieratic pattern, with 80% of traffic flows being located on 20% of the roads, and following a power law distribution. While this may not seem efficient, Jiang (2009) argues that it is in fact necessary, as all levels of streets are needed to connect the city.

Additionally, Masucci and Molinero (2016) noted how efficient cities road networks are when they compared them with the networks derived from a Delaunay triangulation network, of the original network's street intersections, as well as the network derived from the minimum spanning tree of the Delaunay network. They found that the cities which they tested, showed a relatively similar closeness centrality distribution to the Delaunay triangulation network while using comparatively far less road length.

There is a constant tension between redundancy and efficiency within the resilience debate (Feliciotti et al., 2016; Salat, 2017), as the street networks of many cities, especially those built more recently, have been primarily built with efficiency in mind, specifically motor vehicle efficiency. Yet, for cities to be resilient they also require redundancy (Salat, 2011). From the above discussion we can see that well connected complex networks are not only desirable, for their redundancy properties, their flows also tend to a power law distribution which enables them to be efficient at all scales. The next section begins to explore some of the metrics of connectivity that enable us to begin to engage with the morphologies of urban spatial resilience.

Metrics of connectivity

While the previous section has discussed how connectivity is one of the prerequisites for urban resilience, the question now is how to engage with the morphological aspects urban *spatial* resilience though connectivity, without having to develop a myriad of new methods. A promising line of enquiry can be found in Graph Theory, also called Network Theory. Graph Theory is the mathematical study of networks and has been applied to urban context by various authors (cf. Batty (2009, 2013); Boeing (2017b, 2017a); Bourdic et al. (2012); Hillier (2007, 1999); Porta et al., (2006)). This discussion into urban network analysis will draw on this knowledge and is divided into two parts. The first considers the global or overall properties of the network. The second investigates the internal elements of the network and describes their relative importance.

Each of the metrics will be briefly described after which their implications for resilience will be discussed.

Global network metrics

Global network metrics describe the properties of the entire network, also called a graph, and can provide insights into the resilience status of the overall network, or parts of it, and allow us to compare networks with each other (Rodrigue et al., 2016). These metrics are typically applied to the link/edge (i.e. road) node/vertex (i.e. road intersections) elements of networks. This section will give a brief description of a few metrics as well as some initial thoughts what these metrics can tell us about resilience. Each of the metrics has a corresponding formula which can be seen in Table 1.

The **Beta Index**, also known as the link node ratio, is the most basic measure of network connectivity. It is a measure of the relationship between the links and the nodes within a network and tells us how connected a network is (Boeing, 2017a). Disconnected, tree type networks tend to have a beta score of less than 1. A simple network with one cycle/loop, for example, has a beta value of 1, while complex networks have a score greater than 1 (Rodrigue et al., 2016). In terms of resilience, this measure begins to describe the number of connected links (or roads) within the network. A low beta value will indicate an urban network structure that is more typical of a tree-like structure, with many dead ends, and little redundancy. This metric is also one of the indicators for how walkable an area is.

Where the beta index tells us the ratio of links to nodes in the observed network, the **Gamma Index** indicates the extent to which the observed network resembles a fully connected graph, where every node is connected to every other node (Sevtsuk, 2014). In short, the gamma index is the ratio between the observed number of links and the maximum number of possible links. The gamma index ranges from 0 to 1, where 1 indicates a completely connected network. The higher the value the more directly and easily it is to move through the network, from intersection to intersection (Rodrigue et al., 2016; Sevtsuk, 2014).

The **Cyclomatic Number** provides an indication of the redundancy within the network. Instead of indicating the number of unique routes, the cyclomatic number is an index that indicates the number of possible loops or alternative routes within the network. It is a good way to measure the redundancy within a network or sub-network (Bourdic et al., 2012).

In terms of road layouts, a grid with four blocks will have four closed loops (Figure 2), while a tree like network which has many cul-de-sac’s will not have any loops (Figure 3). Treenetworks only have one shortest path between all the nodes. This type of tree layout is often seen within typical suburban layouts. While tree types of layout are more efficient and require fewer roads to connect places, they are very hierarchical and greatly limit travel options (Salat, 2011; Sevtsuk, 2014). Areas with low cyclomatic numbers are more vulnerable to random failure as there are more circulation chokepoints, which force movement though single point in the network and if there is any disturbance in one of these points the entire network fails (i.e. when an accident happens on an important road and the entire area is gridlocked). On the other hand, an area with a high cyclomatic number is more permeable, which results in a higher redundancy within the network. This allows the network to respond to changing circumstances better, thus improving the overall resilience of the area (Bourdic et al.,2012).

Building on the idea of the cyclomatic number, the **Redundancy Index** is additional measure of network choice. The redundancy index is the ratio between the number of cyclomatic number and the maximum cyclomatic number and indicates how vulnerable the network is to divisions (Sevtsuk, 2014). If the index is zero, then the network can be described as consisting of a collection of tree networks. While if the index is one, the network is completely connected with a multitude of possible paths open in case one or more paths fail. The redundancy index is a useful metric for questioning network resilience as it allows us to quickly calculate how vulnerable the global or sub-network network is if certain sections of it were to be removed, say through an accident or natural disaster.

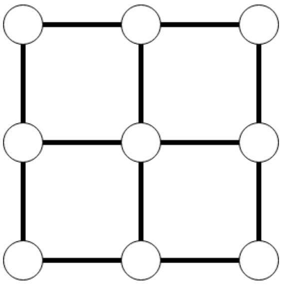

Figure 2.Anurbangridoffourcityblocks:where e = 12; v = 9; Gamma Index = 1/3; Cyclomatic Number=4;MaximumCycles=28;Redundancy Index = 1/7. Source Sevtsuk(2014)

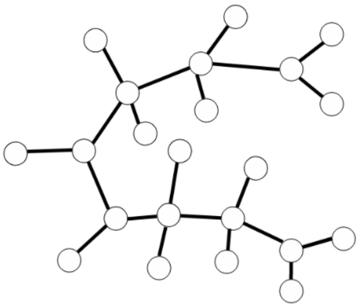

Figure 3. A tree type network: where e = 21, v= 22. Gamma Index ≈ 0.09; Cyclomatic Number = 0; Maximum Cycles = 210; Redundancy Index= 0. Source Sevtsuk (2014)

The global network metrics describe various properties of the entire network. These metrics must be interpreted with care as they are aggregated indicators, indicative of the entire network and do not allow for identification of specific areas within the network which may be more or less vulnerable. To begin to investigate these types of question we must look to alternative metrics which can provide us with more information about the individual components of the network.

Table 1

Global Network Metrics

Metric	Formula	Source
Betaindex	$Betaindex(\beta) = \frac{e}{v}$	(Rodrigue et al.,2016)
GammaIndex	$GammaIndex = \frac{e}{\frac{v^2 - v}{2}}$	(Rodrigue et al., 2016)
CyclomaticNumber	$CyclomaticNumber(\mu) = e - v + g$	(Sevtsuk,2014)
Maximum number of cycles	$Max: Cycles = [\frac{(v^2 - v)}{2}] - (v - 1)$	(Sevtsuk, 2014)
RedundancyIndex	$RedundancyIndex = \frac{e - v + g}{[\frac{v^2 - v}{2}] - v + 1}$	(Sevtsuk, 2014)

Note: e is the number of links; v is the number of nodes; g is the number of connected nodes (excluding cul-de-sac).Indexesofdifferentareascanbecomparedwitheachotherprovidedtheyarenormalised(i.e. μ/Km^2).

Internal network metrics

While the global network metrics allowed us to compare networks with each other, the internal network metrics allow for the comparison different elements within the network and how well they are connected to each other. This allows us to identify specific links or nodes which may be vulnerable. It also allows us to identify areas which may need intervention to improve the connectivity of the larger area.

Internal network metrics use centrality and access measures identify the most important nodes or links within a network (Zhong et al., 2014). A few of the most common measures will be discussed in this section. These measures are typically found within urban spatial network analysis software such as Space Syntax (Hillier (2007)), sDNA [Spatial Design Network Analysis] (Cooper and Chiaradia, (2015)) and UNA [Urban Network Analysis toolbox] (Sevtsuk and Mekonnen, (2012)). The relevant formulae for these metrics can be seen in Table 2.

Table 2

Internal Network Metrics

$C^{r}[i]=\frac{l}{\sum_{j\in G-\{i\};d[i,j]\le r}(d[i,j]\cdot W[j])}$	$C^{r}[i]=\sum_{j\in G-\{i\};d[i,j]\le r}\frac{W[j]}{e^{\beta.d[i,j]}}$
$C_R^{r}[i]=\sum_{j\in G-\{i\};d[i,j]\le r} W[i]$	$C^{r}[i]=\sum_{j\in G-\{i\};d[i,j]\le r}\frac{n_{jk}[j]}{n_{jk}}\cdot W[j]$

Note: $C_C$is Closeness Centrality; C_R is Reach Index; C_G is Gravity Index; C_B is Betweenness Centrality.

i:locationastheorigin;j:destinationlocation;G:network;r:networkradius;d[i,j]:shortestnetworkdistance 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 andk;Beta(β):decayparameterforunits;W[j]:weightoflocationj.Source:modifiedfromSevtsukand Mekonnen (2012) and Kang (2017)

Closeness Centrality, also called integration in Space Syntax (Hillier, 2007), measures the average distance between nodes/links to all other nodes/links along the shortest path (Crucitti et al., 2006; Porta et al., 2006), and is described as “the inverse of the total distance required to reach from i to all surrounding destinations j within the given access radius r”(Sevtsuk, 2014, p. 34). In short, it is an index which tells us how near a location is to any other location and is a useful measure of the relative proximity of a place within the city (Boeing, 2017a), or smaller area when a radius/distance metric is applied to the analysis (Sevtsuk and Mekonnen, 2012). A lower closeness value (weighted or unweighted) indicates that a location has a denser and better connected network than a higher value (if weighted) within a given radius (Kang, 2017). Moreover, as discussed previously, it is possible to speculate about the efficiency of the network as compared to its fragility by comparing the closeness centrality distribution of the network with the closeness centralities derived from a Delaunay triangulation network of original networks the street intersections as well as the network derived from the minimum spanning tree of the Delaunay network (Masucci and Molinero, 2016). Masucci and Molinero argued that the “ratio σ between the total length of the street network and the total length of its Delaunay triangulation as an intuitive measure of the street network efficiency in the primal space” (Masucci and Molinero, 2016, p. 5).

While closeness centrality tells us how close a location is in relation to other locations, the **Reach Index** measures the number of locations that can be reached within a given radius, along the shortest path (Sevtsuk and Mekonnen, 2012). When this metric is weighted per location, i.e. number of people per building, then this metric allows for the calculation of the number of attributes (i.e. people) can be reached within the specified network distance from every location within the network. The reach index is a good measure of access and choice, and allows for the assessment of variation in access within the city (Marcus and Colding, 2014).

The **Gravity Index** builds on the reach index by adding a spatial impedance factor to measure how many locations are accessible within a given distance. The gravity measure considers that accessibility to a location is proportional to the weight (attractiveness) of the destinations surrounding the location and is inversely proportional to the network distance between the location and the destination (Sevtsuk, 2014). The gravity index uses a distance decay function, also called distance friction and denoted as β (beta), to manage the effect of the distance decay along the shortest path. The gravity index shows the attractiveness of a destination as well as the distance or effort required to reach that destination into a single value (Kang, 2017; Sevtsuk, 2014). Additionally, the gravity index is a useful for significant predictions of land-use change (Kang, 2017).

Betweenness Centrality (Choice in Space Syntax), is an indicator which shows the number of shortest paths that pass through a location and is used estimate the “ease with which a location can be accessed *en route* while travelling between other locations” (Sevtsuk, 2014, p. 34 [emphasis in original]). Betweenness is also a good predictor of traffic flow along a path (Rodrigue et al., 2016). The maximum betweenness centrality of a network, which shows the proportion of shortest paths that pass through the most important locations, is also a good indicator of network resilience, as networks with high maximum betweenness are more likely to experience inefficiency or failure should an important link/node be disrupted (Boeing, 2017a).

Conclusion and implications for design

As part of a larger study (cfNel (2018)), the above discussion has engaged with the new field of urban spatial resilience by making the link between resilience and connectivity as well as providing a few measures which can be used to begin to engage with the morphologies of urban spatial resilience. We argued that connectivity is not only a prerequisite needed for the creation of complexity, it is also one of the essential elements required for resilience to emerge. Connectivity dictates the way that goods and information flow and interact. While a lack of connectivity is often the reason some functions fail after a perturbation (Neal, 2013). A multiplicity of connections is thus needed, as it creates network redundancy, which helps to maintain urban functions after a disturbance. Additionally, improved connectivity facilitates the adaptive capacity of a city by improving the potential for interactions and facilitating spaces to reorganise more easily, should the need arise (Salat, 2011). While redundancy is a prerequisite for resilience, efficiency is also needed. No single scale should be optimised over another as this can lead to disjuncture between the various scales. Rather, complex systems achieve efficiency all scales through scale hierarchic organisation of elements that follow power law distributions (Feliciotti et al., 2016; Forgaci and Van Timmeren, 2014; Salat and Bourdic, 2012). This type of distribution means that the same level of complexity is achieved at all scales (Feliciotti et al., 2016).

While one of the main aims of resilience is to enhance the adaptive capacity of a complex system, we must also take care that the system does not become overwhelmed by its own adaptive capacity as we seek to mitigate negative situations (de Roo and Rauws, 2012). For us, connectivity can play a key role in enabling resilience and enhancing the cities adaptive capacity as it manages how element of the city interact at different scales.

However, when designers do intervene we should rather “ascribe to Darwin’s message that it is small changes, intelligently identified in the city fabric, rather than massive, monumental plans, that lead to more successful, livable, and certainly more sustainable environments” (Batty, 2013, pp. 246–247). We suggest that urban design should approach intervention in the city from an incremental approach, targeting modules within the city, and not proposing broad interventions. This allows the city to adjust to changes while also allowing for experimentation within city spaces without disrupting the larger network.

Some possible directions for interventions which alter the connectivity include changing the direction of travel of a street (two way road to one way), changes in mode of travel (bus only lane or pedestrian zone), having multiple modes of travel (car, bus, train, walking) available, providing new and alternative paths (creating raised walkways between areas, as can be seen in sections of Hong Kong) or changing the 'friction' or 'strength' of a link (reduce speed or widen or decrease road widths). More extreme measures may include adding or completely removing connections in parts of cities. However, more research is needed in this field to test and confirm if these approaches are indeed useful.

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