BIRKHÄUSER

DE-CODING THE CITY

How Big Data Can Change Urbanism

Dietmar Offenhuber, Carlo Ratti (Eds)

Andres Sevtsuk

Networks of the Built Environment

"Cities happen to be problems in organized complexity," commented Jane Jacobs on the ballet of daily life on Manhattan's Hudson Street in the 1960s. "The variables are many, but they are not helter-skelter; they are 'interrelated into an organic whole.'" (Jacobs 1969, 433) Jacobs was reacting to the prevailing urban design discourse of her day, which claimed to bring order to complex social life through formal interventions. The problem was, Jacobs argued, that architects and planners had a poor understanding of the social and economic interactions that take place in dense urban environments and their interventions were therefore disconnected from the real needs of a place. Further, it was not clear to what extent the form of the environment played a role in their success at all, since the activities of Hudson Street were shaped by numerous cultural, historical, and geographic factors beyond form.

"How much a park is used depends, in part, upon the park's own design," Jacobs remarked. "But even this partial influence of the park's design upon the park's use depends, in turn, on who is around to use the park, and when, and this in turn depends on the uses of the city outside the park itself. Furthermore, the influence of these uses on the park is only partly a matter of how each affects the park independently of the others; it is also partly a matter of how they affect the park in combination with one another, for certain combinations stimulate the degree of the influence from one another among their components. [...] No matter what you try to do to it, a city park *behaves* as a problem in organized complexity, and that is what it is." (Ibid., 433–434)

Fifty years forward, the challenge of describing and analyzing complex spatial interactions in the built environment still remains one of the central challenges for urban design (Batty 2005). It would be naive to suggest that urban designers lack the interest or the willpower to delve into the social organization and invisible forces that shape places in contemporary cities. On the contrary, there is ample evidence that investigating the workings of diverse and heterogeneous urban environments in detail is widely popular (for example, Belanger et al. 2001; Rienets, Siegler et al. 2009; Busquets 2006; Sorkin 2009).

Some critics have suggested that developing a better understanding of the interactions between social processes and urban form is also hampered by designers' limited education in social sciences. A number of urban sociologists have alerted urban designers to remain wary of what Webber has called "some deep-seated doctrine that seeks order in some simple mappable patterns, when it is really hiding in extremely complex social organization instead" (Webber 1963, 54). While it is true that most designers are not trained in qualitative and quantitative methods of social analysis, there is also a rich body of literature within as well as outside of the urban design field to offer rigorous examples of good social analysis that uncover the complex interaction between the physical configuration of space and its occupancy patterns (Gehl 2010; Whyte 1980; Peattie 1968; Gans 1962). The studies demonstrate that what might appear as complexity to an outsider typically conceals order that remains yet to be uncovered or, as Jacobs put it, organized complexity.

In this chapter we argue that managing spatial and social analysis of complex urban environments is not only challenged by research methods and analytic skills needed to describe and investigate the interactions between the form and function of a place, but also by the conventions of spatial representation in which the problems under study are depicted. We argue that the most pervasive medium for describing the built environment – the plan – comes with certain limitations that make it difficult to use for studying complex spatial interactions between different users of a neighborhood. Every built environment contains a spatial order, which determines relationships of proximity and adjacency between different buildings, public spaces, and routes that connect them. These relationships influence how different circulation routes are utilized, how visible or connected public spaces are, or how conveniently buildings are located with respect to one another. These spatial patterns, in turn, determine what places are better or worse for particular land uses, which public spaces different building tenants routinely encounter, and how the activities of one space might influence the others. We suggest that a network representation of the built environment offers an effective framework for capturing and operationalizing such relationships of urban form.

The plan – a two-dimensional depiction of the form, and sometimes of the functions of a built environment – remains the best known and the most utilized medium of spatial representation among designers and scholars of the city (Conzen 1960; Moudon 1986; Anderson 1993). Plans are powerful tools that convey spatial information in ways that are readily comprehensible to professionals across disciplines. Yet plans can be misinterpreted, and the rich variety of content and meaning they contain is easy to miss (Mandelbaum 1990; Hoch 2002; Ryan 2011). Perhaps most important for the study of complex urban environments, plans store a wealth of information on the built environment, but leave all interrelationships of proximity, adjacency, and interconnectivity between its various elements to be gauged and interpreted by the eyes of a reader. Plans do not embody explicit information about the connections between its elements (e.g., streets, buildings, institutions, etc.); these connections need to be estimated visually by inspecting what is connected to what, how, and why. Put alternatively, plans are rich in elements of the built environment, but poor in conveying the interrelationships between these elements; the quality of their analysis is consequently largely dependent of the quality of their analyst.

Reading spatial relationships from a plan is possible, but labor-intensive and far from trivial. While one-to-one relationships are generally easy to read from a plan – reading a route from a subway station to a particular building is relatively simple – doing the same for one-to-many relationships can be complicated. Gauging the relationships from a subway station to all possible buildings that are located within a ten-minute walk along the available pedestrian routes is not trivial and takes time. Yet this might be an important criterion for deciding the location for a new station. Add to that the constraints of street crossing (e.g., traffic lights, underpasses), a narrowed focus on only buildings of a particular use category (e.g., only residential buildings) and the different sizes of the buildings (e.g., the number of dwelling units in each building) and we quickly arrive at a complex problem that is hard to digest. Business owners choose locations according to access to their clients or suppliers, residents according to nearby amenities, and municipal infrastructure investments are more likely to be approved for more utilized sites. Such relationships are important to understand if planned environments are to attract their desired users and public spaces their desired activity patterns. Gauging how the built environment might impact such decisions from a plan is difficult and requires multiple sets of spatial relationships to be read simultaneously. Doing it fast enough to keep pace with an urban designers' thought process is even more challenging. Human brains tend to operate in a serial manner and are quite poor at processing multiple parallel computations simultaneously (Minsky 1988). The reader may try, for instance, to memorize two or three limited sets of numbers simultaneously. An analysis of spatial relationships in real urban environments may necessitate a processing of hundreds or thousands of such relationships in parallel.

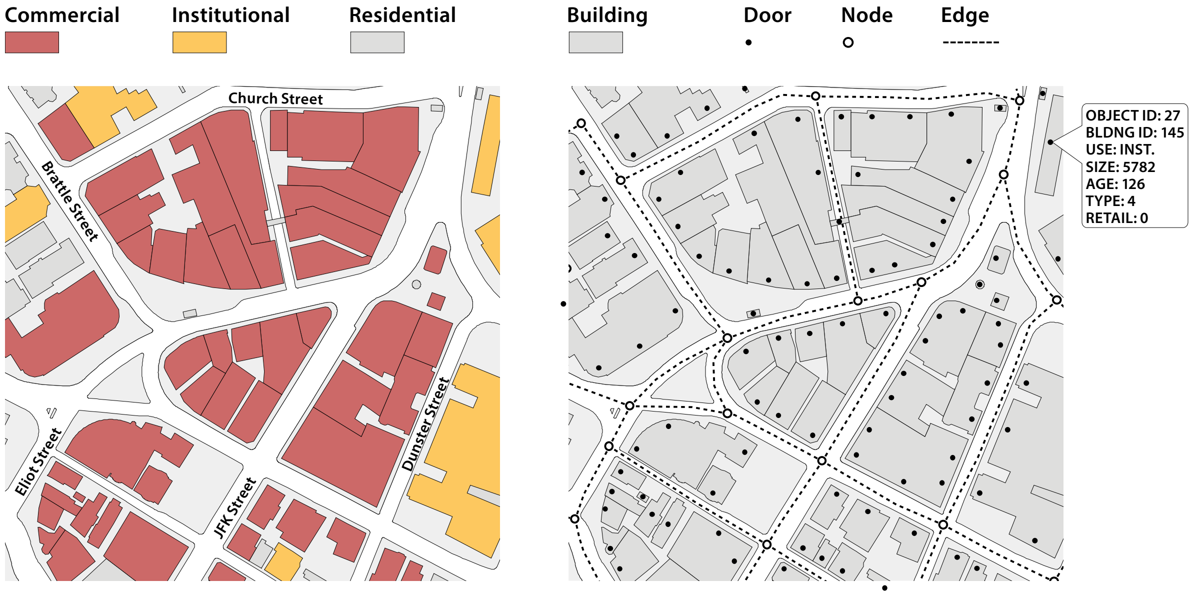
In order to represent and analyze such complex spatial relationships, urban designers and planners have started to use network-based models of the built environment. Unlike traditional plans, network-based representations of urban space encode explicit relationships between the elements of the network, documenting, for instance, how streets are connected to one another, how long the travel times between different districts, buildings, or rooms are, or how many people commute between them. Such linkage information is typically stored in one of two ways. First, it can be stored in a full origin-destination (O-D) matrix, where every element of a plan (e.g., zone, street segment, building, firm, etc.) is shown in a data column next to every destination, and a separate column is used to indicate the desired linkage information about each such connection. The linkage column may contain any kind of connectivity information, such as travel time, the amount of workers commuting between the origin and destination, the amount of economic inputs or outputs exchanged between them, and so on. This approach is relatively easy to analyze using database queries that can retrieve the desired spatial relationships between a set of origins and destinations. But this convenience comes at the cost of information storage – representing relationships between all individual location pairs in a separate table row requires very large tables, which grow as a square of the number of observations. For only 100 locations, the number of connections is 10,000. If all the relationships are symmetrical, that is, if connections from A to B have the same characteristics as those from B to A, then the table can be reduced to half the size. But with tens of thousands of locations, it may still be too large to analyze.

The second, more economical, approach is to represent all spatial relationships with an adjacency matrix. An adjacency matrix does not summarize the information about the full routes between each related location pair in the environment, but instead only stores the immediate neighbor adjacencies for each location. If the environment is modeled as a network of neighborhoods, then the adjacency matrix would capture each neighborhood's relationship to only its immediately adjacent neighborhoods. If the environment is modeled as a network of buildings and streets, then the adjacency matrix would capture each building's relationship to only its immediately adjacent buildings along the street network. Useful network analysis algorithms can then query this information and infer the full spatial relationships between all elements of the network from this shorter table. Querying the adjacency matrix requires more advanced algorithms than querying a full O-D table, but a lot less storage space. Contemporary algorithms for processing such tables allow vast spatial interactions to be analyzed in seconds (Vanegas et al. 2009).

There are a number of different ways of representing such information in networks and tables. What is important, however, is not so much the precise form of the network representation used – centered on land-use or urban form (Bhat et al. 2000), using actual network routes or as-a-crow-flies connections (Anselin 1988), primal or dual network representations (Hillier 1996; Porta et al. 2005), two-element or three-element networks (Sevtsuk 2010) – but the fact that spatial relationships in a given environment are depicted numerically, such that all desired linkages between places are explicitly encoded in a relationship table. These spatial relationships may depict connectivity in terms of traffic, material, information, or financial exchange. This is a major departure from traditional plans that has occurred quietly for most urban designers and physical planners during the past decade. Instead of requiring the reader of a plan to infer complex spatial relationships embedded in the environment visually and intuitively, network-based representations encode such information explicitly and allow the user to access large combinatorial summaries of spatial connections on the fly. Network models automate the analysis of numerous parallel relationships in urban space and allow the analyst to use that information in urban design decision making almost instantaneously. This is profoundly changing how we describe and analyze complex urban environments, paving a way for more informed decision making in real-world planning problems.

In the following we describe one of such models – the Urban Network Analysis Toolbox – developed at the City Form Lab (Sevtsuk and Mekonnen 2012). There are many other network-based approaches to describing built environments; we use the one we have developed to illustrate the more general functionality of network representations of urban space (Levin 1964; Casalaina and Rittel 1967; Rittel 1970; Tabor 1970; March and Steadman 1971; Hillier 1996; Porta et al. 2005; Xie and Levinson 2007; Okabe and Sugihara, 2012; Miller and Wu, 2000; Jiang and Claramunt, 2002 ; Peponis and Bafna, 2008; Vanegas et al. 2012).

The Urban Network Analysis Toolbox – an open-source and free plug-in for ArcGIS – models the built environment using three basic elements: edges, representing paths along which travelers can navigate; nodes, representing the intersections where two or more edges intersect; and buildings, representing the locations where traffic from streets enters into indoor environments or vice versa. Buildings can be replaced by any other point locations on



Origin	Destination	Distance	Transactions
1	2	242	3
1	3	11	0
1	4	95	0
1	5	141	1
2	1	56	2
2	6	136	8
2	7	25	0
3	9	12	0
3	11	85	0

Fig. 1.
Left: **Plan representation of Harvard Square**
Right: **Network representation of the same area, with an adjacency matrix below**

the network: public spaces, transit stations, utility facilities, etc. Our unit of analysis thus becomes a building (or other location identifier on the network), enabling the interrelationships to be computed separately for each building.

Each building, street, and intersection carries an additional set of attributes describing its real-life properties. These attributes, stored in another table, can describe any measurable properties of these elements: for buildings, their size, height, establishment mix, demographic occupancy, etc.; for streets, their directionality, traffic capacity, sidewalk characteristics, etc. The weighted representation of interconnected elements opens up a range of possibilities for studying different kinds of spatial relationships between buildings in a network of city streets. This network representation framework is illustrated in figure 1. The left side of the figure presents a fragment of Harvard Square in Cambridge, Massachusetts, in a plan drawing, with color-coded land uses. The same plan drawing is shown as a network on the right. Each building in the network is connected to its nearest circulation path at a discrete location – its entrance doors in this case. Note, however, that a building can have several doors and connections to the network.

A network representation of both form and function of an area provides a basis for complex spatial analysis. The three elements of urban form describe the physical pattern of urban infrastructure – the two- and three-dimensional geometry of built form and its circulation routes, the shape of public space, and paths that connect them. Using attributes within these categories allows us to further differentiate the parameters of these elements – building volumes, the spacing or placement of buildings with respect to circulation spines, the capacity or direction of routes, etc. Table attributes also allow us to describe the functions of each element – which activities are located where, how many people they accommodate, and how the activities connect with one another. Activities are typically categorized into loose groupings, such as living, working, or playing spaces, but they can also change from one activity to another or intensify in use depending on time of day or day of week. Together, such indicators aggregate into a complex description of a place, where everything can be related to everything else around it (Tobler 1970). The relationships are not helter-shelter, they are explicitly encoded into the adjacency matrix and attribute table, organized by the analyst. Let us now look at the Bugis area in Singapore to apply this type of a representation on a real, complex urban environment.

Bugis is located in downtown Singapore, encompassing an area of roughly a square kilometer. It is a historical area that was developed as part of the Raffles Plan and covered through the nineteenth and early decades of the twentieth centuries with traditional shop houses. Since the 1960s, the area has been gradually redeveloped with multistory deep-floor-plate commercial structures that accommodate a vast, heterogeneous mix of activities.

Figure 2 illustrates an interior view of Bugis Street, a multistory bazaar of hundreds of small retail and food businesses located at the center of the area. There are a total of more than 4,000 individual businesses including 1,769 retailers, 559 service providers, 519 eating and drinking establishments, 130 offices, 38 hotels, 24 educational institutions, and 19 entertainment facilities within an area of roughly 0.8 square kilometers around the Bugis Mass Rapid Transit (MRT) station. Bugis is one of the busiest, and indeed most complex urban environments in Singapore.

Fig. 2.
Interior alley of Bugis Street in Singapore

The area was surveyed by researchers of the City Form Lab in fall 2012, who recorded every door, building, and business, along with their size, use category, and a few other economic characteristics. The survey covered all publicly accessible floors in the area, with roughly half of the businesses on the ground floor and the other half on the upper floors or underground. The researchers also documented the entire pedestrian path network in the area, both indoors and outdoors, on grade, above and below grade – observing over 32 linear kilometers of walking paths within less than a square kilometer of land: 35 percent of these paths were outdoors, 26 percent outdoors but covered (e.g., arcades), and 37 percent were indoors on various levels. **Figure 3** shows this information encoded in a network. The red dots indicate individual businesses, the gray lines the pedestrian paths, and the black lines the ground-floor structural building walls.

We demonstrate network analysis of this area using two types of spatial connectivity indices: Betweenness and Reach (Sevtsuk and Mekonnen 2012). The first involves foot-traffic prediction in different parts of the site; the second models accessibility to food establishments.

In order to estimate where and how people might be walking in different parts of this area, we looked at walking routes from the MRT station to retail destinations in the whole area. According to interviews on site, a large part of the crowd in Bugis comes there to shop by MRT. We based the analysis on the assumption that

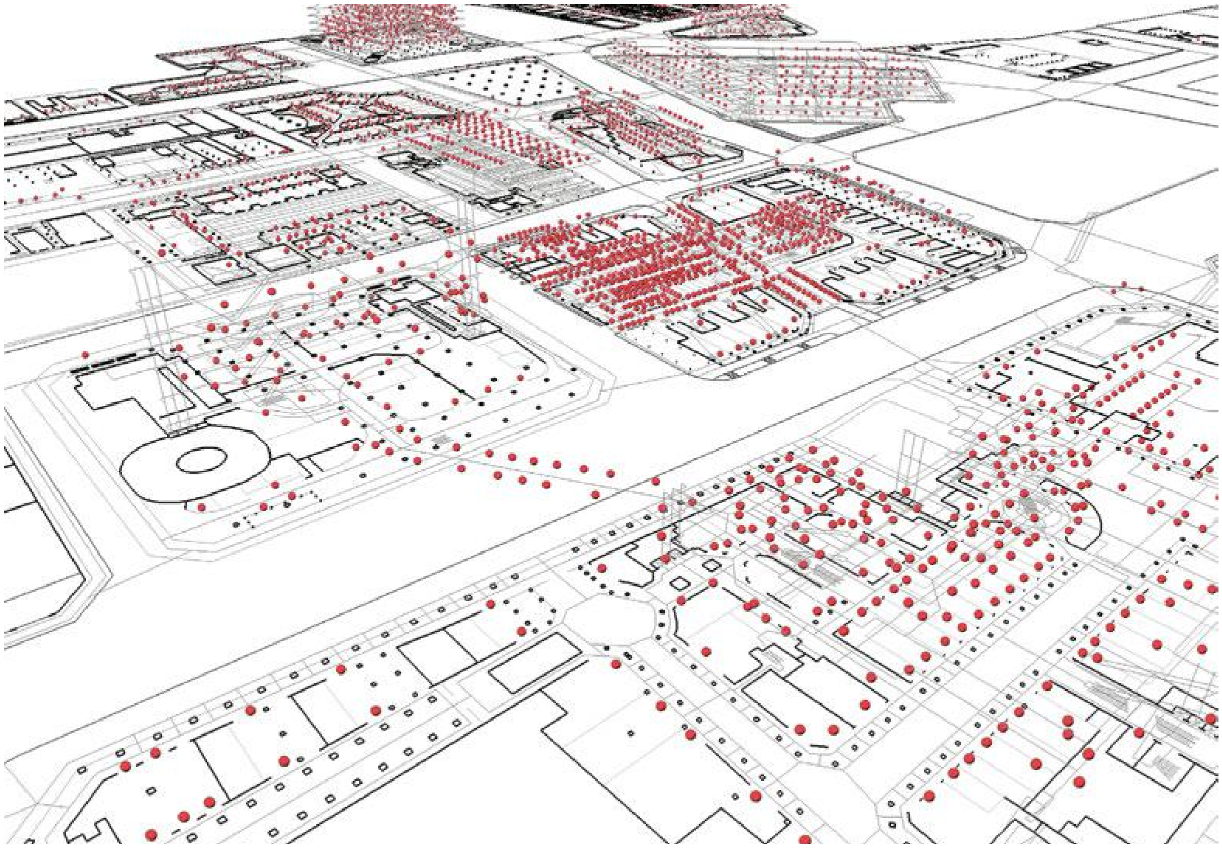


Fig. 3.
Three-dimensional network representation of the Bugis area in Singapore

a walking trip is made from the Bugis MRT station to each of the 1,769 retail establishments in different parts of the site along the shortest available path. We modeled all these paths using Betweenness analysis in the UNA Toolbox and kept track of which network segments are most trafficked in the process. The Betweenness metric thus captured the number of estimated passersby at each network segment who walk from the MRT station to a retail destination along the shortest paths.

Figure 4 shows the results, color-coding the footfall from green to red as the traffic increases. We find the highest expected pedestrian activity in Albert Mall, Bugis Street, and Bugis Junction – all major shopping destinations in the area. There is also a peak of activity near Arab Street and Haji Lane, both historical streets, lined almost continuously with stores in old shop houses. Each of these places is indeed crowded in reality (figure 2). Perhaps more important, network analysis allows us to predict not only general areas of activity concentration, but even particular

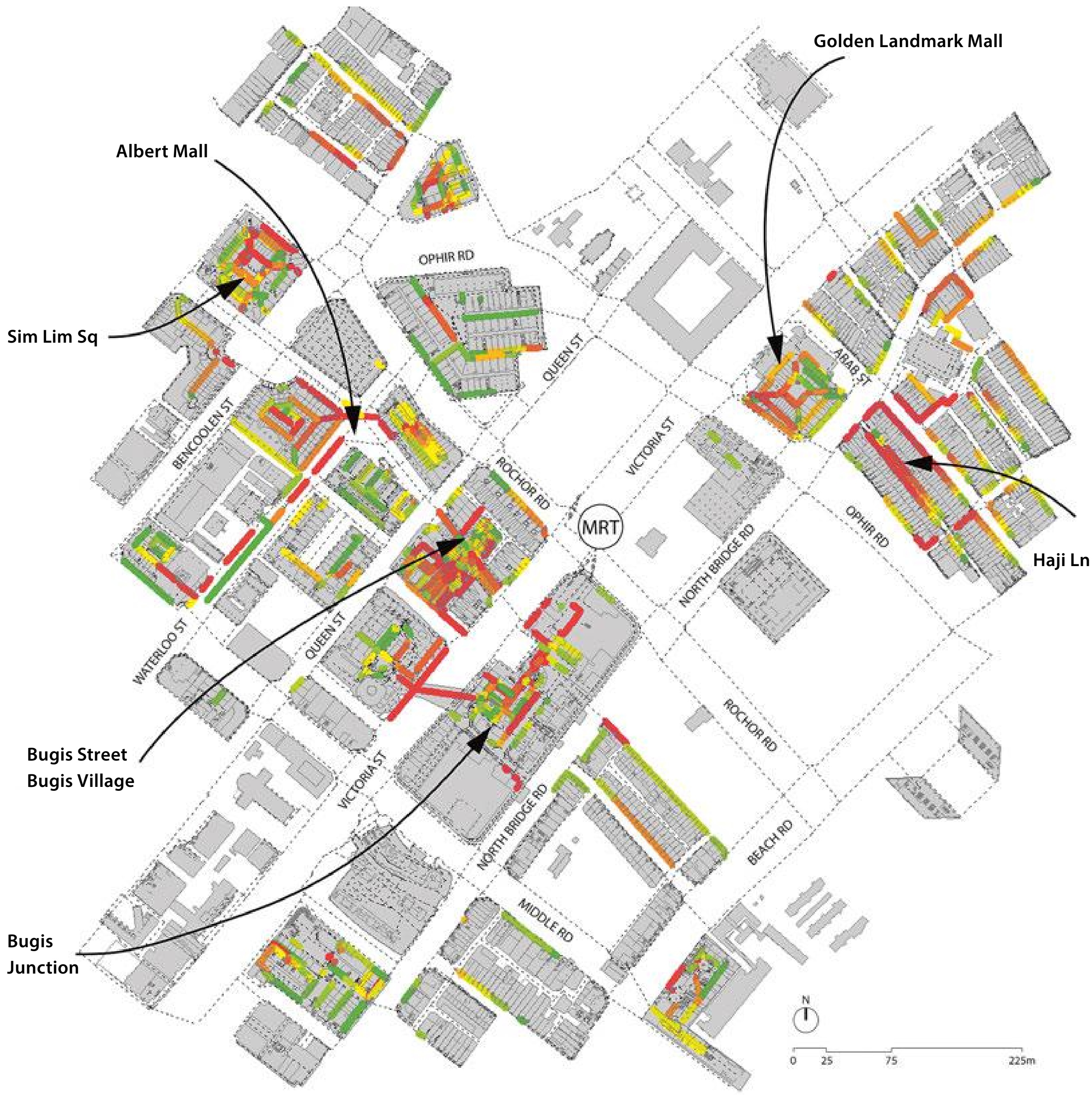


Fig. 4.
Betweenness analysis, indicating expected pedestrian traffic from the Bugis MRT station to all individual retail destinations in the area

Number of food establishments within 200 m

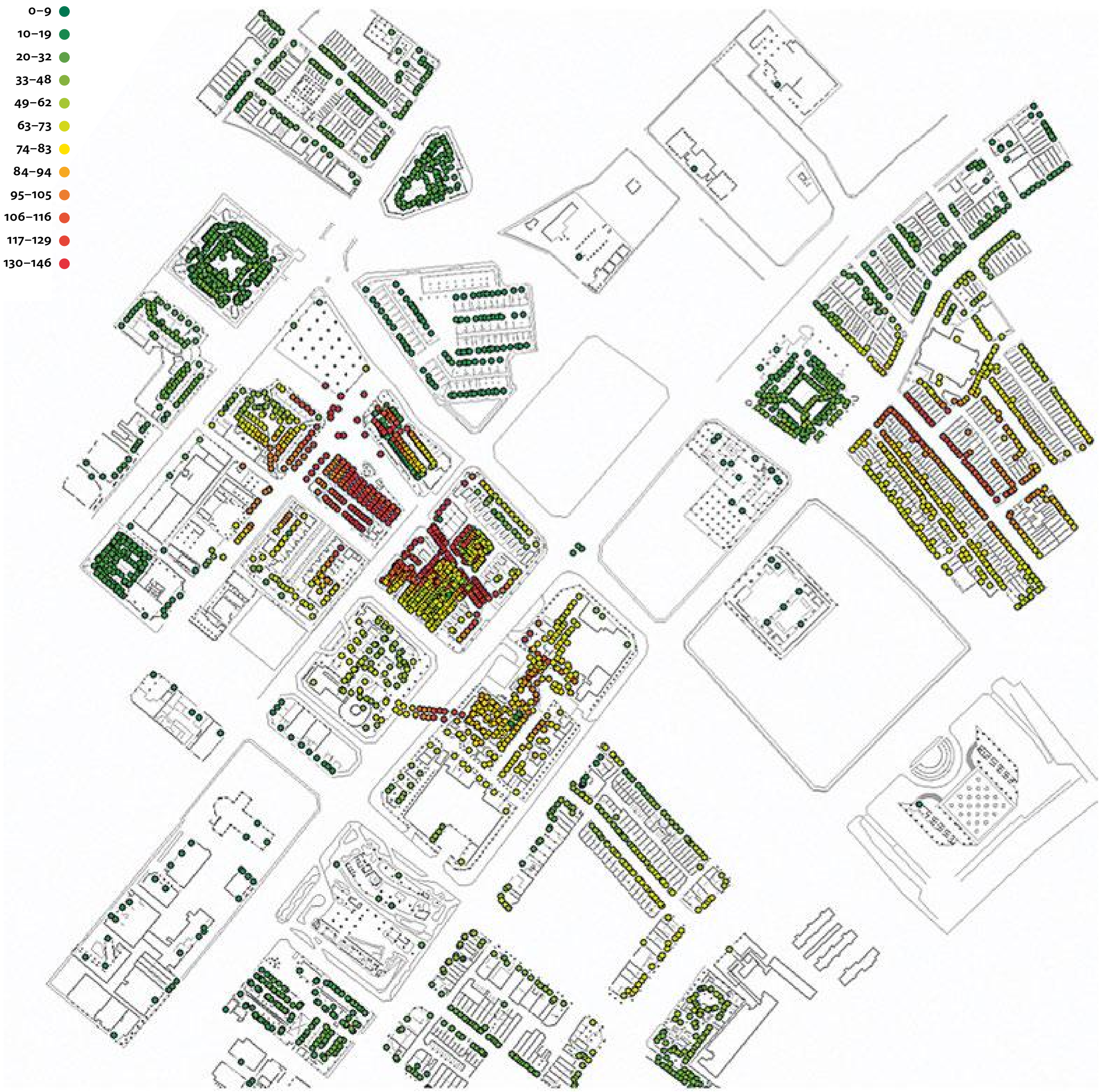


Fig. 5.
Reach analysis, indicating how many eating and drinking places can be reached on foot within a 200-meter radius from each door

street segments or indoor corridors throughout a whole district that are likely to attract a lot of traffic. The variation in movement flow on different segments can be an important factor for explaining their business mix and use patterns. Eating establishments, for instance, often prefer to locate on paths with high foot traffic between other origins and destinations. Businesses that do not depend entirely on passersby but value customer spillovers from other businesses, may occupy the second-best locations that remain near pedestrian currents, but on side streets, where rents are cheaper (Sevtsuk 2010).

When we analyzed which locations in this area have best access to food establishments, we see that restaurants and drinking places do locate quite close to retail destinations and the pedestrian routes that lead to them. **Figure 5** illustrates a network-based Reach accessibility metric specified to eating and drinking establishments within a 200-meter walking radius. The Reach index estimates how many particular types of destinations – food establishments, in our case – are available from each origin within a given walking radius (e.g., 200 meters). The more eating and drinking destination available, the higher the index.

The results in **figure 5** suggest that restaurants, hawker stands, and bars are typically clustered near retailers and the pedestrian paths that lead to them.[1] The highest concentration is found between Albert Mall and Bugis Street, where numerous food stalls cluster at the Albert Market and Food Center. There is also a concentration of food vendors in Bugis Street and Bugis Junction and on Arab Street and Muscat Street, which branches off to its right. In front of Albert Center, a pedestrian can reach up to 146 different food establishments within a 3-minute walk. These four areas are the centers of gravity for food. Overall, there are three times as many retailers as food establishments in the area, but even the lighter green locations on the map reach 30 to 50 eating and drinking venues in a 200-meter walking radius, suggesting that the area is not poor in culinary options.

If we zoom in on one of the walking paths between the Bugis MRT station and a retail store – a computer hardware shop on the fourth floor of Sim Lim Square electronics mall – then we can further qualify the characteristics of a particular route in our analysis

[1] We do not assess the statistical significance of these location choices here, but an interested reader may find such an analysis in Sevtsuk (2010).

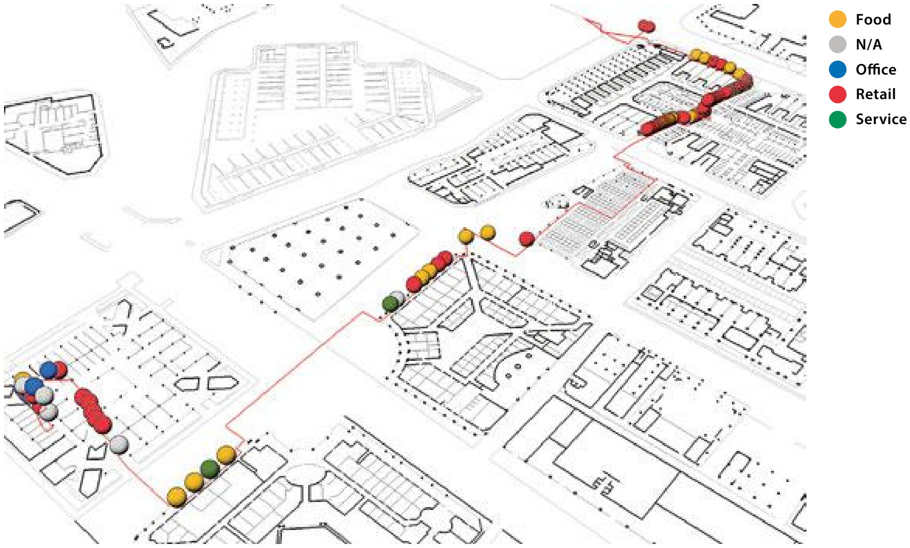


Fig. 6.
A typical walking route from a store on the fourth floor of Sim Lim Square electronics mall to the Bugis MRT station

(figure 6). This path, which depicts a typical shopper's visit to the area, passes 86 businesses before arriving at its destination, 58 of which are retailers, 20 eating places, 8 offices, and 3 service establishments. A comparison of such paths leading to different socio-economic destinations can be valuable for a number of applications – explaining, for instance, the attraction of different paths to pedestrians, how different groups of people experience the city, or for studying microeconomic clustering between establishments.

A networked representation of the built environment presents a powerful framework for describing and analyzing complex urban environments. It is already being used in numerous digital urban models, and its applications are likely to grow quickly in the coming years. Unlike traditional plans, network models of urban space explicitly encode information about the connectivity between different actors and places they represent, making complex spatial analysis between the different elements of the environment possible within seconds on a computer. They overcome the slow and challenging process of reading spatial relationships, typical of traditional plans. But the analysis of spatial networks therefore also depends on the relationships that have been encoded into their tables. Documenting such relationships is an important first step in making use of such methods.

Networked representations of city environments are not, however, alternatives to traditional plans, but rather complements. As urban designers, we know that visual readings of plans are more nuanced, sensitive, and powerful than anyone might be able to explain. Plan reading will remain vital to urbanists. Underlying network connections embedded in these plans can simply augment the static representations with powerful spatial interconnections that are hard to gauge otherwise. They help automate labor-intensive counting and measuring tasks that a reader of the plan may not be able to perform mentally, and allow her to utilize such information instantaneously for studying or manipulating the plan.

The graphic plan interfaces of network models will also allow the analyst to overcome the shortcomings of an overparameterized model. The interrelationships of form and function that network models embody are of course not comprehensive and can miss a number of important dimensions of a place – its history or its broader social, cultural, or environmental context. But the graphic interface of network models allows them to be interpreted in the same way as traditional plans, with supplements. A holistic approach to urban spatial analysis still requires "a pragmatic outlook [that] embraces context and seeks continuity among diverse viewpoints" (Hoch 2000, 54). Digital interconnectivity between the elements of a plan improves rather than hampers holistic thinking.

Finally, we should remember that a novel representation of a place does not necessarily lead to a better understanding of its underlying complexity. But by providing a clear framework for describing a multitude of simultaneous spatial relationships embedded in its structure, network models of the built environment eliminate a major burden of reading such relationships visually and allow the designer to focus on the analysis rather than the description of the problem.

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