Topological Qualities of Urban Streets and the Image of the City: A Multi-Perspective Approach

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Abstract: Previous studies of the influence of topological qualities of urban street network on the image of the city are based mainly on centrality and connectivity measures taken from graph theory. The paper suggests instead a multi-perspective approach combining graph theory and Q-analysis. Although Q-analysis shares some similarity with graph theory, it enables us to deal with a multidimensional chain of connectivity. The suggested approach is applied to the case of the city of Tel Aviv by using a geographic database of the street network and subjective data acquired from Tel Aviv residents' production of sketch maps. The study's findings provide preliminary evidence for the relevance of the multi-perspective approach for understanding the relationships between structural qualities of the street network and the image of the city from local and global levels.

1. INTRODUCTION

Much evidence has been collected indicating that the physical characteristics of an urban environment have the potential to affect the acquisition of environmental spatial knowledge (Cubukcu and Nasar, 2005; Garling et al., 1986; Weisman, 1981). In his seminal work "The image of the city", Lynch referred to this potential effect of the urban environment with the term *legibility* of the cityscape, meaning "the ease with which its parts can be recognized and can be organized into a coherent pattern" (Lynch, 1960, p.2). The underlying order derived from a legible city allows people to familiarize themselves with the environment, move about and spatially orient themselves. An image of a city may be analyzed into three components: identity, structure and meaning. The appearance of an object in the environmental image depends on its "distinction from other things…as a separable entity", which makes it easier to identify the object according to its spatial or pattern relation to other objects and its "meaning for the observer, whether practical or emotional" (Lynch 1960, p.8).

When the focus is on the physical qualities of the urban environment and how they relate to the attributes of identity and structure, legibility becomes synonymous with *imageability,* namely, "that quality in a physical object which gives it a high probability of evoking a strong image in any given observer" (Lynch, 1960, p. 9). The underlying idea of imageability is that at a higher level of abstraction, people share common views about the stronger, more significant features of their environment. In this respect, studies on how physical qualities of a given urban environment affect its imageability can be placed into two categories. The first focuses on the identity of urban elements that stem from their distinctive visual quality (Abu-Ghazzeh, 1997; Abu-Obeid, 1998; Haken and Portugali, 2003; Rosvall et al., 2005); while the second stresses the structural properties of an urban element, namely, its role in the city as an integrated whole (Conroy-Dalton and Bafna, 2003).

Structural properties are examined mainly in topological terms since the focus is on spatial relationships among the city's elements. Much research has shown that a topological analysis can be

used as an appropriate means to evaluate the effect of structural qualities of an urban element on imageability, as well as on other aspects of spatial cognition. Studies concentrating on street networks have found that topological properties, described mainly by centrality measures of network connectivity, could be reliable indicators for describing and predicting the effect of street network topology on the city's imageability. These studies have also found that the imageability of a given street segment can be influenced by the topological properties of integration or closeness (i.e., the short topological depth from all other street segments/axial lines; see Conroy-Dalton and Bafna, 2003; Shokouhi, 2003), connectivity (Haq and Zimring, 2001) and betweenness (Tomko et al., 2008). It should be noted that these topological properties have also been found appropriate for evaluating wayfinding performance, mainly with reference to the overall street network or to paths within this network (Kim, 2001; Penn, 2003; Omer and Goldblatt, 2007; Yun and Kim, 2007).

Geographic databases related to the city's infrastructure are increasingly available nowadays for use in analysis of the topological properties of urban street networks together with their links with objective and subjective data about human behavior. Thanks to this possibility, the concept *imageability* has been investigated recently with respect to new practical objectives, mainly the construction of automatic navigation tools based on geographic databases. Potential applications can involve selecting salient features such as verbal references in route directions and assisting the route generation process itself. For example, Tomko et al. (2008) have used network connectivity measures, to define a hierarchical model of urban street networks for the provision of route directions. Claramunt and Winter (2007) suggested a formal model of the salience of a city's structural elements, to be identified by measures taken from graph and space syntax (Hillier and Hanson 1984) theories. These studies are based on the assumption that topological street measures can predict the pattern of movement and thus determine one's experience of the urban layout.

Despite the progress described above, we still have inadequate knowledge about the involvement of urban structural qualities in the construction of the image of the city. One of the essential questions in this context is which structural properties are significant for imageability? The aim of the current study is to suggest application of a multi-perspective approach based on graph theory and Q-analysis to the structural investigation of the relationship between an urban street network and the image of the city. We believe that both graph theory (more specifically, centrality measures) and Q-analysis are complementary; hence, combining the two may provide a robust approach to structural analysis. Q-analysis in particular enables us to deal with structural properties from the perspective of multidimensional chains of connectivity (Jiang and Omer, 2007). It thus has the potential to offer insights different from those obtained with Graph theory's centrality measures.

In the following sections we present a conceptual discussion of the link urban street network, imageability and topology, with a special focus on the distinction between Graph theory and Q-analysis as topological descriptions of street networks. We then describe the results of the investigation on the relationship between structural properties and the urban street network's image as computed with measures taken from both methodologies, including a comparison between them. We conclude with some thoughts on the relevance of a multi-perspective approach for investigating the relationship in question.

2. TOPOLOGY OF URBAN STREET NETWORKS AND IMAGEABILITY

Streets or paths are the predominant of city elements; parts of those networks may become important elements due to certain characteristics that strengthen their image in observers' minds (Lynch, 1960; 1990). Lynch mentioned several such characteristics: concentrated spatial use or activity along a street, a special façade, proximity to unique features and spatial characteristics like the width or narrowness of streets (Lynch, 1960, pp. 49-51). With reference to the structural qualities of individual streets within a city, he noted that a street can acquire importance or uniqueness due to its place within the street network − such as its location in a "path intersection" or a "branching of streets" − when these features are treated as strategic points (p. 98). However, as Conroy-Dalton and

Bafna (2003) argue, Lynch's statement "does not offer any arguments for why some elements are selected over others, claiming instead that their distinctively visual characteristics are responsible" (2003, p. 59.4). In this respect, it is interesting to note that Lynch was aware of the absence of appropriate tools for estimating the quality of structure, and noted that "… there was a lack of information on element interrelations, patterns, sequences and wholes. Better methods must be evolved to approach these vital aspects" (Lynch, 1960, p.155). However, it is clear that this aim is more achievable today, with the development of network analysis methods and access to massive digital geographic databases.

A topology of urban streets takes individual streets as nodes and street intersections as edges of a connectivity graph (Figure 1, where the kite-shaped graph is taken from Krackhardt (1990)). The graph forms a basis for structural analysis using the centrality measures (Jiang and Claramunt, 2004) initially developed for the description of social networks (Freeman, 1979). Three centrality measures – *degree, closeness* and *betweenness* – are used to describe the status of individual streets in terms of which streets intersect which other streets. (In space syntax terms, these topological properties are called connectivity, global integration and choice, respectively.) *Degree centrality* indicates how many other streets are connected directly to a particular street, a characteristic that reflects the level of a street's integration with its neighboring streets. *Closeness* indicates how close a street is to other streets by computing the shortest distances between every street node to every other street node, a feature that reflects how well a street is integrated within the network. *Betweenness* centrality indicates the extent to which a street is located between streets that connect pairs of streets; as such, it directly reflects the intermediate location of the specific street. The values of these measures obtained for a sample network are illustrated in Table 1.
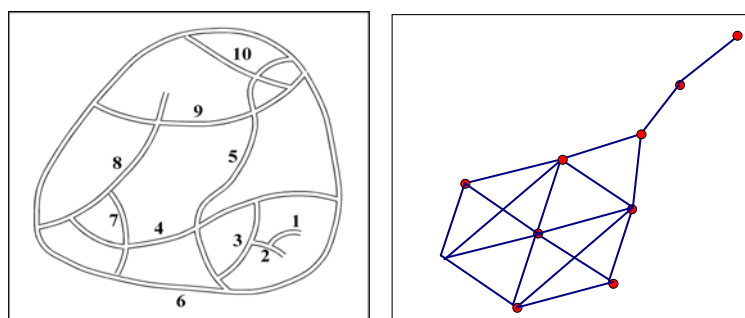

Figure 1: Geometric (left) and topological (right) representation of a notational street network

Street	Degree	Closeness	Betweenness
1	1	0.31	0.00
2	2	0.43	0.22
3	3	0.60	0.39
4	5	0.64	0.23
5	5	0.64	0.23
6	6	0.60	0.10
7	3	0.50	0.00
8	4	0.53	0.02
9	4	0.53	0.02
10	3	0.50	0.00

Table 1: Centrality measures for the notational street network shown in Figure 1

The relationship between the structural qualities of urban streets and imageability has been investigated in previous studies through the use of the values of the topologically derived centrality measures when compared to subjects' perception tests. These studies have reported that the appearance of a street in the sketch maps of people who visited a space was found significantly correlated with one or more values of the centrality measures described above (e.g.: Haq and Girotto 2003; Shokouhi, 2003; Yun and Kim, 2007). The underlying logic of this research approach is the assumption that streets that have greater structural importance – i.e., higher centralities – tend to be places with which people have more experience, making them more prone to imageability. in this paper, the examination of structural qualities from the point of view of multidimensional chain of connectivity is motivated by the awareness that the dimensionality of the street network has the potential to assist and complement the street network's examination from the aspect of imageability. For that purpose, we adopt the multidimensional topological method of Q-analysis for use in a structural analysis of the street network.

Q-analysis is a mathematical language for the description and analysis of structural complexity, initially developed from algebraic topology by Atkin (1974, 1977). It provides a computational language for the structural description of relationships among a set or between two sets of objects, using geometric and algebraic representations. For the sake of simplicity, we present the main procedure applied with Q-analysis with respect to street networks. In Q-analysis terms, we represent the street network as a simplicial complex in which streets and street interactions are represented as simplices and vertices.

We first generate an incidence matrix in terms of how one street intersects anoher, i.e., $\lambda = S \otimes S$: if the streets S_i and S_j from set S (i.e., $S_i, S_j \in S$) are intersected, then the corresponding entry of the matrix is 1, otherwise 0, as follows:

$$\Lambda_{ij} = \begin{cases} 1: & if\ (s_i, s_j) \in \lambda \\ 0: & otherwise \end{cases} \qquad [1]$$

Using Equation [1], our example of a street network (Figure 1) can be represented as an incidence matrix as follows:

$$\Lambda =$$

	1	2	3	4	5	6	7	8	9	1
1	0	1	0	0	0	0	0	0	0	0
2	1	0	1	0	0	0	0	0	0	0
3	0	1	0	1	1	0	0	0	0	0
4	0	0	1	0	1	1	1	1	0	0
5	0	0	1	1	0	1	0	0	1	1
6	0	0	0	1	1	0	1	1	1	1
7	0	0	0	1	0	1	0	1	0	0
8	0	0	0	1	0	1	1	0	1	0
9	0	0	0	0	1	1	0	1	0	1
1	0	0	0	0	1	1	0	0	1	0

Thus, each street S_i can be considered a simplex in $K_S(S;\lambda)$. For instance, street *3* is represented as a 2-dimentional simplex, $\sigma^2(1) = <2, 4, 5>$. Two key concepts of Q-analysis are q-nearness and q-connectivity. Two streets are q-near if and only if they intersect q+1 common streets, e.g., streets *4* and *5* are 1-near since they share streets *3* and *6*. Two streets (simplices) are q-connected if they are q-near or there is a chain of streets (simplices) between them that are q-near. For instance, the streets *1* and *3* have no common street, but they are 0-connected due to the fact that both streets are 0-near with

street *2*. Thus, q-nearness relates to a pair of streets that intersect while q-connectivity relates to a pair of streets that do not intersect but are connected via a chain of intermediate q-near pairs. In effect, Q-analysis is intended to detect q-connected components at every dimension of a simplicial complex ranging from 0 up to q-1. For example, the Q-analysis of the street network in Figure 1 leads to the following q-connected components (equivalence classes) at different dimensions:

q = 0: {1, 2, 3, 4, 5, 6, 7, 8, 9, 10}

q = 1: {2} {3, 4, 5, 6, 7, 8, 9, 10}

q = 2: {3} {4, 5, 6, 8, 9} {7} {10}

q = 3: {4} {5} {6} {8} {9}

q = 4: {4} {5} {6}

q = 5: {6}

The number of simplices varies from one dimension to another and forms a so-called structure vector Q; In the above example the structure vector is: Q = {1,2,4,5,3,1}. Large entries in Q indicate that the structure is, at a certain point, fragmented or disconnected, while small entries mean more integrated structures. Hence, the structure vector Q enables street network examination at a global level.

Q-analysis can also assess the status of individual simplices within the complex by means of the eccentricity index. In street network terms, eccentricity indicates how a street is unique from other surrounding streets. This index is defined by the relation between a dimension where a street is disconnected and another dimension where the street is integrated. It is formally defined as follows:

$$Ecc(\sigma_i) = \frac{\hat{q} - \check{q}}{\check{q} + 1} \qquad\qquad [2]$$

where $\hat{q}$ or top-q denotes the dimensionality of the simplex (σ_i); $\check{q}$ or bottom-q denotes the q level where the simplex is connected to any other simplex. According to this definition, if a street is q-connected at its dimensional level of $\hat{q}$, the Eccentricity of the simplex is equal to 0. Alternatively, a simplex with a non-zero Eccentricity is eccentric from its surrounding simplices and therefore not fully embedded within the complex, i.e., the higher the Eccentricity value, the more eccentric the simplex. The denominator $\check{q}$ +1 in Equation [2] is meant to attach great weight to the uniqueness in the lower dimension. However, this weighted dimensional does not necessarily apply to all phenomena (Atkin, 1974, ch. 6). In the context of imageability it is reasonable to assume that a street's dimension, i.e., its degree value, can be significant. Hence, in this paper, we use Eccentricity without considering a dimension's weight but only its depth, as follows:

$$Ecc'(\sigma_i) = \hat{q} - \check{q} \qquad\qquad [3]$$

For instance, according to Equation [3], the eccentricity values of the streets in the complex presented in Figure 1 are Ecc ` (*6*) =4; Ecc (4), (5) =2; and Ecc (2), (3), (7), (10) =1 while street 1 has 0 Eccentricity value. Namely, other than street 1, all the streets are unique since they are connected uniquely or exclusively to set of streets, i.e., there is a difference between their $\hat{q}$ and $\check{q}$ values.

Thus, unlike Graph theory's centrality measurement, a street acquires a high eccentricity value if it is different from every other street in the sense of uniqueness rather than only in the sense of importance or function in the network's flows. This means that when we refer to an individual street in a street network from this perspective, the street will receive a high value if it connects to certain streets exclusively and there are many such streets. The consideration of exclusiveness or uniqueness can be significant with respect to the possibility of a street being imageable since a street's high uniqueness means it can be distinguished from others streets with respect to its connectivity in the street network.

The possibility of examining the specific structure of connectivity at each dimension can potentially enrich our observations at the global level. This possibility may be relevant for explaining imageability since it allows us to identify how streets are connected, e.g., to identify a distinct or fragmented component of connected streets or sets of streets with a similar connectivity pattern. The structure of connectivity at each dimension is also expressed by a structural vector that gives an overall view of the integration between streets in different dimensions. Q-analysis thus has the potential to offer different views when compared to Graph theory's centrality measures. The following empirical study of the Tel Aviv street network attempts to evaluate this potential.

3. THE TEL AVIV STREET NETWORK: STRUCTURAL QUALITIES AND IMAGEABILITY

The study of Tel Aviv street network and imageability was conducted in two stages. First, we constructed an aggregate urban image by means of a survey conducted among of 32 Tel Aviv residents. These residents were asked to "draw a map of Tel Aviv and its dominant elements (no more than 15 elements are to be included)". An aggregate map was then constructed based on the street elements in those individual images. This aggregate urban image included the 35 streets mentioned in common by the residents. Then, the imageability level of each given street was determined by the frequency of its appearance in the aggregate urban image, that is, the number of sketch maps in which the street appeared. In the second stage, we used the geographic data network of Tel Aviv (a total of 1767 streets). From these streets, we choose the section in which all the 35 imageable streets are included. By applying this selection method, the 195 main Tel Aviv streets in the network were chosen. These streets are shown in Figure 2, together with their imageability level.

Based on the collected data, we calculated the correlation between imageability and the streets' centrality values as computed by Q-analysis and Graph theory measurement. A significant correlation was found between imageability and *eccentricity* (as defined in equation [3]): $r=0.695$; $R^2 = 0.483$, ($p < 0.0001$). The correlation of imageability with *Degree* was $r= 0.665$; $R^2 = 0.443$, ($p < 0.0001$), with *Closeness* it was $r=0.398$; $R^2=0.158$, ($p< 0.05$), while the correlation for *betweenness* was $r=0.417$; $R^2= 0.158$ ($p< 0.05$). This analysis indicated that the imageability level was affected mainly by the topological properties of *eccentricity* and *degree* and much less by *closeness* and *betweennes*. We should note that the former properties reflect the topological centrality of the street from the local perspective whereas the latter does so from a global perspective. The correlation of imageability with eccentricity and degree is illustrated in Figures 3. We then used multiple regression to estimate how the combination of eccentricity and degree variables influenced the level of imageability. In this analysis, the correlation becomes $r=0.736$ and $R^2= 0.541$. This finding is highly significant, $p < 0.0001$. The correlation between these topological properties and imageability is illustrated in figures 3. A comparison between the spatial patterns of these topological properties (figure 4) and

their similarity with the spatial pattern of imageability in Tel Aviv street network (figure 2) illustrates their potential to complement each other.

Figure 2: Imageability level of Tel-Aviv's main streets

Further examination of the image of Tel Aviv's street network based on the Q-analysis of the aggregate image of the city $K_I(I; \lambda)$ that presents in table 2, provides some deep insight into the relation between imageability and structural qualities of street from global view. Comparison between this topological structures to the topological structure of street network indicates that there is certain similarity between them. For example, we can take a look on the streets at dimension q=5 of $K_I(I; \lambda)$ in table 2, where the most nine imageable streets which actually constitute the skeleton of the image of Tel Aviv city, are gathered into one connected component. Five of them belong to the same equivalence class in $K_s(s; \lambda)$ (at dimension q=2) – the streets Even gvirol (2) Ben yhoda (25), Dizingoff (44), Derech namir (55) Hayrkon (66).

It is interesting in this respect to note that strongly connected imageable streets also received high Eccentricity values: Hayarkon, Dizengoff, Ibn Gvirol, Derech Namir and Arlozorov received Eccentricity values greater than 4.0 (Ecc' ≥4). This similarity implies links between the structure of tangible geographic connections between streets and the intangible conceptual connections of these same streets in the image of the city. These findings provide preliminary evidence of the relevance of

the multidimensional chain of connectivity examined here for understanding the relationship between structural qualities and imageability regarding the street network.

Throughout the research, we studied the image of the city using both graph theory centralities and Q-analysis. We now show how the two approaches complement each other in capturing the image of the city. On the one hand, the graph theory centrality provides a description of the state of individual streets in the functioning of the entire street network; hence, it reflects city residents' experience of the network. On the other hand, Q-analysis provides a description of how much a given street network's connectivity is unique. The possibility of examining street network connectivity from different dimensions also complements graph theory centrality measures by enabling exploration of how functionally dominant streets are connected, thereby enabling construction of the structural skeleton of the street network within the image of the city.
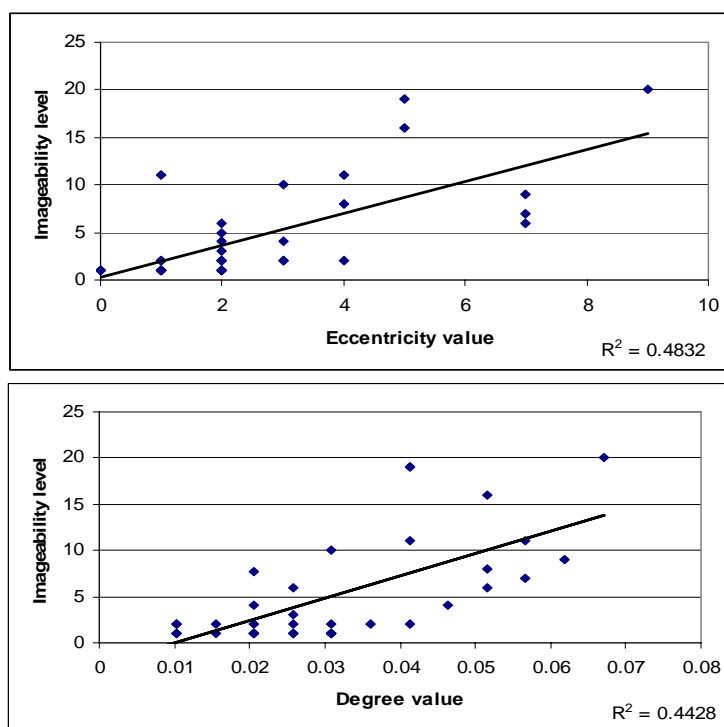

Figure 3: The correlation of Imageability with Eccentricity level of Tel-Aviv's main streets

Figure 4: Degree (left) and Eccentricity (right) values of Tel-Aviv's main streets

q = 5:	{ Even Gvirol, Ben Yehuda, Dizengoff, Derech Namir, Hayarkon, Ayalon, Allenby, Arlozorov, Nordau}
q = 6:	{ Even Gvirol, Ben Yehuda, Dizengoff, Hayarkon, Ayalon, Allenby} {Derech Namir} {Arlozorov}
q = 7:	{even Ggvirol, ben yhoda, dizingoff, hayrkon, ayalon, alenbi,} {derech namir } {arlozerov }
q = 8:	{even gvirol, ben yhoda, dizingoff, hayrkon, ayalon} { alenbi} {derech namir }
q = 9:	{ even gvirol, ben yhoda, dizingoff, hayrkon, ayalon} {alenbi}
q = 10:	{ even gvirol, dizingoff, ayalon} { hayrkon} { ben yhoda}
q = 11:	{ even gvirol , ayalon} {hayrkon} {dizingoff}
q = 11:	
q= 15:	{ even gvirol} {ayalon} { dizingoff}
q =14:	
q= 18:	{ even gvirol} {ayalon}
q =19:	{even gvirol}

$$\underset{19}{\qquad} \underset{5}{\qquad} \underset{0}{\qquad}$$

Q = {1,2,2,2,3,3,3,3,3,3,2,3,3,2,1,1,2,3,2,1}

Table 2: Q-analysis of the image of Tel Aviv's street network; $K_I(I; \lambda)$ (q ≥ 4)

4. CONCLUSION

This paper investigated possibility of exploring the relationship between the topology of urban street networks and the image of the city at both local and global levels from a multiple perspective through the application of centrality and Q-analysis methodologies. We found that at the local level, this approach enables us to assess the uniqueness of individual streets in the network while at the global level we could observe different components of connected streets from different dimensions. The empirical study conducted using the case of Tel Aviv street network demonstrated how the multi-perspective approach provides new insight into the topology of urban streets and the image of the city. Due to this study we can conclude that the multidimensional chain of connectivity embodied in supplementing Q-analysis with graph theory centrality measures has the potential to enrich the study of the structural relationships between a city's street network and its image. Nonetheless, we wish to stress that these findings are based on one city only. Hence, further study is needed to evaluate the contribution of this approach to networks and cities different in size, character and topology.

Acknowledgements

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