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WHY ANGULAR CENTRALITIES ARE MORE SUITABLE FOR SPACE SYNTAX MODELING?

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ABSTRACT

The street network's angular properties were found more suitable than metric properties for capturing the observed pedestrian and vehicle movement flows in space syntax modeling. Some studies relate this state to the underlying street network structure that create the potential for movement across the network. The aim of this paper is to clarify why the angular structure of the network has superiority over the metric structure. The investigation entailed analysis of street network' centralities and movement flows obtained through agent-based simulations conducted for two cities that differ in the pattern and size of street network. The findings indicate that the superiority of the angular structure can be explained by two structural properties: (i) a multi-scale correlation between to-movement and through-movement potentials (centrality measures) of the same distance type; and (ii) an overlap between movement potentials of different distance types across scales of the network. These structural properties create coherent and dominant angular foreground structures that fit movement flows in both study cities.

KEYWORDS

Movement potentials, Distance type, Scale, Space syntax

1. INTRODUCTION

The spatial distribution of movement in street networks is an essential component for a city's functioning and dynamics. Understanding the effects that shape the movement of pedestrians and vehicles is crucial for predicting traffic flow and enhancing efficiency, safety, sustainability and livability in urban environments. Previous studies have explained movement flows in urban street networks by factors such as the street network's morphological and physical aspects, land-use patterns, residential and employment densities, as well as access to public transit (e.g., Desyllas et al., 2003; Hillier and Iida, 2005; Omer et al., 2015). However, at its core, the spatial distribution of movement flows is related to two types of effects: the street network's *movement potentials* and the *individual's spatial behavior*. These effects are explained as follows: the network's structure creates movement potentials (i.e. 'network effects') whereas individuals, by choosing the shortest routes in the network, determine how these potentials will be utilized (e.g. Hillier, 2012).

Although route choice is affected by various factors which can differ from the shortest routes (e.g. Manley, 2015; Turner, 2009), the common guiding assumption behind most research is that people try to minimize trip length, based on their distance perception. When calculating the shortest routes to their destinations from within the network, people use three basic types of distance (Hillier and Iida, 2005): *Metric distance*, *topological distance* (the number of changes of direction that have to be made on a route) and angular distance (the sum of the angles characterizing the direction changes made on route). Hence, several types of movement potentials – metric, topological and angular – embedded within the network, which are rooted in the individuals' spatial behavior.

Studies that examined the correlation of movement flows with topological, angular and metric street network centrality properties (i.e. movement potentials) in different urban areas (e.g. Hillier and Iida, 2005; Hillier, 2009; Jayasinghe et al., 2015; Turner, 2007; Xia, 2013) have shown that the correlations with angular street networks' centrality properties tend to be higher than the correlations with topological properties but mainly higher than the correlations with metric properties. The relevance of the street network's topological-angular properties for capturing the observed pedestrian and vehicle movement flows in the network was supported by many other studies (e.g. Hillier, 2009; Jiang, 2009; Jiang et al., 2008). In addition, empirical evidence has been obtained regarding the correspondence between the street network's topological-angular properties and retail land use patterns in various cities (e.g. Omer and Goldblatt, 2015; Scoppa & Peponis, 2015; Vaughan et al., 2010), features that are strongly related to patterns of movement flows in urban networks.

Some researchers (e.g., Hillier and Iida, 2005; Hillier, 2012; Penn, 2001) have argued that movement flows in urban networks appear to be related mainly to the dominance of the topological and the angular distances in individuals' spatial behavior. Other studies have nonetheless suggested that the underlying street network structure can also determine movement flows, irrespective of individuals' spatial behavior (Jiang and Jia, 2011; Omer and Jiang, 2015). Further indications of this 'independence' of aggregate movement flows from individuals' spatial behavior is the lack of variability found in the predictability of movement flows despite significant differences in human travel patterns (Song et al., 2010). However, it is yet to be ascertained how the underlying street network structure contributes to some degree of 'independence' of movement flows in the network. In other words, there is no comprehensive answer available for how the 'network effect' works and why the topological-angular structure of the network has superiority over the metric structure.

Several street networks' structural properties are related to movement flow. The first structural property of the network is the emergent multi-scale centrality in the network what called by Hillier (2009; 2016) 'pervasive centrality'. According to this view multi-scale pattern of linked centres arises in cities through a well-defined process of self-organization, based on the relationship between the street network structure and movement at all scales. This process by which the pattern of 'pervasive centrality' evolves in cities is essentially occurs at all scales in the foreground network (the main streets/ longer lines), though it interacts with the structure of the background network (small streets/shorter lines). Hence, the foreground and background structures are both components of a locally and globally efficient system of inter-related to-movement and through-movement potentials (Hillier, 2016). This intricate pattern of movements at all scales is related to the angular structure of the network. Moreover, the conjunction between to-movement and through-movement was also found to be significant property of the angular structure (Vaughan et al., 2010; Hillier et al., 2012).

The second structural property is a structural overlap that exists between street network's movement potential of different distance types. Although previous studies have referred to the relevance of overlapping between movement paths at different scales for enhancing efficient and sustainable movement in cities (Hiller, 2009; Salingaros, 2005), no attention is given to overlapping between distance types. We argue that the examination of overlap between street network's movement potentials of different distance types, with an explicit reference to individuals' spatial behavior, might also explain the observed corresponding between the angular foreground structure and movement flow in the network.

The aim of this paper is to compare between the angular and metric street network structures by focusing on the structural properties discussed above: (i) an emergent multi-scale correspondence between to-movement and through-movement potentials (centrality measures) of the same distance type; and (ii) an overlap between movement potentials of different distance types across scales of the network.

To achieve this aim, the analysis was concentrated on angular and metric street network' structures (centrality measures) and movement flows obtained through agent-based simulations conducted for two Israeli cities.

In the following section we describe the cities studied, the measurement methods employed, and the data, together with the agent-based model constructed to simulate the various types of distance movement. The research findings and conclusions appear in the third and final section.

2. DATASETS AND METHODS

2.1. SELECTING STUDY CITIES, DATA, AND ANALYSIS

The two cities chosen for the study – Kfar Saba and Beer Sheva – differ in their street patterns, land-use distributions and size (Figure 1), features that enable the examination of consistencies in the structural properties. In addition, both cities are locationally independent, with no directly adjoining cities and hence no need to confront any 'edge effect,' which can critically impact on the results of a space syntax analysis (Gil, 2015). Kfar Saba, founded in 1912, developed mainly through continuous urban growth. The city is characterized by a predominantly orthogonal street pattern, with retail activities concentrated in its center. In contrast, Beer Sheva, a relatively young city, developed according to a comprehensive city plan after establishment of the State of Israel in 1948. The city is characterized by hierarchical street patterns and its residential neighborhoods were designed according to the 'neighborhood unit' model (Omer & Goldblatt, 2015). The differences between such cities may be reflected in movement flows (Marshall, 2005; Jiang and Liu, 2009).

Data for the cities` street networks (updated for 2012), as GIS layers, were obtained from GISrael (a geographic information database for Israel offered by the company "Mapa"). Data on non-residential buildings were obtained from the *Survey of Israel* - MAPI (the official Israeli government agency for Mapping, Geodesy, Cadastre and Geoinformatics).

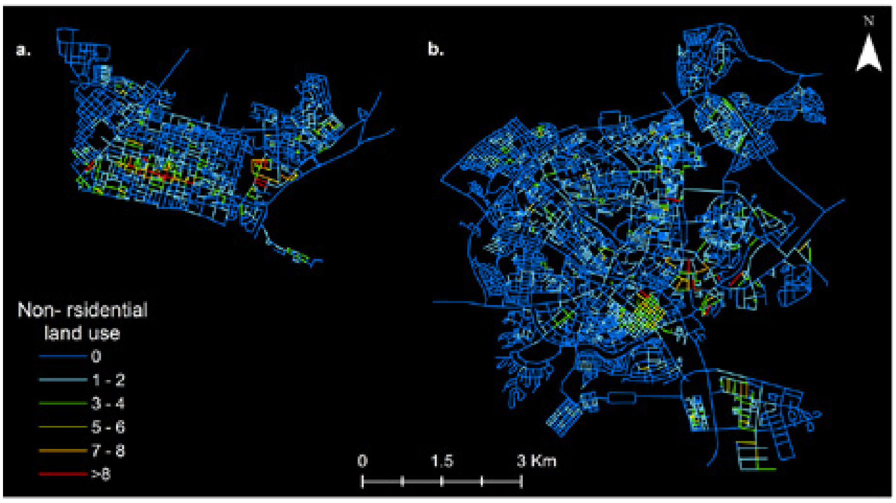

Figure 1 - Street segment maps of the study cities: Kfar Saba (a) and Beer Sheva (b). Streets are visualized by spectral colors according to the frequency of non-residential buildings.

2.2. MEASUREMENT OF STREET-NETWORK MOVEMENT POTENTIALS

The space syntax approach allows description of the street network's movement potentials with centrality measures that are generally computed on the basis of either axial or segment maps (Hillier and Iida, 2005). Axial maps are constructed with the smallest set of straight axial (visual) lines covering the urban street network. Axial maps can subsequently be transformed into connectivity graphs, in which the axial lines and the intersections between lines appear as the graph's nodes and links, respectively. The centrality of each axial line within the network is then computed based on graph connectivity attributes. Segment maps are constructed by means of the line segments connecting junctions of axial lines, a feature that facilitates configurational analysis on a finer scale than do axial lines. Segment analysis also allows consideration of angular (least-angle distance) and metric distance (Hillier and Iida, 2005) as well as variability in the distribution of traffic volumes.

Two types of centrality measures are used in the space syntax approach for describing a street network's movement potential – *Integration* and *Choice* – measures that correspond with the graph theory-based measures closeness and betweenness, respectively. Closeness represents a given street segment's accessibility within the network (i.e. its to-movement potential) while betweenness represents the extent to which a segment functions as an intermediate location within the network (i.e. its through-movement potential). The betweenness measure actually counts the number of times a segment lies on the shortest path between all pairs of origins and destinations in the network. The segment-based measures used in this paper are identical to those defined by Hillier and Iida (2005, pp. 481-483):

$$\text{Closeness}\ (S_i) = \frac{n-1}{\sum_{k=1}^{n} d\ (S_i, S_k)} \qquad 1)$$

where d is the shortest (topological, angular or metric) distance from a given street segment S_i to every other street segment (S_k) in the segment map. Betweenness is defined as:

$$\text{Betweenness}(S_i) = \sum_{j=1}^{n} \sum_{k=1}^{n} \frac{P_{jik}}{P_{jk}} \qquad 2)$$

where P_{jk} denotes the shortest paths from j to k, and P_{jik} the shortest paths from j to k that pass through street segment S_i.

Each centrality measure was computed at several metric radii – 250, 500, 750, 1000, 1250, 1500, 1750, 2000, 2500, 3000, 4000, 5000 m – and over the entire urban area (radius n), as used in the space syntax research (Hillier, 2009). Construction of the segment maps and computing space syntax measures was completed with Depthmap software (version 10.14, UCL), and visualized with ESRI`s ArcMap (ver. 10.3) GIS software.

2.3. AGENT-BASED SIMULATION

The simulation model we employed was designed with the NetLogo (ver.5.3.1) environment (Wilensky, 1999). Segment maps of Kfar Saba and Beer Sheva were transformed into NetLogo environments from the ArcGIS software (ver. 10.3). Two types of agents were defined according to how they would choose the shortest path – metric and angular – between origin-destination pairs. The shortest metric path was computed with the Dijkstra algorithm (Dijkstra 1959) within the NetLogo framework, while the shortest angular distance was obtained by computing cumulative angular change between origin and destination.

The probability of a street segment being chosen as a destination is directly proportional to its accessibility in the network (i.e. closeness value values):

$$\text{Closeness}_{\text{Acc}}(S_i) = \frac{\text{Closeness}(S_i)}{\sum_{k=1}^{n} \text{Closeness}\ (S_k)} \qquad 3)$$

where n is the total number of streets segments; and S_i is the closeness value of a given street segment (S_i) as computed by formula (1). The measure $Closeness_{Acc}$ is computed for each of the two distance types –angular, and metric. Agents were programmed to use their respective destinations according to the computed closeness measures, e.g. metric agents selected movement according to accessibility as computed by the metric closeness formula.

During initialization of each simulation run, agents' movement origins (starting points) are randomly created. Once they reach their first destination, they choose their second destination according to the $Closeness_{Acc}$ measure, and so forth. Agents are programmed to choose the shortest path according their type. For each simulation run of 36k iterations, we assigned 15 agents to each of the two types (a total of 45 agents). For each simulation run, the aggregate movement flows of each of the two agent types was computed at the segment level by the *gate counts* method (e.g. Jiang and Jia, 2011).

3. RESULTS

The geographic distributions of the betweenness and closeness centralities by distance type, together with the simulated movement flows of each agent type (agents selecting the shortest angular or metric route), are shown for Beer Sheva and Kfar Saba in Figures 2. The maps show that the to-movement (closeness) and through-movement (betweenness) potentials of the angular distance type tend to be similar relative to those of the metric distance. It can be also seen that in both cites the metric to-movement potential (closeness) tends to be especially concentrated close to each city's geographical center while the metric through-movement potential is distributed relatively more equally throughout the entire network. In addition, while the angular through-movement potential is concentrated along a few streets, particularly along the long lines, the metric through-movement potential is distributed more equally along a relatively greater variety of line lengths.

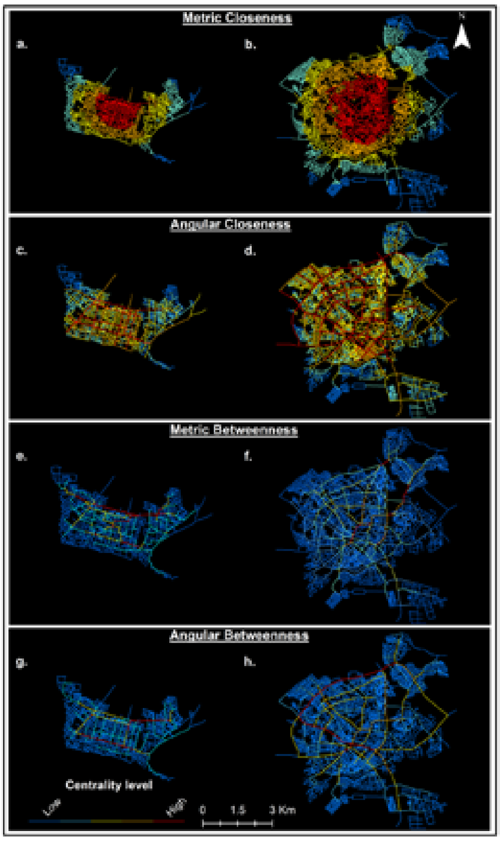

Figure 2 - Spatial distribution of centrality measures (movement potentials) at the segment level in Kfar Saba (a, c, e, g) and Beer Sheva (b, d, f, h).

This differential correspondence between the to-movement and through-movement potentials of the angular and metric structure, as demonstrated graphically by the correlations obtained between the centrality measures of each distance type across scale, is presented in Figure 3. It can be seen that the overlap between the to-movement and through-movement potentials of angular distance is relatively higher comparing to metric distance, and especially at the local scales. In addition, the distance types also differ in the change of overlap between the movement potentials across scales.

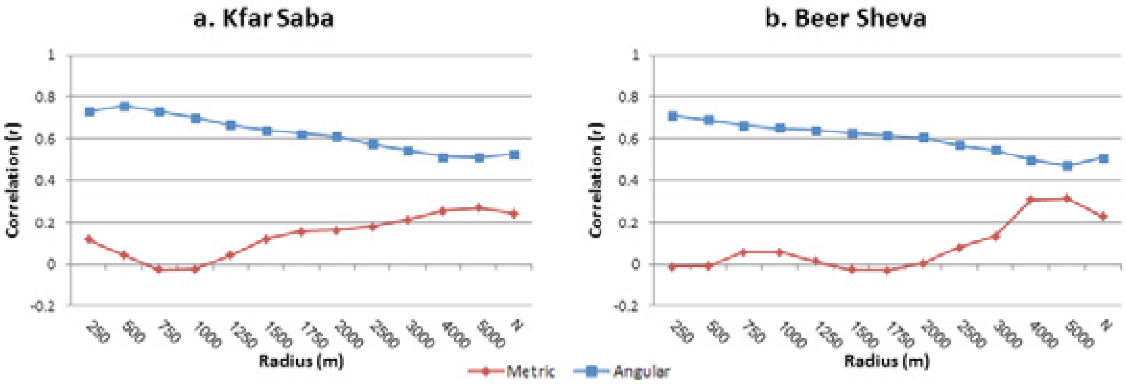

Figure 3 - The correlations between betweenness and closeness centrality measures (level of correspondence between to-movement and through-movement potentials) of the same distance type at different metric radii.

3.1 MULTI-SCALE CENTRALITY IN THE NETWORK

To identify the spatial patterns of the correspondence between the to-movement and through-movement potentials in the angular and metric structures of the street networks a detailed analysis was conducted at the segment level for both cities. The conjunction between the movement potentials across scale was examined using a k-means clustering algorithm of MATLAB (ver. 9.1). K-means clustering is an iterative, data-partitioning algorithm that assigns n observations to exactly one of k clusters defined by centroids, where k is chosen before the algorithm starts.

The results of the analysis (figure 4) enable to make a distinction between the foreground and background structures of the street network. It can be seen clearly that in both cities the angular foreground structure reveals more clearly emergent multi-scale centrality reflected in intensifying of the correspondence between the to-movement and through-movement potentials from the local to global scales. The segments of the angular foreground structure are also creating more coherent spatial structure than the metric foreground structure. In other word, to-movement and through-movement potentials are integrated spatially well in the angular foreground structure. It can be also seen that the spatial patterns of the angular segment clusters that increase across scale tend to reach higher values than the metric segment clusters, especially at the larger scales.

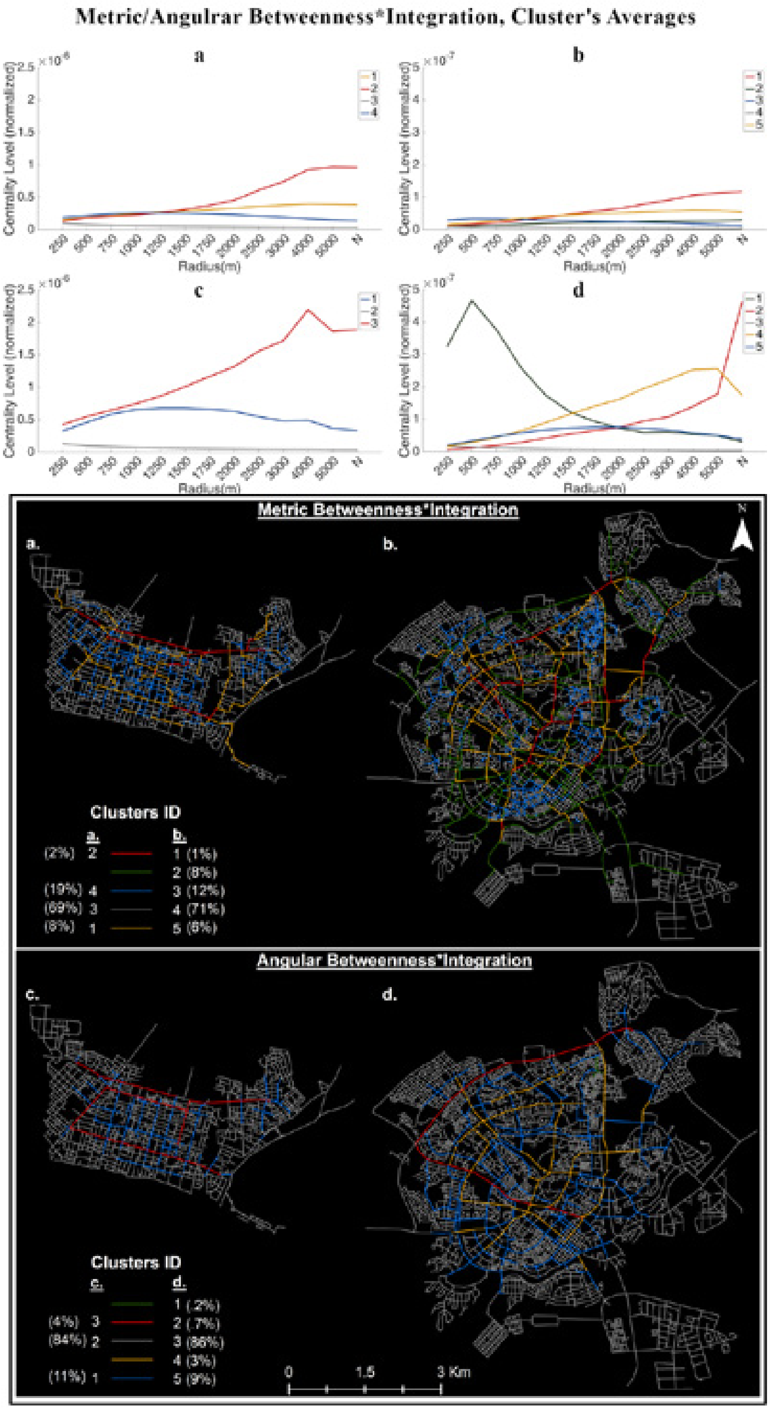

Figure 4 - Multi-scale centrality in the metric and angular network at the segment level in Kfar Saba and Beer Sheva (a, c and b, d, respectively). The relative amount of segments in each cluster appears in brackets. The total street segments in Kfar Saba and Beer Sheva are 2,923 and 9,178, respectively. To normalize the Betweenness and Integration centrality measures, the values of each measure for each segment was divided by the sum of all segments. Then, the combined centrality measure (Betweenness * Integration) was computed by multiplying the normalized centrality measures` values of each street segment.

3.2 STRUCTURAL OVERLAP BETWEEN DISTANCE TYPES IN THE NETWORK

The simulated movement flows of metric and angular agents are presented in Figure 5. It can be seen clearly that the angular movement flows are concentrated relatively on the main lines of the networks in both cities. The shortest routes of all types of agents tend to pass through the long axial lines (with minimal angularity) but, unlike the angular agents' shortest routes, the metric agents' shortest routes are also distributed among relatively shorter axial lines (mainly in the city's geographical center).

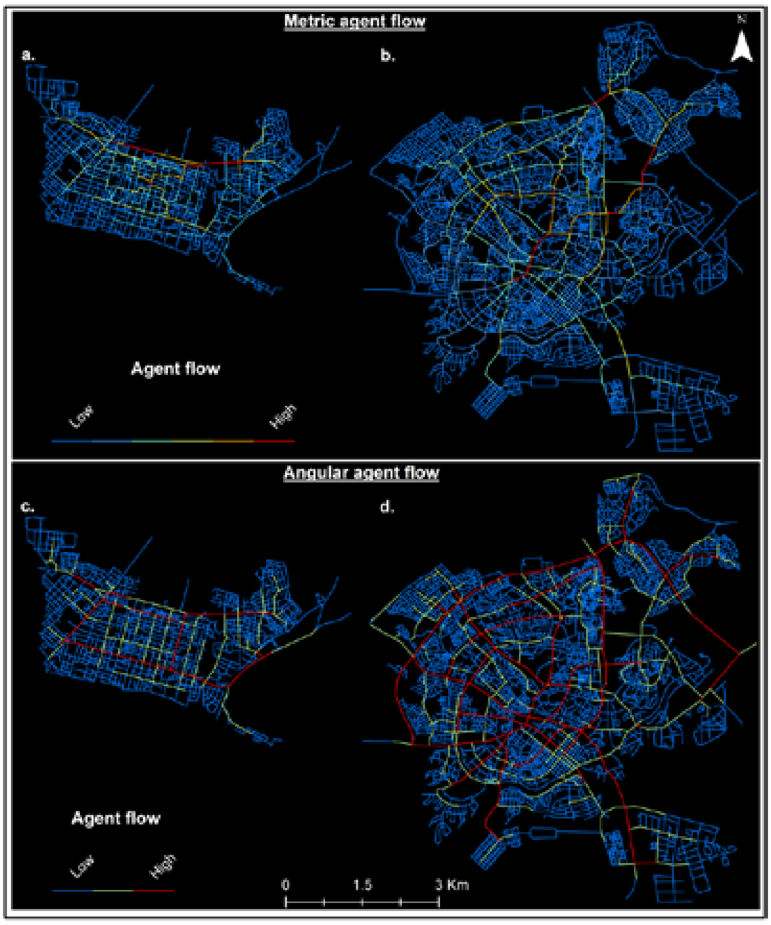

Figure 5 - The spatial distributions of aggregate flows of angular and metric agents at the entire area/city scale (Rn) in Kfra Saba (a,c) and Beer Sheva (b,d).

Since the movement potentials of metric and angular distance types overlap to some degree, actual movement according to a given distance type may simultaneously utilize the movement potential of other distance types (i.e. metric and angular shortest paths for a given origin-destination pair might overlap to some degree). The agent-based simulation was implemented in order to examine this mutual utilization of movement potentials by different distance types.

In order to clarify the mutual utilization found between the movement potentials of the distance types, the correlations of the simulated metric and angular aggregate flows with the metric and angular centrality measures across scales (metric radii) were examined (see Figure 6). The graphs in Figure 6a show how metric agents utilize metric and angular movement potentials, while the graphs in Figure 6b show how angular agents utilize the same movement potentials. The results clearly indicate the presence of systematic overlapping and mutual utilization between the two types of movement potentials. That is, each agent type also utilizes the movement potential of the other distance type. However, this mutual utilization of movement potentials is, in both cities, asymmetric: metric agents tend to utilize the angular movement potential more than angular agents utilize the metric movement potential, especially concerning the to-movement potential (closeness centrality).

The correlations of the aggregate flows are clearly higher with angular closeness than with the metric closeness at all scales, no matter which distance type — metric or angular — the agents use. This mutual utilization also exists with respect to the through-movement (Betweeneess) potential, implying that utilization of a given shortest route may involve the concurrent utilization of another type of shortest route. However, as a result of the different levels of overlap between the movement flow types across scales (see also figure 3), the asymmetric utilization of to-movement potentials is more prominent at local scales, with the asymmetrical utilization of through-movement potentials more prominent at higher scales. These tendencies are quite consistent for both cities.

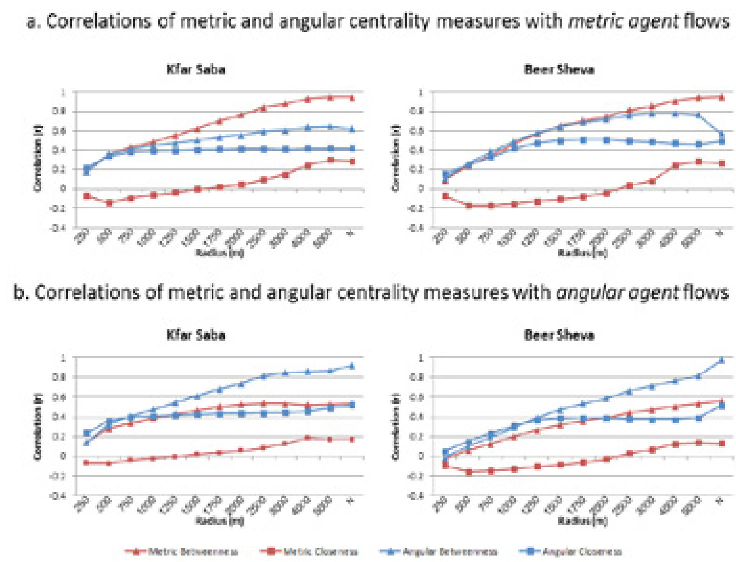

Figure 6 - Correlations of metric and angular centrality measures with (a) metric agent flows and (b) angular agent flows.

The asymmetric utilization is reflected well when the analysis is concentrated on the angular structure, as illustrated in figure 7: metric agents tend to use the angular through-movement potential (figure 7 b, d) more than do angular agents use the metric potential (figure 7 a, c). In other words, metric shortest routes pass over angular shortest routes more than metric shortest routes pass over angular shortest routes. Hence, as a result of structural relations between distance types within the street network, the angular movement potentials of the network are utilized more often than are the metric movement potentials.

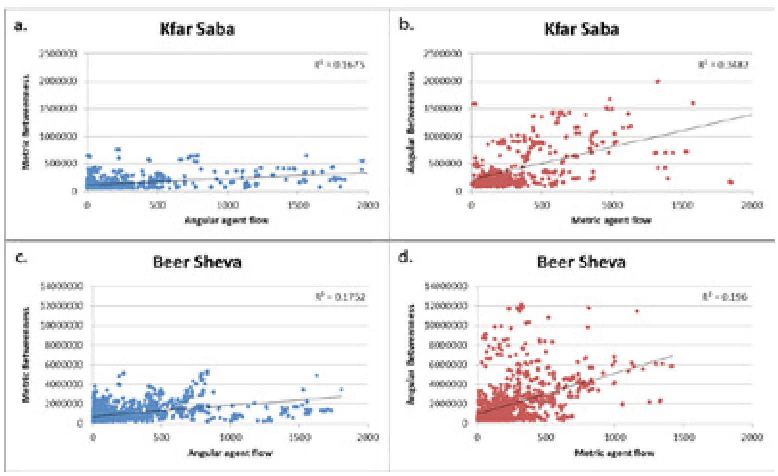

Figure 7 - Metric and Angular Betweenness VS Metric and Angular agent flow. Only segments with betweenness value above mean value of each centrality measure is presented. These segments are defined according to the "head/tail" break classification (i.e. the first 'head' part of the classification; for more details see: Jiang 2013).

4. CONCLUSIONS

The study findings reveal systematic differences between the angular and metric structures of the study cities' street networks. First, the angular foreground structure exhibits more coherent spatial pattern of emergent multi-scale correspondence of the to-movement and through-movement potentials than the metric foreground structure. Second, an asymmetric utilization between the movement potentials of different distance types is found: angular movement potentials are more-intensely utilized than metric movement potentials, particularly those of the foreground structure of the network. In addition, as the simulation results show, these street network's structural properties contribute to a certain degree of independent of the aggregate movement flows on individuals' spatial behavior. The movement flows of different agent types subsequently tend correlate with the angular structure of the street network. These tendencies are consistent with the network's pattern and size of the study cites – Beer Sheva and Kfar Saba. Overall, this study sheds light on how structural properties within the network create coherent and dominant angular structure that fit movement flows. However, further work is needed based on real-world variables that are related to the relationship between street networks' structural properties and movement flows, such as land-use patterns.

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