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FOREGROUND NETWORKS DURING URBAN EVOLUTION:
The effect of length and connectivity on street network integration

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Abstract

The relationship between local and global aspects of street networks is discussed according to the effect of size, length and connectivity of foreground network lines on the axial map integration. The foreground network is defined according to the set of lines with choice (betweenness centrality) values above a high percentage threshold. The quantitative analysis of three historical stages of cities on the Adriatic and Ionian coastline is supported by a unique database of axial map representations. The empirical evidence demonstrates that the foreground network length and connectivity, rather than size, explain axial map integration at high and significant levels. This effect is stronger for larger cities; it transcends various national contexts in the region, while it is more evident for cities that include gridiron street patterns. By comparing between actual and theoretical axial maps, the study shows that the link between local aspects of foreground networks and global integration is a unique feature of urban street networks rather than a generic network feature.

Keywords: *street network, foreground network, choice, metric length, connectivity, integration*

Theme: *Urban Space and Social, Economic and Cultural Phenomena*

Introduction

One of the most powerful descriptions of the syntactic structure of cities (Hillier, 1996; Hillier and Hanson, 1984; Peponis and Wineman, 2002) consists of highlighting quasi-linear radials that connect the main center of the city with the periphery, and the multiple centers with each other – they reflect the linear movement between specific destinations within the city. While it is shown that these lines tend to include some of the longest lines in the axial map of the city (Hillier, 1999; Hillier 2002; Hillier et al. 2010), the effect of topological and metric properties of these lines on the global syntactic structure of the city is not fully scrutinized. The relationship between metric and topological properties of axial maps has occupied an increasingly important role in space syntax studies (Ratti 2004; Hillier and Iida, 2005; Peponis et al., 2008; Hillier et al. 2010). These studies have proposed theoretical generalizations on the interaction between metric and topological aspects of street networks. However, their findings are based on the analysis of single or a few cities. To date, no studies have offered generalizations on the relationship between metric and topological aspects of street networks based on the analysis of large samples of cities.

Topological choice of an axial line, also called betweenness centrality in graph theory, measures the number of times a line acts as a bridge along the shortest path between two other lines in an axial map. Hereafter, 'topological choice' is referred to as 'choice'. Volchenkov and Blanchard (2008) have considered choice alongside the other topological measure of integration to study power-law distributions in axial lines combined from the axial maps of five cities. Since it was made part of the Depthmap analytical toolbox (Turner 2001, 2010), the measure has found its widest application in the study of foreground network in urban systems (Hillier, 2009). The foreground network has been defined as the set of streets with high choice that connect urban centers in a city. The measure of choice is used in analyzing metric, topological and geometric distances of street networks represented with street segments between intersections. The distribution of syntactic and choice values according to various radii has been shown to demonstrate the application of the principles of centrality and fuzzy boundaries in cities.

Similar to segment analysis, the calculation of choice in axial map analysis tends to highlight a fundamental spatial structure of the city, consisting of streets that act as bridges during travels between most locations in the city. However, in contrast to segment representations, the measure of choice in axial maps has not been discussed as thoroughly, in part since the values of choice in axial maps tend to concentrate in a few lines that preempt the correlations with behavioral and space use data in cities.

The aim of this paper is to discuss the effect of metric and topological aspects foreground network streets on the overall topological characteristics of the street network. It differs in two main levels from previous studies on this subject: first, it makes generalizations based on the empirical analysis of a large sample of cities studied according to three historical stages; second it explains the integration of an axial map according to connectivity and metric length of a few lines with the highest topological choice value.

Foreground Network

A sample of 62 cities from a previous study (Shpuza, 2013) is considered comparatively according to three historical stages between 1800 and 2010 in order to explore the effect of foreground networks on the global spatial structure of the city. The cities are located in six countries along the coastlines of Adriatic and Ionian seas that stretches from the Mani Peninsula in Peloponnese to the southern point of Sicily (table 1). The first historical stage is chosen from the 19th century; the middle stage is chosen to be around WW2; the third stage includes maps from the period 2002-2010. Street networks of historical stages are represented with axial maps drawn manually over raster images. Axial maps were analyzed with UCL Depthmap software (Turner, 2010). Hereafter, 'axial lines' are referred to as 'lines'.

The sample includes a wide variety of street patterns in the historical cores and in the accrued areas. One of the most noted characteristics in the region is the nature of two kinds of 19th century extensions: First, in many cities in Italy and Greece, the added areas were organized in orthogonal grids (i.e. gridiron patterns) following Napoleonic influence in Italy and Greece (Calabi, 1984; Wassenhoven, 1984). Second, in all coastal cities of Albania, Montenegro, Croatia and Slovenia, the accrued areas completely lack gridiron streets, with the exception of Pula and Rijeka on the Croatian coast.

The foreground network is defined according to the lines with choice values above a threshold. Four thresholds are compared in order to determine the foreground network with most effect on the overall axial map: 1) the highest 90% choice values, 2) the highest 80% values, 3) 70% choice values, and 4) the 60% choice. The 90% subset is produced by removing lines with 'deep blue' color in the measure of choice layer, given the default 10 colors setting in Depthmap. Second, a smaller 80% foreground network is defined by further removing lines within the next 10% choice range in 'lighter blue' (figure 1), and so on for the other two choice thresholds. The effect of foreground network on axial map integration is scrutinized at three levels: the number of lines, the length of lines, and the connectivity of lines of the foreground network.

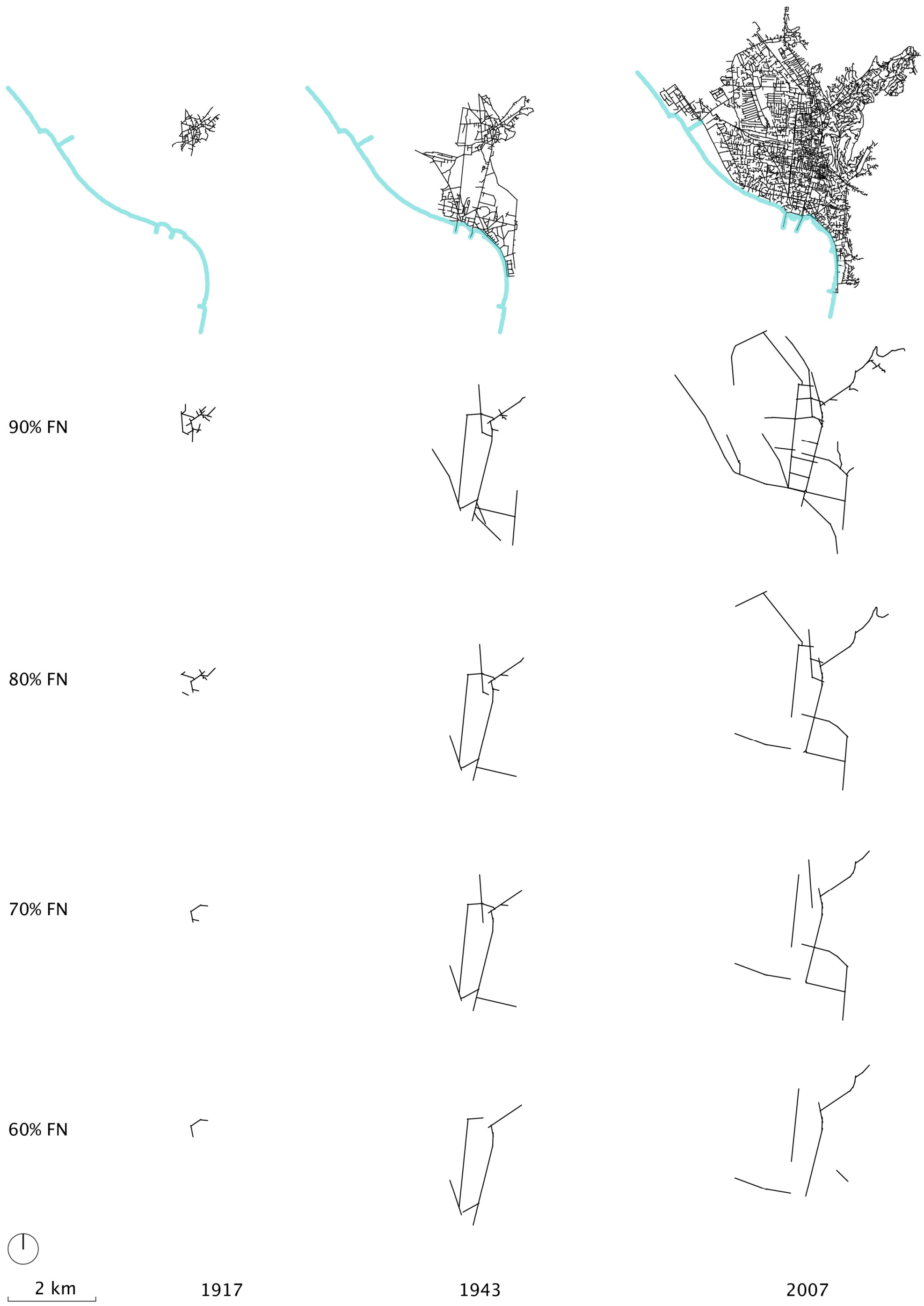

Figure 1 Vlorë in three historical stages 1917, 1943, 2005 (from left to right). Axial maps with coastline in light blue (top row); 90% foreground networks (second row); followed by 80%, 70% and 60% foreground networks.

Foreground Network Size

First, let us examine the relationship between foreground network size and axial map size, before we address whether the foreground network size has an effect on the axial map integration. Network size is measured according to the number of axial lines (table 1).

Table 1 (first part) The sample of sixty-two towns and cities along the Adriatic and Ionian coast (listed counterclockwise from Peloponnese to Sicily) over three historical stages. Size of actual and theoretical axial maps AM and foreground networks FN for cities in third historical stage. N is the number of axial lines; NFN90 is the number of lines in the 90% choice foreground network; NFN80 is the number of lines in the 80% choice foreground network etc. Cities with a considerable percentage of area covered by grid street patterns are denoted with (*).

	City Country	Historical Stage Year			Actual					Theoretical	
					AM	FN				AM	FN
					N	N_{FN90}	N_{FN80}	N_{FN70}	N_{FN60}	N	N_{FN80}
	Historical Stage	1	2	3	3	3	3	3	3	3	3
	GREECE										
1	Koroni	1829	1945	2003	284	110	50	27	16	260	55
2	Methoni	1831	1945	2003	325	31	11	7	3	253	58
3	Pylos *	1830	1943	2003	349	102	53	27	16	338	58
4	Zakynthos	1892	1934	2003	610	50	27	11	7	616	35
5	Patras *	1894	1943	2007	5730	121	68	33	18	5385	71
6	Aigio *	1836	1951	2002	1665	72	26	13	8	1239	114
7	Korinthos *	1894	1943	2003	793	63	39	28	18	732	40
8	Nafpaktos *	1837	1951	2006	822	50	18	11	10	824	19
9	Lefkada	1827	1948	2005	618	36	18	11	5	494	31
10	Vonitsa	1828	1951	2003	425	46	17	9	5	369	42
11	Preveza	1800	1944	2003	934	33	15	10	5	754	63
12	Corfu	1805	1955	2004	3177	97	47	31	22	2872	116
	ALBANIA										
13	Sarandë	1925	1945	2006	2418	225	141	67	42	2390	143
14	Vlorë	1917	1943	2007	5607	111	39	19	13	4731	54
15	Durrës	1876	1943	2007	6401	81	43	23	18	6004	23
	MONTENEGRO										
16	Budva	1838	1941	2005	1123	114	59	34	23	945	34
17	Kotor	1838	1943	2005	768	76	42	21	16	763	45
	CROATIA										
18	Dubrovnik	1837	1943	2007	1633	174	89	51	36	1612	100
19	Korčula	1836	1940	2003	373	73	44	36	28	410	54
20	Hvar	1827	1950	2007	583	103	71	56	28	569	67
21	Stari Grad, Hvar	1834	1968	2007	525	75	36	26	17	528	42
22	Makarska	1835	1934	2005	826	26	8	7	6	794	54
23	Split	1831	1951	2008	6359	140	57	34	19	5091	68
24	Šibenik	1825	1956	2010	1339	94	38	23	17	1293	44
25	Zadar	1826	1943	2008	4176	112	54	24	18	3642	88
26	Senj	1839	1944	2009	736	92	51	26	15	726	72
27	Rijeka-Kastav	1865	1950	2007	12003	429	228	172	115	11184	284
28	Opatija-Volosko	1897	1943	2007	1068	121	51	31	20	1070	52
29	Pula *	1820	1942	2007	2017	108	49	32	20	1652	77
30	Rovinj	1820	1943	2006	1079	125	63	45	35	983	69
31	Poreč	1820	1943	2006	820	51	27	14	9	813	45
32	Umag	1873	1943	2005	701	41	29	12	6	698	39

Table 1 (second part)

	City Country	Historical Stage Year			Actual					Theoretical	
					AM	FN				AM	FN
					N	N_{FN90}	N_{FN80}	N_{FN70}	N_{FN60}	N	N_{FN80}
		1	2	3	3	3	3	3	3	3	3
	SLOVENIA										
33	Piran	1818	1943	2005	389	90	52	29	19	361	41
34	Izola	1818	1935	2009	866	35	16	9	6	804	35
35	Koper	1819	1956	2006	1933	77	48	30	17	1889	51
	ITALY										
36	Muggia	1818	1942	2006	684	115	66	45	39	661	44
37	Trieste *	1836	1942	2006	7295	115	38	25	21	5890	161
38	Monfalcone	1892	1944	2007	2309	80	32	18	14	2179	37
39	Grado *	1825	1943	2005	351	43	22	10	7	350	19
40	Venice	1838	1956	2005	3440	269	156	95	61	3005	142
41	Chioggia-Sottomarina	1808	1933	2007	2603	101	47	25	16	2357	73
42	Cesenatico *	1818	1933	2007	910	51	24	18	10	878	26
43	Fano *	1818	1951	2007	1672	61	23	12	8	1454	40
44	Ancona *	1818	1943	2007	4506	80	29	13	8	4458	79
45	Ortona *	1819	1943	2007	545	71	40	14	10	502	56
46	Manfredonia *	1819	1943	2007	1242	56	32	15	10	1222	38
47	Barletta	1819	1943	2006	1328	42	18	13	9	1071	52
48	Trani *	1819	1943	2005	2123	25	9	6	6	1959	22
49	Molfetta *	1819	1943	2007	1134	35	10	7	3	894	35
50	Bari *	1819	1942	2006	2814	73	27	16	9	2164	19
51	Monopoli *	1800	1943	2007	1615	58	23	16	12	1556	29
52	Brindisi *	1819	1943	2005	2248	80	46	26	18	2051	48
53	Otranto	1820	1943	2007	519	89	42	17	10	498	78
54	Gallipoli *	1836	1943	2006	716	42	19	12	8	656	33
55	Taranto *	1863	1943	2007	2186	51	31	23	17	2070	35
56	Crotone *	1905	1943	2005	803	32	15	7	5	632	34
57	Reggio di Calabria *	1844	1943	2002	3275	135	54	21	12	2670	26
58	Messina *	1844	1942	2002	7298	104	46	24	18	6783	86
59	Catania *	1820	1942	2007	9914	141	28	16	11	8584	154
60	Augusta *	1823	1943	2007	485	47	25	17	17	713	31
61	Siracusa *	1842	1942	2005	2769	66	34	22	11	2520	79
62	Avola *	1850	1955	2007	1271	11	4	3	2	868	36
	Min	1800	1933	2002	284	11	8	3	2	350	19
	Max	1925	1968	2010	12003	429	228	172	115	11184	284
	Mean	1839	1944	2006	2186	88.0	43.0	25.4	16.9	1963.4	61.2

The scatterplot between N and N_{FN90} has an exponential distribution of data points, (figure 2), with a correlation (R^2=0.409). All correlations presented in the paper are significant at p<0.0001. The log-log plot between the two measures shows an even distribution of data points (figure 2), although the correlation is lower (R^2=0.319) than the normal scale plot. Therefore, the relationship between axial map size and foreground network size is considered according to the logarithmic scale.

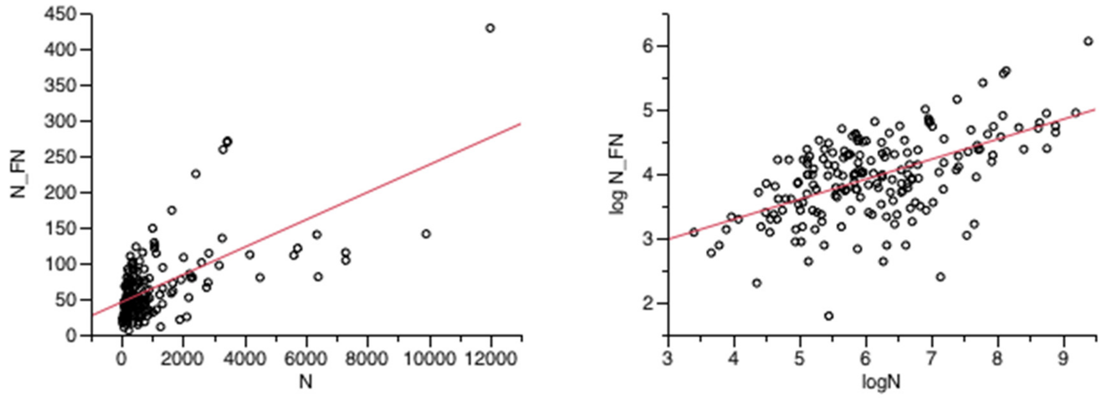

Figure 2 Scatterplots of *N* vs N_{FN90} in normal scale (left) and log-log scale (right) for sixty-two Adriatic and Ionian coastal cities in three historical stages.

The coefficient *R* is calculated as the ratio between N_{FN} and *N* in logarithmic scale

$$R = \frac{\log N_{FN}}{\log N} . \quad (1)$$

The ratio *R* is calculated for four foreground networks, 90%, 80%, 70% and 60%. The minimum value of R_{90} is found for Chioggia-Sottomarina 1808 (0.33), while the maximum for Korinthos 1894 (0.91). The mean value of R_{90} for three historical stages S1, S2, and S3 decreases consecutively (0.71 → 0.67 → 0.60). The mean value of ratio R_{80} decreases consecutively (0.58 → 0.54 → 0.49), the mean R_{70} decreases (0.48 → 0.45 → 0.42), while the mean R_{60} changes (0.39 → 0.38 → 0.36).

The scatterplot between values of integration I_A and R_{90} for the sample of 186 cases is studied to test whether the proportion of the 90% foreground network size to axial map size explains the global integration of the city (figure 3). The linear regression between the two measures shows a negative correlation (R^2=0.306). Similarly, the regression between I_A and R_{80} for the 80% foreground network shows a negative correlation (R^2=0.337), indicating a weak effect of the proportion of lines of the foreground network on the axial map integration. The effect of the 70% and 60% foreground network size on integration is even smaller with regression between I_A and R_{70} at (R^2=0.325), and between I_A and R_{60} at (R^2=0.303).

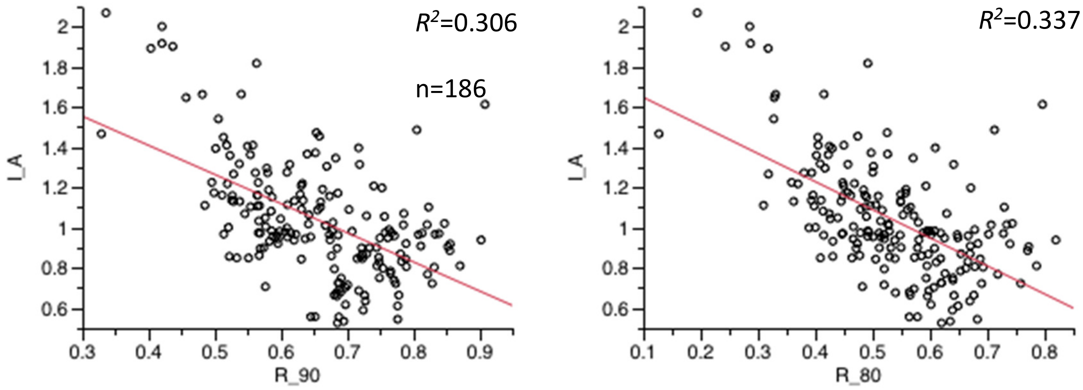

Figure 3 Scatterplots of I_A vs R_{90} (left), and I_A vs R_{80} (right) for sixty-two Adriatic and Ionian coastal cities in three historical stages.

Foreground Network Length

The second step involves examining the effect of foreground network length on axial map integration. While the axial map integration I_A is not affected by the mean length $L^\wedge$ of the axial map, shown by the correlation (R^2=0.245) in figure 4, the correlation between values of integration I_A and foreground network length $L^\wedge_{FN90}$ is (R^2=0.557) indicating that the effect of metric properties of streets on integration can be explained according to the subset of lines in the foreground network. The higher the mean length of lines in the foreground network, the higher the axial map integration. This correlation is also much higher than the correlations between the proportion of network size and integration, discussed above.

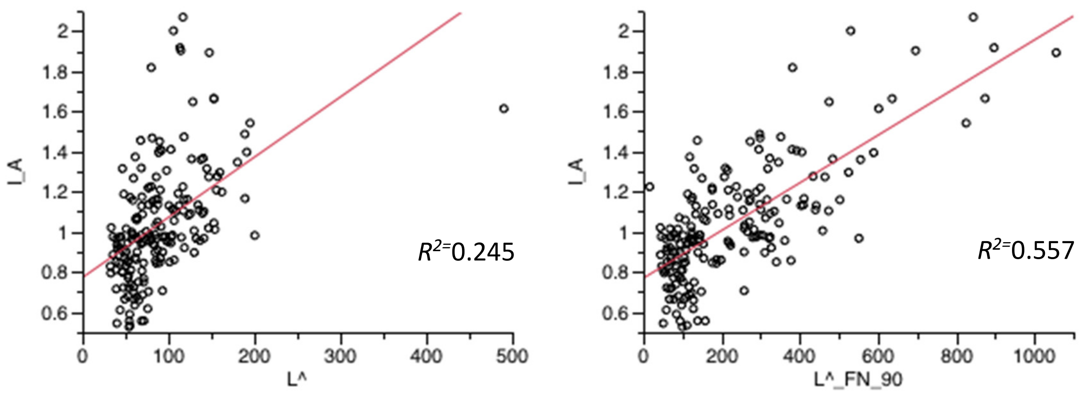

Figure 4 Scatterplots of I_A vs $L^\wedge$ (left), and I_A vs $L^\wedge_{FN90}$ (right) for sixty-two Adriatic and Ionian coastal cities in three historical stages.

The distribution of data points in the plot I_A vs $L^\wedge_{FN90}$ resembles a hockey stick shape, composed of a cluster of points in the lower left corner vertically placed, thus lacking correlation, and a more distributed cluster of points up and to the right following the regression line (figure 4). This raises the possibility that subsamples of cities could have distinct correlations between the two measures. The sample is thus considered split into: 1) two subsamples, one with and one without cities containing gridiron street patterns; 2) three subsamples based on historical stages; 3) three subsamples based on three band sizes of axial maps.

For cities with grids street patterns, the correlation I_A vs $L\text{^}_{FN90}$ increases to (R^2=0.584), slightly more than the correlation for the entire sample; it decreases to (R^2=0.326) for the subsample of cities without grids (figure 5). This indicates that the foreground network length is a better predictor of integration in cities that contain gridiron street patterns than in those that do not. It should be noted that the foreground network in cities with grid patterns is composed to a great extent of streets that are part of grid patterns.

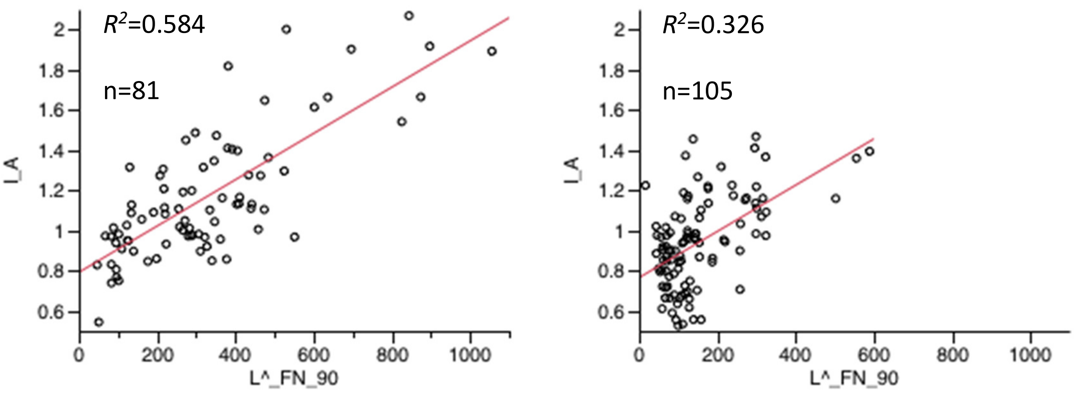

Figure 5 Scatterplots of I_A vs $L\text{^}_{FN90}$ for two subsamples of 27 cities with grids in three evolution stages (right), and 35 cities without grids (left).

The correlations of I_A vs $L\text{^}_{FN90}$ for all three subsamples split according to historical stages improve in comparison to the entire sample (figure 6), indicating that the impact of foreground network length on integration has different manifestations during historical stages. It is the highest in S1, it decreases in S2, and it increases again in S3, as shown by the correlation coefficients (R^2=0.695, 0.573 and 0.747).

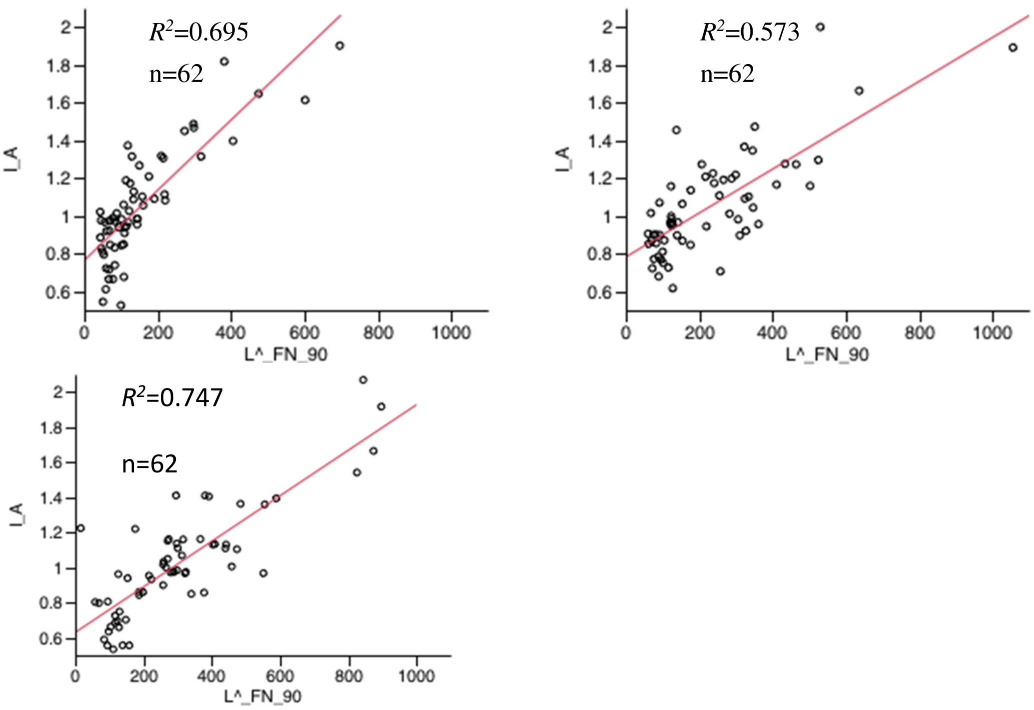

Figure 6 Scatterplots of I_A vs $L\text{^}_{FN90}$ for three subsamples of cities in first historical stage (up left); second stage (up right); third stage (left).

The correlations of I_A vs $L\hat{}_{FN90}$ for three subsamples split according to axial map sizes increase consecutively from smaller to medium to large size cities (R^2=0.540 → 0.584 → 0.788), (figure 7). This shows that larger the city size, the greater the effect of foreground network length on integration. The growth during urban evolution is thus associated with an increasing impact of metric length of foreground network on topological structure of cities.

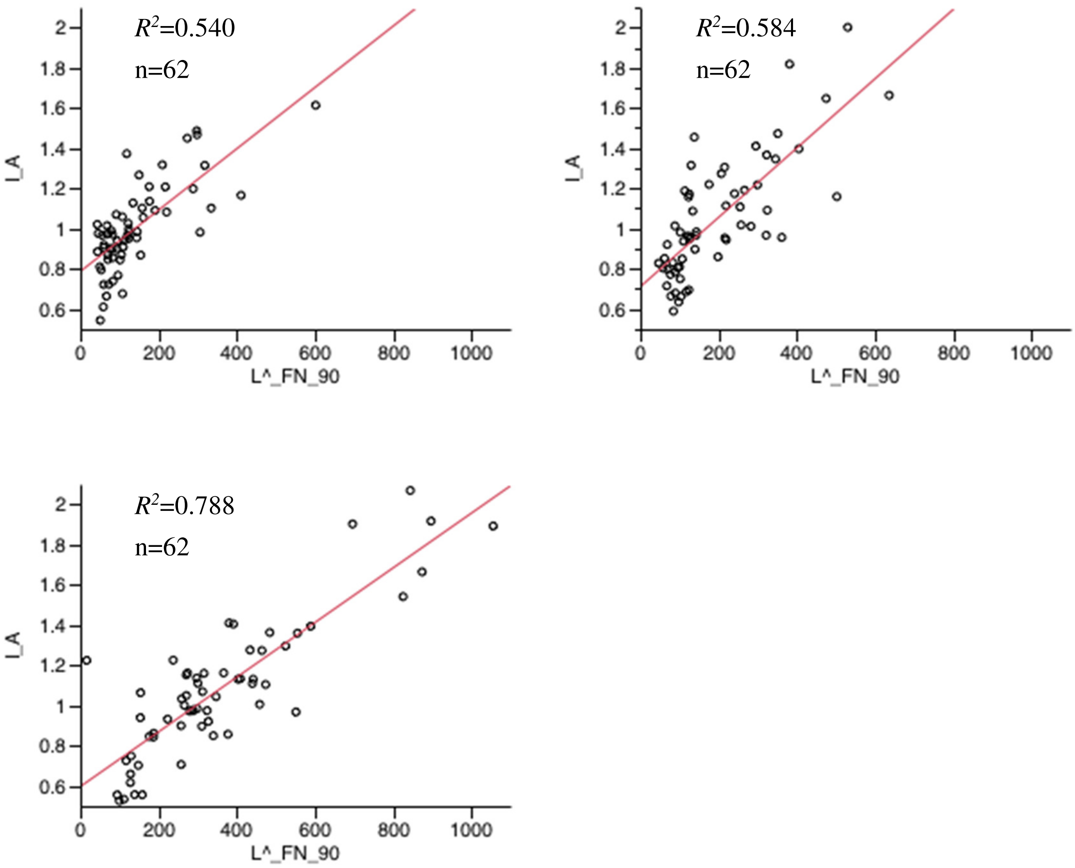

Figure 7 Scatterplots of I_A vs L_{FN90} for three subsamples of cities in three size ranges: lower 62 (up left); middle 62 (up right); and upper 62 (left).

Further, the 80%, 70% and 60% foreground networks are analyzed according to the same steps as above for the purpose of understanding the effect of the choice value range on integration. These foreground network correlations are discussed only according to the regression coefficients without illustrating the scatterplots (table 2).

Table 2: Linear regression coefficients R^2 in scatterplots I_A vs $L\hat{}$, I_A vs $L\hat{}_{FN90}$, I_A vs $L\hat{}_{FN80}$, I_A vs $L\hat{}_{FN70}$, I_A vs $L\hat{}_{FN60}$, I_A vs $C\hat{}$ and I_A vs $C\hat{}_{FN80}$ calculated for the Adriatic and Ionian sample and its subsamples. The highest coefficient values for the sample and subsamples are shown in bold.

Sample, subsample		Length					Connectivity	
	n	I_A vs $L\hat{}$	I_A vs $L\hat{}_{FN90}$	I_A vs $L\hat{}_{FN80}$	I_A vs $L\hat{}_{FN70}$	I_A vs $L\hat{}_{FN60}$	I_A vs $C\hat{}$	I_A vs $C\hat{}_{FN80}$
Adriatic Ionian	186	0.245	0.557	0.560	0.545	0.540	0.331	0.653
Gridiron	81	0.138	0.584	0.577	0.551	0.542	0.194	0.675
Non-Gridiron	105	0.195	0.326	0.385	0.390	0.410	0.339	0.526
1st Stage	62	0.269	0.695	0.589	0.568	0.598	0.340	0.556
2nd Stage	62	0.244	0.573	0.557	0.535	0.509	0.442	0.755
3rd Stage	62	0.370	0.747	0.749	0.739	0.720	0.338	0.756
Small	62	0.345	0.540	0.582	0.536	0.511	0.338	0.392*
Medium	62	0.253	0.584	0.645	0.651	0.666	0.498	0.852
Large	62	0.353	0.788	0.793	0.779	0.717	0.434	0.792

* The regression coefficient increases to 0.667 after removing the outlier Chioggia-1808.

Most of the highest correlations between I_A and $L\hat{}_{FN}$, shown in bold in table 2, are found for the 80% foreground network: for the sample as a whole, for the subsample of third historical stage cities, the subsample of 62 small size cities, and 62 large size cities. In contrast, in cities with grid patterns integration is most affected by the length of the 90% foreground network, and in cities without grid patterns integration is most affected by the length of 60% foreground networks. Also, the subsample of 62 medium size cities has the highest correlations for the 60% foreground network. The 90% foreground network shows the highest correlation between length and integration for the first and the second historical stage cities. However, the differences observed among correlations in four foreground networks are small. Further, the analysis will focus on the 80% foreground network.

Foreground Network Connectivity

Third, let us examine the effect of foreground network connectivity on axial map integration. As expected, the axial map integration I_A has a weak correlation with the mean connectivity $C\hat{}$, shown by the correlation (R^2=0.331) in figure 8. The measure of $C\hat{}_{FN80}$ quantifies the mean connectivity of lines that belong to the foreground network measured in the context of the original axial map, and not the foreground network. For the 80% foreground network, the correlation between I_A and $C\hat{}_{FN80}$ is much higher (R^2=0.653). The higher the mean connectivity of lines in the foreground network, the higher the axial map integration. The correlation is also higher than the correlations found between length and integration.

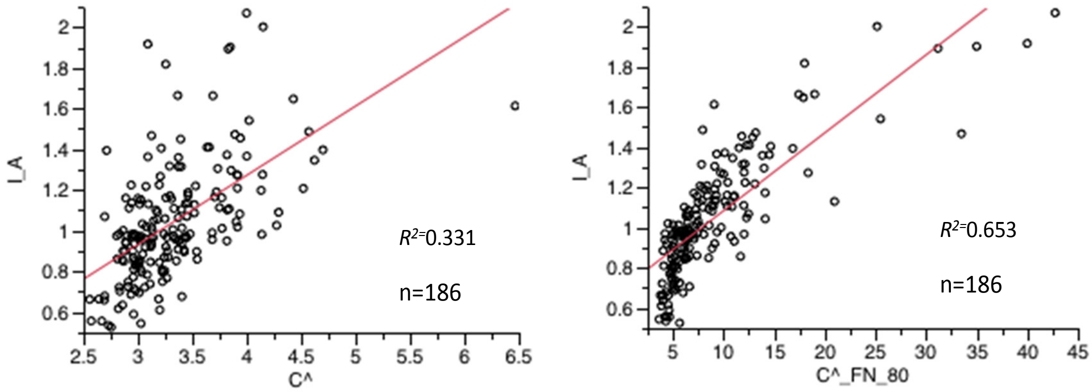

Figure 8 Scatterplots of I_A vs $C^\wedge$ (left), and I_A vs $C^\wedge_{FN80}$ (right) for sixty-two Adriatic and Ionian coastal cities in three historical stages.

The relationship between foreground network mean connectivity and axial map integration is examined for eight subsamples similar to the previous section. Most correlations between connectivity and integration are higher than those between length and integration (table 2). Exception to this is the subsample of 62 smallest cities where the correlation between connectivity and integration (R^2=0.392) is lower than the one between length and integration. A closer look of the scatterplot shows that the outlier Chioggia-1808 affects the low correlation. The 80% foreground network in Chioggia-1808 consists of two lines of the main spine that connect most other streets in the city. When the outlier is excluded, the correlation improves to levels comparable with other subsamples (R^2=0.667). In conclusion, many regression coefficients that are close or above the (R^2=0.8) mark indicate high levels of predictability of the axial map integration from the mean connectivity of foreground network.

Unique Features of Foreground Networks in Cities

Is the relationship between local properties of foreground networks and global properties of axial maps a generic network feature or is it unique to cities? The question is tackled by comparing the correlations for the sample of Adriatic and Ionian cities to a sample of theoretical axial maps generated by consistently modifying the actual axial maps. Theoretical maps are constructed by means of removing axial lines or portions of axial lines that fall inside a shape region defined by offsetting the urban shape perimeter inward with the distance

$$o = \sqrt{\frac{A}{\pi}} - \sqrt{\frac{A}{2\pi}}, \qquad (2)$$

where A isthe area of urban shape hull. The formula implies the removal of a circular hole from the core of a circle such that the area of the remaining donut shape equals half of the original circle.

Each city is modified according to the offset shape removal thus producing a sample of 186 theoretical axial maps (figure 9). Urban shapes are always less compact than the circle, therefore holes removed according to the offset distance defined above are always smaller than half of the urban area. There are cases in the sample when offsetting the urban shape perimeter produces regions scattered in several islands. Despite many elongated and fragmented urban shapes in the sample, offsetting the perimeter always produces internal holes and guarantees the generation of theoretical axial maps that differ from the original actual maps. In general, given that urban shapes become more elongated and more fragmented from the first historical stage to the third, the removed holes are relatively smaller for larger cities. This could explain the smaller differences between actual and theoretical axial maps for large and third stage cities, discussed further on.

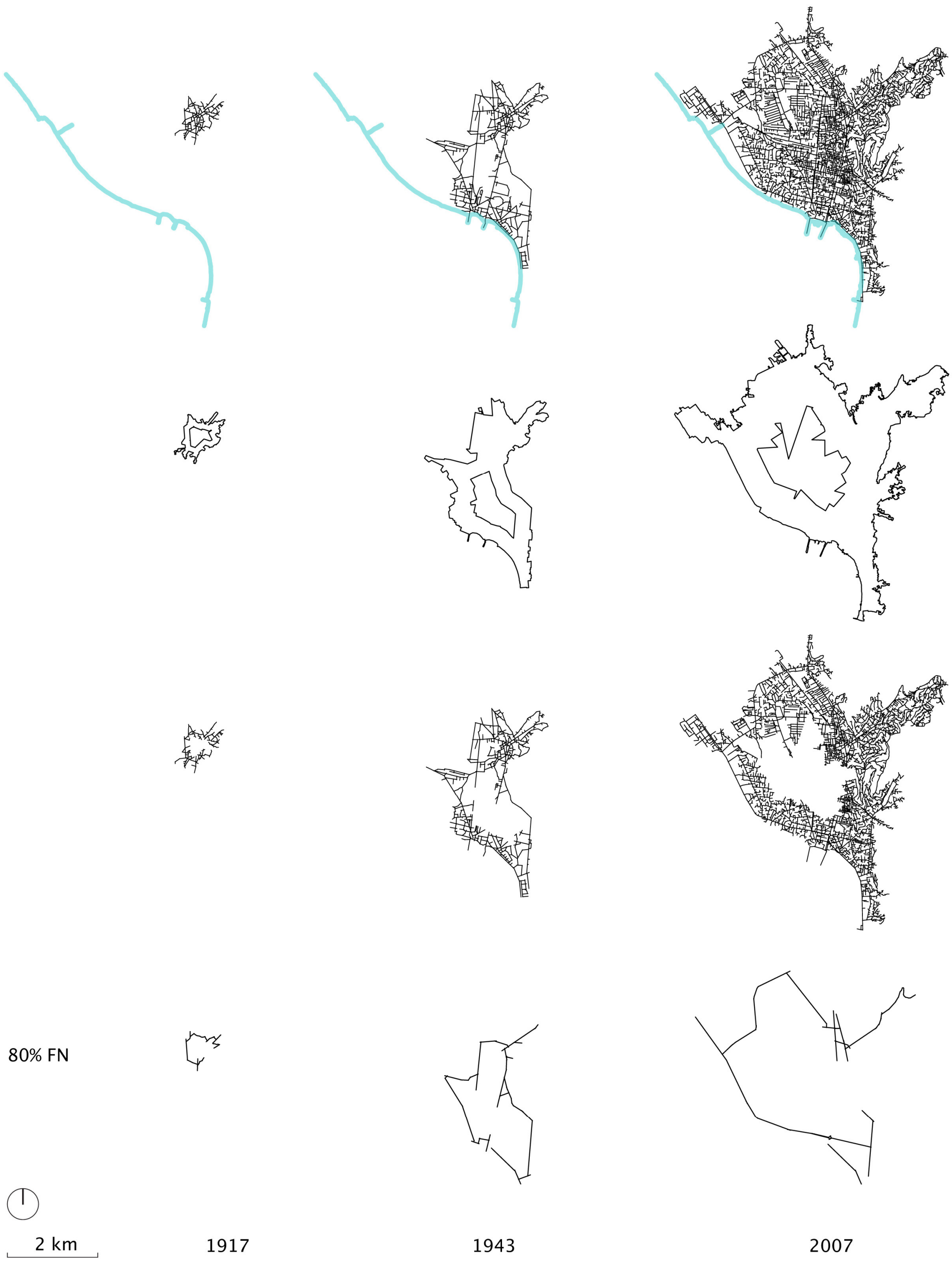

Figure 9 Vlorë in three historical stages 1917, 1943, 2005 (from left to right). Axial maps with coastline in light blue (top row); donut areas defined by offsetting the urban shape perimeter and removing holes (second row); axial maps of modified urban areas (third row); their 80% foreground networks (above).

The modification of the axial maps according to regions defined by offsetting the urban shape perimeter has three main effects: First, in most cases, the removed holes include parts of dense historical core in cities, leaving generally a sparser grid around the donut region. Second, the removal of central regions interrupts the main street structure radiating from the center of the city, therefore producing axial maps with circular or C-shape peripheral foreground networks. Third, the deletion of central areas cuts through several urban blocks, thus generating a great number of dead-end axial lines that connect to the emerged peripheral foreground network in hierarchical fishbone patterns.

The sample of theoretical axial maps is studied according to the effect of 80% foreground network mean length $L^{\wedge}_{FN80\_T}$ and mean connectivity $C^{\wedge}_{FN80\_T}$ on integration I_{A_T} of theoretical donut axial map. Theoretical axial map measures are denoted with the additional subscript 'T'.

For theoretical axial maps, the correlations between foreground length and global integration are low, having a maximum of (R^2=0.600) for the 62 largest cities. The comparison between actual and theoretical cities (table 3) shows that the correlations decrease for theoretical cities. The extent of this change, quantified by the percentage of the relative change, ranges between -10% and -43% for foreground network length versus axial map integration correlations. Thus, the removal of central regions in axial maps leads to a weaker effect of length on axial map integration. This seems to suggest that, since theoretical donut shapes affect an increase in distances between locations inside the shape, theoretical axial maps lack the distance-minimizing mechanism of foreground networks in actual cities.

Table 3 Comparison between linear regression coefficients R^2 in scatterplots of actual axial maps I_A vs $L^{\wedge}_{FN80}$, I_A vs $C^{\wedge}_{FN80}$ and theoretical axial maps I_{A_T} vs $L^{\wedge}_{FN80\_T}$, I_{A_T} vs $C^{\wedge}_{FN80\_T}$ for the Adriatic and Ionian sample and its subsamples. The highest coefficient values for the comparison between actual and theoretical sample and subsamples are shown in bold.

Sample, subsample		Length			Connectivity		
	n	I_A vs $L^{\wedge}_{FN80}$	I_{A_T} vs $L^{\wedge}_{FN80\_T}$	Rel. Change %	I_A vs $C^{\wedge}_{FN80}$	I_{A_T} vs $C^{\wedge}_{FN80\_T}$	Rel. Change %
Adriatic Ionian	186	0.560	0.408	-27	0.653	0.548	-16
Gridiron	81	0.577	0.329	-43	0.675	0.545	-19
Non-Gridiron	105	0.385	0.338	-12	0.526	0.427	-19
1st Stage	62	0.589	0.486	-17	0.556	0.427	-23
2nd Stage	62	0.557	0.362	-35	0.755	0.574	-24
3rd Stage	62	0.749	0.556	-26	0.756	0.699	-8
Small	62	0.582	0.351	-40	0.392*	0.434	11*
Medium	62	0.645	0.580	-10	0.852	0.753	-12
Large	62	0.793	0.600	-24	0.792	0.734	-7

* The relative change is -35% after removing the outlier Chioggia-1808.

The relative change for the correlations between foreground network connectivity and axial map integration ranges between -7% and -35%, slightly less than the change observed for the relationship between length and integration. Given the central location of holes in theoretical donut shapes, the centrality-maximizing mechanism of foreground networks is weakened in theoretical cities.

In conclusion, the strong correlations between local aspects of foreground networks and global axial map integration observed for actual cities, which are weaker for theoretical axial maps, suggest the existence of unique features of urban systems and illustrate the application of the centrality principle in urban street networks (Hillier, 2002). The degree to which length and connectivity of a foreground network explain the axial map integration can quantify the intelligibility of an urban street network. In other words, cities that are located far from the regression lines in scatterplots of length versus integration, and connectivity versus integration, are less intelligible than those located near the slopes. Theoretical cities produced by removing central regions of axial maps, also illustrate examples that lack the intelligibility of street networks.

Conclusions

The study addresses the relationship between metric and topological aspects of urban street networks by quantifying the effect of foreground network mean length and mean connectivity on the axial map integration. The study demonstrates significant results supported by a sample of 62 cities on the Adriatic and Ionian coastline analyzed in three historical stages. The foreground network is defined in four resolutions according to lines with the 90%, 80%, 70% and 60% highest values of choice (betweenness centrality), while it is shown that the 80% foreground network has the strongest impact on the overall axial map. The impact of foreground network on the axial map integration does not depend on the ratio between the foreground network size and axial map size, and is strongest for the measure of connectivity followed by the metric length. The effect is stronger for larger cities, for those in the third historical stage 2002-2010, and for those that contain gridiron street patterns. The study demonstrates that strong correlations of foreground network length and connectivity to axial map integration are a unique feature of urban street networks rather than a generic feature of all networks. They illustrate the application of the principle of centrality in street networks, and can be used to gauge the intelligibility of street networks.

Foreground networks often result from the system of historical roads connecting the city to neighboring settlements. Also, they constitute the set of streets that undergo major transformations in cities with fluid growth patterns. Therefore, the study not only demonstrates important links between metric and topological aspects of street networks, but also suggests important insights about urban growth processes. In one hand, the findings could help formulate urban planning strategies at the city scale, and in the other hand, they support urban design principles that prioritize interventions on foreground streets.

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