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Configurational properties and the internal geography of local-regional urban spaces:

findings of a multiscale-based analysis of the Tuscany's road-circulation networks.

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ABSTRACT

In the past decade, Space Syntax has made considerable strides towards understanding the spatial relations among local and regional continua, as numerous studies proved to address configurational properties within regional networks. Those became possible after the introduction and development of Angular Analysis, that, alongside the adoption of Road-Centre Line graphs, allowed researchers to stitch together different scales and model them into cohesive territorial representations. Despite that, configurational analysis of large networks still poses important challenges regarding models' morphological accurateness, which hinders observation of certain network properties like fractalities, which are obscured due to the insufficient detail on regional models' representation. With those points in consideration, we discuss the procedures to create a high-detail multiscale configurational analysis while maintaining morphological accurateness across scales and address the findings of this experiment. The objective is to compare the configurational properties of regional, provincial and municipality scales for the Tuscany region, describing the internal geography of urban contexts within the regional road-infrastructure to emphasize how disparities in connectivity and network density may concentrate movement or lead to spatial segregation. Beyond this, we discuss how the construction of several comparable configurational models can enable the investigation of certain network properties – fractality and homothetic behaviour. Then, we impart on how those recursive regularities in-between the urban-regional spatial structure, evidenced by Space Syntax' centrality measures of NAIN and NACH can be used and extrapolated to indicators suitable for exploratory studies in urban analysis.

KEYWORDS

Space Syntax, Regional Analysis, Homothetic Behaviour, Fractals, Road-networks

1 INTRODUCTION

Situated in central Italy, covering a territorial extent of 22,985 km^2, and with more than 66,700 km of roads, the Tuscany region holds an important position within the Italian road-infrastructure. Its relevance as one of the main connection paths between the northern and southern regions of the Italian peninsula can be traced back to the ancient Roman Republic. *Consular roads*, such as the *Via Aurelia* – constructed around 241 BCE, coursing through *Pisae, Luca* and *Cosa* (*Pisa*, *Lucca* and *Grosseto*); and the *Via Cassia* – built around 187 BCE, coursing through *Florentia* and *Pistoria (Firenze* and *Pistoia*), were set within Tuscany, at the time, the *Etruria* territory, and assured that the influence of Rome reached the rest of the European Continent. Although few traces of these ancient roads remain, materialized in small preserved paved sections and still-standing Roman bridges, the routes themselves continue to be used nowadays and constitute an integral part of the Italian highway system, above throughout Tuscany.

While a vast literature covers the characteristics of the historical (Hutton, 1926; Sordi, 1971; Villa, 1995) and current (Pazzagli, 2003; Caroti, Piemonte, 2010; Buratti et al., 2021) road-infrastructures in Tuscany, several gaps on the spatial knowledge about their configurational properties persist, as no extensive analyses that describe the entire regional road-circulation network configuration were conducted. The configuration provides useful indicators for both urban and regional planning as those can describe the movement patterns within urban areas and in-between territorial scales. It also has correspondences with the placement of economic activities (Altafini & Cutini, 2021) and may inform about the *relative importance* and overall fragility of certain areas in the road-network structure, being crucial to the territorial risk and post-disaster assessments (Giuliani et al., 2020; Cutini & Pezzica, 2020). In the same manner, multiscale configurational analyses of large road-networks can have a role in the theoretical developments oriented for urban-network analysis, as patterns that are *quasi-fractal* (Mandelbrot, 1977; 1983) or that exhibit recursive regularities tend to be manifested across the scales. Although discussing those spatial properties can be, at a first moment, oriented to the conceptual side of network analysis, if better understood, they could demonstrate themselves useful for urban studies, as means to identify certain characteristics of urban sprawl and urban-regional hierarchical dynamics, hence, merit further investigations.

In that regard, considering the potential developments involved in addressing movement patterns in large multiscale road-circulation networks, we proceed to construct a complete configurational analysis of the Tuscany regional road-circulation network, which comprises different scales based on the administrative limits of the region, province, and municipality. For that, we use the *Space Syntax Angular Analysis*' measures of Normalized Angular Integration (NAIN) and Normalized Angular Choice (NACH) to describe the centralities hierarchies for *to-movement* and *through-movement* within the system. This paper, beyond being an original description of the configurational patterns found in Tuscany's road-circulation network, has the objective to uncover and interpret certain recursive regularities that were found in the centrality hierarchies' distribution across the different scales, investigating their spatial characteristics to propose further uses for these network properties in urban-regional analysis.

2 SPACE SYNTAX APPLIED AT REGIONAL ANALYSIS

2.1 A brief evolution path of space syntax-based regional analysis.

Space Syntax was conceived as an urban-based spatial analysis, therefore, is mainly focused on understanding the *social logic of space* that existed behind the patterns of pedestrian movement (Hillier & Hanson, 1984). For that purpose, the *isovist* spatial representation (Benedikt, 1979), on which *Axial Analysis* was conceived, consisted of an appropriated spatial unit. It represented the "natural path" taken by an individual when considering its field of view. Therefore, an optimal approximation for pedestrian movement patterns within the spaces. Nevertheless, when vehicular movement is considered, the movement patterns depicted by *isovists* tend to be less accurate, moreover, across larger areas, *Axial Analysis* is excessively demanding in computational terms, as drawing *isovists* bound to extensive *convex spaces* can become a daunting task. While the *Angular Analysis* (Dalton, 2001; Turner, 2001) development was not focused on solving these issues, being interpreted, at the time of its conception, as an incremental development bounded to *Axial Analysis*, it is undeniable that its continued improvement as an independent analysis method contributed to addressing the large spaces problem. Alongside the adoption Road-Centre Line graphs (Turner, 2005; 2007) in place of the *isovist* representation, *Angular Analysis* has opened the possibilities for upscaling *Space Syntax* measures of movement beyond the boundaries of urban settlements, as the computational and methodological restrictions posed by *Axial maps* construction were supplanted. In addition to that, as demonstrated in the first studies of Turner (2009) and Van Nes (2009) the regional-based *syntactic measures* are capable "stitch" together relationships amongst different sized urban spaces and identifying movement patterns that define the regional centres and sub-centres, a dimension that remained rather untouched throughout *Space Syntax' Axial Analysis*. Krenz (2017) continued the discussion about the soundness of *Space Syntax-based* regional analysis, and incorporated notions from economics' locational theories (Christaller, 1933) in order to describe the centres and sub-centres hierarchical patterns verified in Turner (2009), thus proposing a review of the concepts about what is "local or global" in configurational analysis. In the decade that accompanied Krenz' (2017) study, several experiments proved to upscale the size of the road-networks that could be analysed with *Space Syntax*, which ranged from regional to superregional approaches, as in Hanna, et al., (2013); Serra et al (2015); Braga et al. (2017), Serra & Hillier, (2019), Altafini et al. (2020) and Altafini & Cutini (2021). As those contributions demonstrated robust results in addressing movement patterns within large networks, they established *Space Syntax-based* regional analysis as a plausible field of research that can be associated with the other consolidated exploratory methods for urban-regional analysis.

Still, despite these significant developments, *Space Syntax-based* regional analysis continues to present persistent hindrances in its diffusion. The main obstacle is the construction of detailed large road-circulation network configurational models. Given the considerable number of road-elements, modelling regional spaces with *Angular Analysis* often requires extensive computing times, which in turn, to be viable, require extensive graph generalization processes. In that aspect, this explains why most of the cited studies focus on a single scale assessment as, while simplification reduces computing complexity and time, it often renders comparisons among different scales inaccurate due to certain road-elements non-representation. This trade-off between generalization, processing times and accuracy is one of the main issues that remain to be addressed in *Space Syntax* methods, which still impede the general diffusion of its instrumentation as an alternative for regional road-circulation networks analysis. This gap ought to be taken as an opportunity for novel technical and methodological improvements on how *syntactic* measures are estimated, as the procedures for estimation remain largely the same since its creation by Turner (2001; 2005) and the normalization methods devised by Hillier et al. (2012). Moreover, it can also be an interesting field for the application of advancements related to *fractals* and recursive regularities found in urban-networks.

2.2 Urban-regional Networks: Fractals and Homothetic Behaviour

While discussed in the literature since the works of Batty & Longley (1986; 1994), the notion that cities are fractal structures – that is, self-similar across scales – has been explored in recent years to determine the underlying characteristics of urban networks (Kirkley et al, 2017; 2018). Still, few contributions were set to observe how these structural invariants function – or if they are also manifested – on urban-regional scales. An interesting take regarding fractals and regional spaces was proposed by Yamu & Van Nes (2017) that conceived a multifractal model to illustrate, from a hierarchical standpoint, the principles of city organization within regional spaces. Their model uses fractal measurements to define the urban hierarchies, assuming a topographical representation of centres and sub-centres, in a logic akin to Christaller's *Central Place Model* (1933) – which is also evidenced as a *quasi-fractal* model (Arlinghaus, 1985). Furthermore, it integrates *Space Syntax* local and global NAIN and NACH measures to evaluate the centrality logics that lead to different degrees of movement in each place, which also define cities' overall hierarchies. While Yamu & Van Nes (2017) approach interpreted fractals as means to determine the urban hierarchies' principles, the analysis of the fractal properties within the network structure at regional scales lies outside their scope. These points were, in part, addressed in Altafini & Cutini (2020) approach, which aimed to identify the nature of these structural invariants at regional scales after noticing visual similitudes in *betweenness centralities* hierarchies across different scales. They proposed that those recursive regularities found for *Space Syntax'* NACH measure could be interpreted as a sort of network-based *homothetic behaviour*. First defined in mathematics by Chasles (1852; 1870), *homotheties* (from *homothiesis*

– or *similar position*) occur when a transformation of an affine space by a factor λ results in invariance of this space form, orientation, and configuration, even though its overall scale (size) changes (Berger, 1987). Therefore, if two objects or parts of those objects have distinct sizes, yet conserve the same general form, they can be considered a *homothetic* toeach other. Fractals themselves are an example of *homothetic behaviour*, being objects that exhibit properties of self-similarity across different scales. In networks, the *homothetic behaviour* would imply that a section of the system, that is modelled independently, would retain a regularity in their centralities hierarchies' distribution when compared to a larger section of this network, modelled independently as well, that contains it. Therefore, the smaller network section must maintain its overall properties – configuration, hierarchies, and centrality values – when confronted with the same area modelled on another scale. Although thoroughly investigated and proved as a theoretical concept by Altafini & Cutini (2020), no practical uses in urban-regional analysis, other than cartographical developments, were proposed for these *homothetic behaviours* in this first contribution, which represents an opportunity for the development of the research.

3 DATASETS AND METHODS

The configurational analysis of Tuscany considers the regional road-infrastructure outlined in the *Grafo Iter.net*, a RCL graph dataset constructed and maintained by the Tuscany Region's *Sistema Informativo Territoriale ed Ambientale* - SITA (2016; 2019a). The database is constructed based on several pairs of Regional Technical Charts *(Carte Tecniche Regionali – CTR)*, scaled at 1:10,000 and 1:2,000. Therefore, this graph depicts road-infrastructures' morphologies with a level of detail up to the neighbourhoods or quarters in urban areas. This regional graph was then sectioned in QGIS 3.16 (2020) in accordance with Tuscany's administrative limits of region, province, and municipality. In this section, a buffer radius (1km for provinces; 300m for municipal areas) was applied to conserve the road-continuities across the administrative limits; where continuities could not be maintained, road-elements were sectioned and modelled independently, which causes some municipalities to have more than one model. Through this, we established individual road-graphs for regional (1), provincial (10), and municipal (289) scales. The graphs were then exported to DepthmapX 0.8 (2018) where we proceeded with the *Angular Segmentation* process and the estimations of *Angular Integration* and *Angular Choice*.

Initial modelling tests for the region resulted in unfeasible processing time-lapses for the original road-graph (Table 1). This can be attributed to the elevated number of segments that are created from the continuous road-elements in the *Angular Segmentation* process, that associated with the $O(n^2)$ algorithm used by DepthMapX 0.8 (2018) to calculate mean-depth and integration (Turner, 2004) results in long processing time-lapses.

Table 1: Comparison between the number of road-elements prior and after angular segmentation for the Tuscany Road Graph and their respective estimated processing time-lapses

	Road-elements prior Angular Segmentation	Road-elements after Angular Segmentation	Δ% Elements to segments	Processing time-lapse*

Non-Generalized	393.660	4.657.114	1083,02%	≈7,5 Months
Generalized	389.477	1.251.610	221,35%	≈2,5 Months
Δ% Generalization	1,06%	73,12%	-	-

* As estimated by the DepthmapX 0.8 software.

This impracticality prompted an ulterior generalization process that employed the Douglas-Peucker (Douglas, Peucker, 1974) simplification algorithm, available in QGIS 3.16 (2020) through the integrated GRASS GIS suite *(v.generalize)*. Since the intention was to preserve the overall network geometries, the generalization algorithm was applied with a limited angular tolerance value (0.1), that only removed small changes of direction in polylines that represented circles – highway accesses and roundabouts. This considerably diminishes the number of segments that are created after *Angular Segmentation* (Altafini & Cutini, 2020) (Table 1). The resulting generalized Tuscany Road-Graph with the established territorial divisions can be observed in Figure 1.

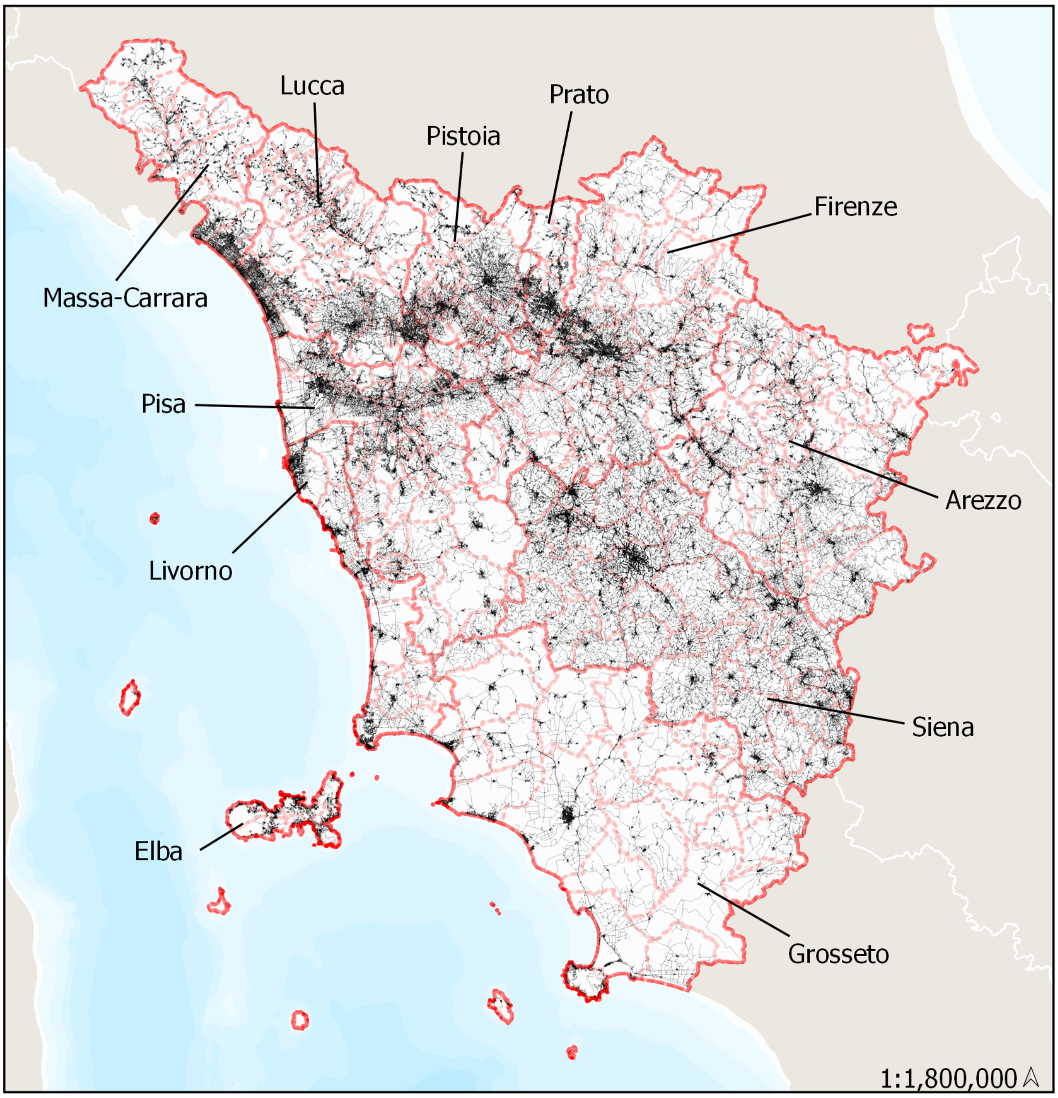

Figure 2: Tuscany regional road-circulation network and territorial divisions

Gains in terms of processing time-lapses for the regional model were significant, with important improvements in time-lapses also for the provincial and municipal scales (Table 2). At the same time, this limited angular generalization process contributes to maintaining morphological structure in the system, as it does not eliminate nor oversimplify the road-elements that represent crossings or access roads. In effect, maintaining such elements constitutes a difference that distinguishes the graphs in this research from the skeletal graphs used for previous studies at a regional scale (Turner, 2009; Serra & Hillier, 2019), moreover, allowing accurate comparisons across scales.

Table 2: Average approximated modelling processing times of region, provinces and municipalities for non-generalized and generalized networks converted in Angular segment maps.

	Region*	Provinces*	Municipalities*
Non-Generalized	≈7,5 Months	≈ 23 – 72 Hours	≈ 2 – 8 Minutes
Generalized	≈2,5 Months	≈ 7 – 18 Hours	≈ 10 seconds – 3 Minutes

* As estimated by the DepthmapX 0.8 software.

The generalized regional graph is sectioned in accordance with the proposed administrative limits, and once again we exported to DepthmapX 0.8 (2018) to construct the *Angular Integration* and *Angular Choice* models. With the base *Angular Segmented Analysis* models completed, we calculated the Normalized Angular Integration (NAIN) and the Normalized Angular Choice (NACH) (Hillier et.al 2012) in the same software (Table 3). This normalization process allows the comparison of configurational analysis that differ in terms of Total Depth, and therefore is a necessary step to any comparative multiscale analysis.

Table 3: Angular analysis centrality measures and formulas.

Indicator	Calculation in a grid with n road-elements
Angular Integration	$AInt_{\alpha}^{\ell}(x) = \frac{1}{MD_{\alpha}^{\ell}(x)}$
Normalized Angular Integration (NAIN)	$NAIN = \frac{n^{1.2}}{ATD_{\alpha}^{\ell}(x)}$
Angular Choice	$ACh_{\alpha}^{\ell}(x) = \sum_{i,z}^{n} \sigma^2 (j,x,z) \; with \; j \neq z$ $\sigma^2(j,x,z) = \begin{cases} \ell(i) \,.\, \ell(z), & path\ j\ to\ z\ through\ x \\ \ell(x) \,.\, \ell(z)/2, & x\ is\ the\ origin\ of\ i \\ \ell(x) \,.\, \ell(z)/2, & x\ is\ the\ destination\ of\ z \\ 0 & above\ conditions\ are\ false \end{cases}$
Normalized Angular Choice	$NACH = \frac{Log(ACh_{\alpha}^{\ell}(x)+1)}{log(ATD_{\alpha}^{\ell}(x)+3)}$

The modelled datamaps are then exported as *Mapinfo* (.mif) files to QGIS 3.16 (2020). In GIS we spatialized the configurational data using an equal count (quartile) distribution, in order to be able to highlight the integration cores and *preferential routes* on the system, as we can restrict the models to an iconography representing only the 20% of the total number of elements with highest centrality values for NAIN and NACH.

Alongside the configurational models, we also exported a table file (.xlsx) used to construct correlation graphics between the scales. These correlations follow similar principles to those used to estimate *Axial Synergy* (Hillier, 2007) – which correlates local (R3) and global (Rn) systems to observe the relations between the internal structure and the larger structure in which the smaller system is embedded. We use these synergy correlations to investigate the nature of the recursive regularities found in multiscale models' centrality distributions. Since it is not possible to perform the synergy correlation among different models in DepthmapX 0.8 (2018), we constructed an R script that performs the Pearson correlation between the configurational models. If R-squared distributions are significative, we deem that the models have a sufficient correspondence between value and position, and therefore, can be considered *homothetic* (Altafini & Cutini, 2020). With the models organized in QGIS 3.16 we can proceed to the qualitative and quantitative analysis of the Tuscany road-circulation networks.

4 RESULTS AND DISCUSSION

Configurational analysis and the results' spatialization for the Normalized Angular Integration (NAIN) measure for the regional scale demonstrate that there are significant territorial disparities in movement distribution and in *relative accessibility* patterns within Tuscany (Figure 2).

Associated to differences in the road-infrastructure cohesiveness, these territorial disparities in spatial configuration establish, not only noticeable divides between northern and southern areas of Tuscany, but also characterize another – more subtle – territorial divide, among the urbanized environments and hinterlands, in terms of these spaces' integration and overall accessibility.

Integration cores tend to be concentrated in northern Tuscany, and comprise three significant conurbations between *Pisa, Firenze, Lucca,* and *Massa-Carrara* provinces. The area morphology is mainly characterized by stretches of orthogonal grids – comprising the modern urban expansions created between the 1920's and 1980's – intertwined with the historical urban centres – often set within medieval walled towns and *urbanized-rural* areas. In general, however, those integration cores follow linear structures alongside interstate roads that connect the provincial capitals, both throughout the inner Tuscan territory and along its coast. The coastal road that characterizes the integration core that extends across *Pisa, Livorno* and *Grosseto* provinces is the *Via Aurelia – SS1* set on the same route once occupied by the Roman *consular road*; this road establishes the main connections with the *Lazio* region and the capital Rome. It can be noticed, however, that Tuscany's meridional areas, especially within the Grosseto province, possess a sparser road-circulation network, which is due to the presence of larger forested protected areas and cultivation fields when compared to the other provinces. In the southern areas, the road-circulation system tends to be less cohesive and more dependent on long stretches of road that cross the territory and count with few connections which influence the integration cores distribution and overall reach at this scale. This logic is repeated to a lesser degree throughout all Tuscan hinterlands, which in the north are inserted within the mountain ranges *Appennino Tosco-Emiliano*, and in the centre-south, across the hills that comprise the *Colline Toscane* and the *Chianti* and *Pitigliano* wine cultivation areas; these correspond the *segregated* areas at the regional scale.

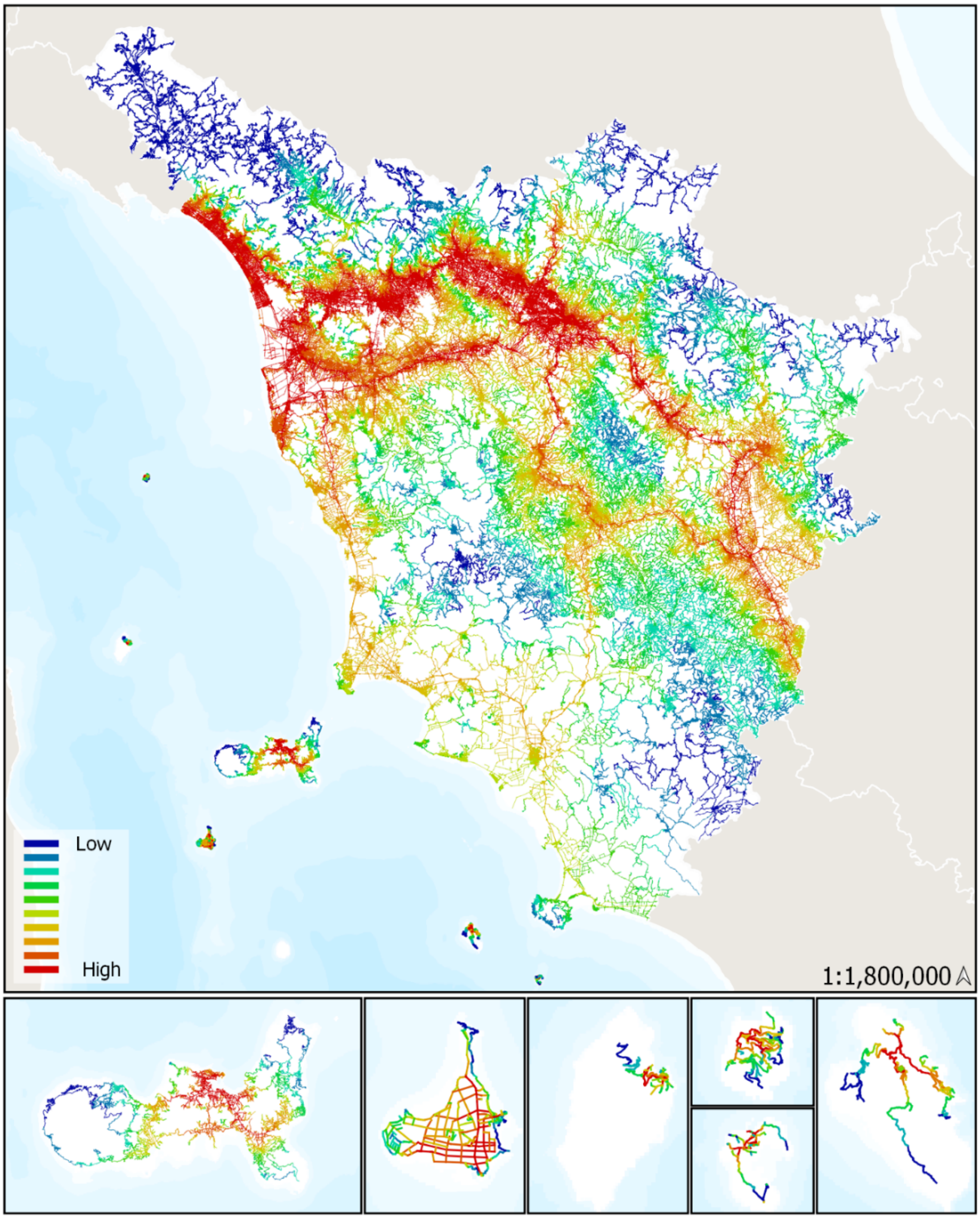

Figure 2: Normalized Angular Integration (NAIN) - Tuscany regional road-circulation network

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NAIN's numerical results reveal that integration values at regional scale tend to have both a modest amplitude and absolute values. Such results can be attributed to the system Total Depth, which is considerable, as well as to the number of road-elements in the *system*, given by the node count. It can also be highlighted that, despite having a high value for maximum connectivity (∨Connectivity), the average connectivity is low (2,56). This result can be explained by addressing Tuscany's hinterlands road-circulation network structure– both in the mountains and in the plains – that possess several stretches of road with sparse connections. It is noteworthy to mention that the larger systems in Tuscany – the region and, as later discussed, the provinces – follow similar NAIN value patterns.

Table 4: NAIN ranges and statistics Tuscany regional road-circulation network

NAIN - Value Ranges	Configurational Statistics			
0.037 - 0.102 (Low)	∨Total Depth		∨NATD*	
0.102 - 0.127		548,400,000		27.12
0.127 - 0.147	∧Total Depth		∧NATD*	
0.147 - 0.166		73,988,800		3.66
0.166 - 0.183	Total Depth Avg.		NATD* Avg.	
0.183 - 0.197		130,905,000		6.47
0.197 - 0.211	∨Connectivity		∨Angular Integration	
0.211 - 0.225		12		20286.40
0.225 - 0.239	Connectivity Avg.		Node Count	
0.239 - 0.273 (High)		2.56		1,225,140

*Normalized Angular Total Depth (NATD) is given by the inverse expression of NAIN.

As a general result, the NAIN model for regional scales establishes that the disparities in road-infrastructure density and configuration lead to distinctive patterns of centrality amongst northern and southern areas in Tuscany. The septentrional urban areas possess better defined conurbations that extend across the provincial capitals and configure areas with high *relative accessibility*. The provincial capitals in the centre-south, despite being rather large urban settlements, are deprived of the same conurbation patterns present in *urbanized-rural* areas of northern Tuscany. In those areas, integration cores follow interstate roads, which demonstrates their importance for *relative accessibility* at a regional scale. Despite the lower movement potentials, the urban areas located in the centre-south, above all, the provincial capitals can be deemed as secondary movement attractors in the region, being important to the Tuscany overall centralities' hierarchical structure. Normalized Angular Integration (NAIN) at the provincial scale provides another dimension regarding the subtle differences in integration/segregation patterns amongst urbanized and non-urbanized territories in Tuscany (Figure 3).

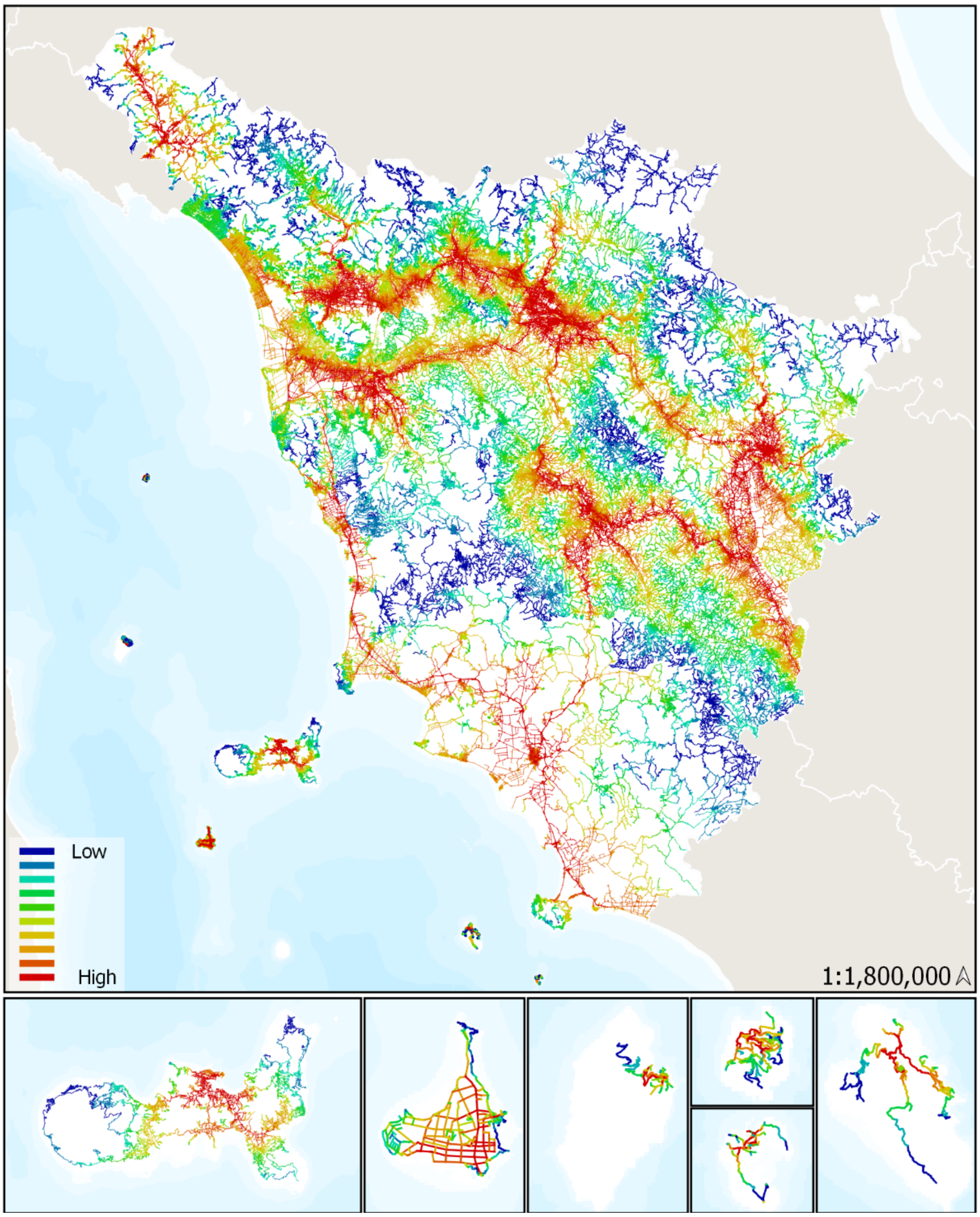

Figure 3: Normalized Angular Integration (NAIN) - Tuscany provincial road-circulation network

Provincial models, when analysed individually, tend to be better suited to describe the distinctive spatial transitions in the integration patterns between compact conurbated urban areas and their *urbanized-rural spaces*. This assessment can evidence localised differences in *relative accessibility* amongst local (municipal) and global (regional) scales, remarking the areas in which the cities' integration cores begin to fade in strength towards the segregated hinterlands of the regional space, which establishes a clear hierarchy between urban and rural (Figure 3). Still, when the provincial models are compiled in a regional map (Figure 3), it can be observed that the integration core structures that were depicted in the regional model (Figure 2) tend to be maintained in most provinces – at least in terms of their general position. These patterns of visual similitude for NAIN are a rather unexpected result, as depth differences among regional and provincial road-circulation networks are significant and the fact that integration *(closeness centralities)* is depth-dependent even when normalized (Hillier, et al, 2012). Such qualitative results suggest that there is a certain degree of scaling – or fractality – (Volchenkov & Blanchard, 2008) regarding the centralities distribution in-between the regional and provincial systems, therefore, these recursive regularities are an indication that, on larger scales, centralities tend to converge to similar distributions if the network spatial and morphological characteristics are equally similar.

Table 5: NAIN ranges for the Tuscany provincial road-circulation network

NAIN - Value Ranges for Provinces				
Arezzo	Firenze	Livorno	Lucca	Grosseto
0.035 - 0.089	0.037 - 0.099	0.063 - 0.213	0.039 - 0.070	0.056 - 0.074
0.089 - 0.112	0.099 - 0.127	0.213 - 0.260	0.070 - 0.088	0.074 - 0.083
0.112 - 0.131	0.127 - 0.146	0.260 - 0.285	0.088 - 0.107	0.083 - 0.097
0.131 - 0.148	0.146 - 0.161	0.285 - 0.302	0.107 - 0.127	0.097 - 0.112
0.148 - 0.161	0.161 - 0.176	0.302 - 0.319	0.127 - 0.144	0.112 - 0.132
0.161 - 0.175	0.176 - 0.190	0.319 - 0.337	0.144 - 0.161	0.132 - 0.147
0.175 - 0.189	0.190 - 0.205	0.337 - 0.354	0.161 - 0.169	0.147 - 0.162
0.189 - 0.206	0.205 - 0.222	0.354 - 0.373	0.169 - 0.174	0.162 - 0.171
0.206 - 0.222	0.222 - 0.238	0.373 - 0.399	0.174 - 0.183	0.171 - 0.180
0.222 - 0.250	0.238 - 0.271	0.399 - 0.467	0.183 - 0.200	0.180 - 0.202
Massa-Carrara	Pisa	Pistoia	Prato	Siena
0.030 - 0.050	0.049 - 0.097	0.040 - 0.076	0.030 - 0.092	0.058 - 0.115
0.050 - 0.055	0.097 - 0.120	0.076 - 0.100	0.092 - 0.119	0.115 - 0.132
0.055 - 0.059	0.120 - 0.155	0.100 - 0.121	0.119 - 0.144	0.132 - 0.150
0.059 - 0.061	0.155 - 0.177	0.121 - 0.140	0.144 - 0.162	0.150 - 0.164
0.061 - 0.062	0.177 - 0.194	0.140 - 0.159	0.162 - 0.181	0.164 - 0.177
0.062 - 0.068	0.194 - 0.206	0.159 - 0.175	0.181 - 0.195	0.177 - 0.191
0.068 - 0.073	0.206 - 0.215	0.175 - 0.189	0.195 - 0.209	0.191 - 0.205
0.073 - 0.079	0.215 - 0.223	0.189 - 0.199	0.209 - 0.220	0.205 - 0.220
0.079 - 0.085	0.223 - 0.233	0.199 - 0.207	0.220 - 0.228	0.220 - 0.234
0.085 - 0.095	0.233 - 0.263	0.207 - 0.228	0.228 - 0.246	0.234 - 0.281
Avg. Provincial ∨NAIN – 0.250				
Avg. Provincial ∧NAIN – 0.043				

An investigation, from the quantitative standpoint, attested that the average maximum (∨) NAIN values for the provincial scale models (0.250). In the same manner, individual ∨NAIN results for the provincial models tend to be – in most cases – on pair with the ∨NAIN values attained in the regional scale model (0.273) (Table 5). This is another indication that their similarities are not only restricted to the visual aspect.

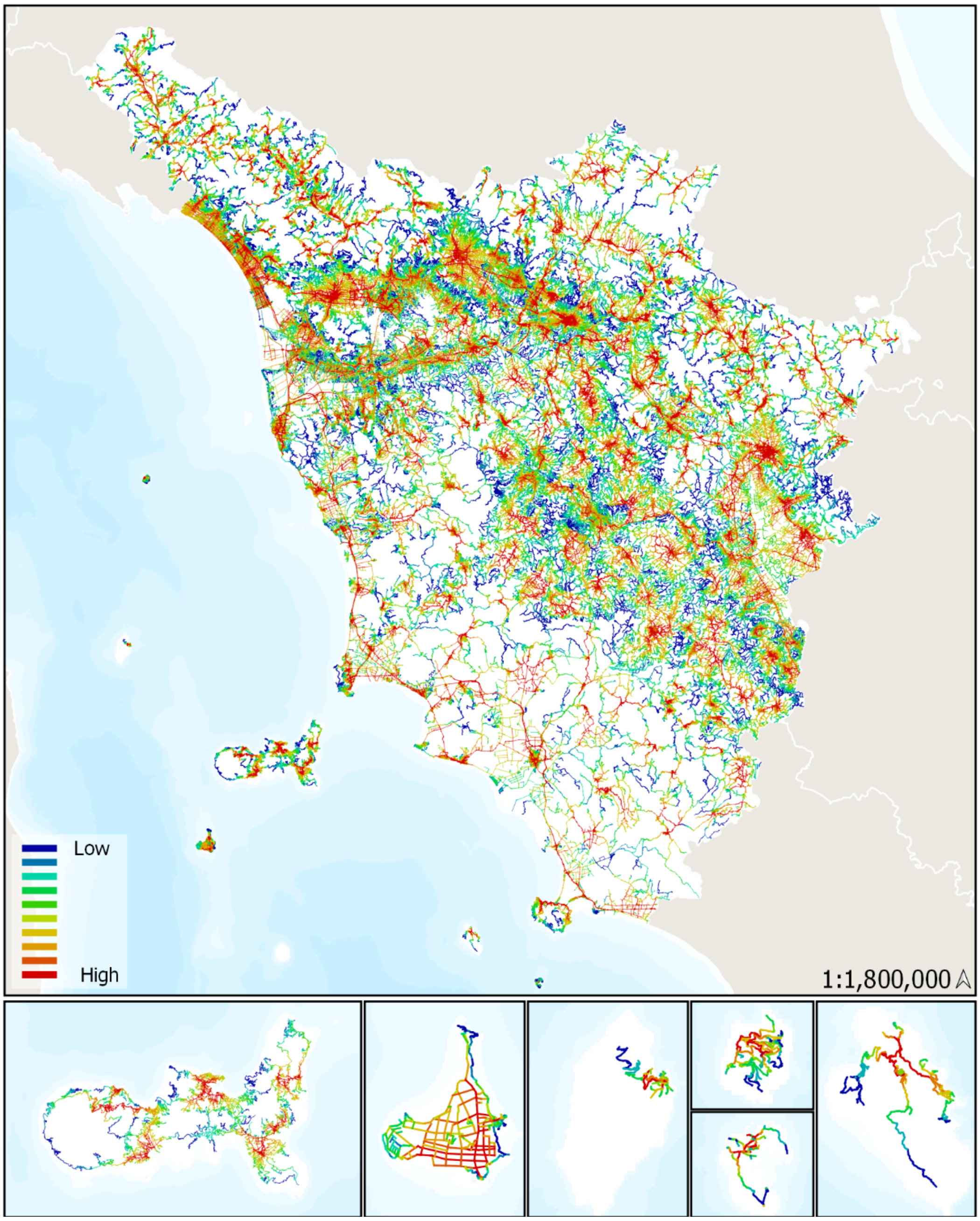

Figure 4: Normalized Angular Integration (NAIN) - Tuscany municipal road-circulation network

Nevertheless, relevant outliers to this newfound similitude are found in *Livorno, Massa-Carrara*, and *Grosseto* provincial models. Still, these divergences can be attributed to particularities in their spatial configurations which are: or more sparse and linear-based – as in the cases of *Livorno* and *Grosseto* –; or affected by considerable *edge effects* (Gil, 2017), that distort the results near the most compact area that should concentrate integration – as in the *Massa-Carrara* province. In all cases, non-cohesive sprawl is what defines scale differences.

Configurational analyses and the results' spatialization for the Normalized Angular Integration (NAIN) models at the municipal scale (Figure 4) demonstrates quite distinctive *relative accessibility* patterns when compared to the previously discussed regional and provincial models (Figures 2, 3).

At this scale, the visual similitudes in centralities hierarchies' distribution, observed in NAIN regional and provincial models, give place to a visualization of the localised *to-movement* patterns. In that aspect, while the regional and provincial scales apprise the territorial divides amongst urbanized environments and their hinterlands, at the municipal scale the NAIN models will inform the overall *relative accessibility* differences found inside the urban areas, with remarks on their cores and peripheries, depicting patterns of integration and segregation at the urban scale. When the municipal NAIN models are organized on a regional map, the resulting patterns resemble the results attained through the estimation of *angular segment analyses* (ASA) using metric distances (Hillier et al. 2009; Yamu & Van Nes, 2017), even though our analysis is topo-geometric. The created *patchwork* of models then evidences a localized spatial differentiation – a territorial divide – between the urbanized areas. There are the urban cores, or spaces comprised of integrated and well-connected road-elements assume a *quasi-fractal* pattern (Batty & Longley, 1986; 1994; Yamu & Van Nes, 2017) and represent the regional centres and provincial *sub-centres*; and there are the urbanized peripheries, that represent spaces of transition set in-between those cores, constituted by *relatively segregated* areas of the road-circulation network; those form the urban sprawl limits – or the urban cores *fuzzy boundaries* (Yang, & Hillier, 2007; Yang, 2019). From a morphological standpoint, Tuscany possesses an extensive range of urban forms. While an in-depth analysis regarding morphology can be made, this lies outside our scope. Hence, for our purposes, we categorize the urban integration cores according to their configuration and within two main groups: compact and linear. A third group was established to include "mixed" configurations, as certain areas cannot be deemed compact or linear. Compact urban cores have a predominance of orthogonal grid structures – characteristic of larger urban settlements, such as the provincial capital, *Firenze* –; or tend to be smaller regular and, sometimes, irregular grids that are, however, confined within the walled parts of historical urban centres – as observed in historical settlements such as in *Pisa* and *Lucca*. Linear urban cores, instead, tend to be associated: or with towns in mountain or hinterland areas that have a small urban centre; or with urban spaces that are structured around an interstate road, such as those within the northern Tuscany conurbation.

From a quantitative standpoint, we can divide the NAIN values for the 289 municipal models into several ranges, in accordance with their maximum values (∨NAIN), to observe patterns related to its integration cores; average scores for ∨NAIN are set around 0.39 (Table 6). Although most provinces tend to have the majority of the municipalities' models, with integration values set below the average ∨NAIN, important outliers are observed in the provinces of *Livorno* and *Pisa*, where ∨NAIN values tend to be closer and, mostly, higher than the average. This trend can be related to the predominant road-circulation network configuration of the urban cores of the municipalities within those provinces, which is linear. These linear integration core structures tend to concentrate *relative accessibility* in a single group of contiguous road-elements at an urban scale, whereas *to-movement* potentials tend to be more distributed across the orthogonal grid-based systems with compact integration cores.

Table 6. Average √NAIN ranges for the Tuscany municipal models, total count, and distribution of values under and over the average √NAIN for the municipalities according to their respective provinces.

Avg. vNAIN	Total	< Avg. vNAIN	%	> Avg. vNAIN	%
0.392372006	289	184	63,7%	105	36,3%
Municipality Count.	Total	< Avg. vNAIN	%	> Avg. vNAIN	%
Arezzo Province	38	28	73.7%	10	26.3%
Firenze Province	42	26	61.9%	16	38.1%
Grosseto Province	30	21	70.0%	9	30.0%
Livorno Province	22	10	45.5%	12	54.5%
Lucca Province	37	27	73.0%	10	27.0%
Massa-Carrara Province	18	14	77.8%	4	22.2%
Pisa Province	38	16	42.1%	22	57.9%
Pistoia Province	22	14	63.6%	8	36.4%
Prato Province	7	4	57.1%	3	42.9%
Siena Province	35	24	68.6%	11	31.4%

In that aspect, the integration cores that have a "mixed" urban form tend to be less integrated than cores that are; or exclusively compact, surrounded by defined segregated boundaries, such as in *Firenze* and *Prato*; or tend towards linearity, as in *Pisa*'s and *Siena*'s integration cores. These dynamics tend to repeat across other, smaller, municipal models and explain the configuration patterns found in Tuscany's urban spaces.

Modelled at regional scale, the Normalized Angular Choice (NACH) for the Tuscany road-circulation network demonstrates that the *betweenness centralities* assume a distinctive hierarchical pattern, where the road-elements highlighted in red represent the systems' *preferential routes* structure (Figure 6) These *preferential routes* correspond to the road-elements with the highest vehicular flow probabilities in the network, therefore, tend to be set on roads categorized as primary – interstate roads and regional highways and secondary – the urban extents of these roads as well as urban avenues and *boulevards*. Nevertheless, *through movement* is well-distributed across the Tuscany territory, and even reaches areas considered segregated in the regional NAIN model (Figures 2, 3), for example, the mountain passes of the *Appenino Tosco-Emiliano* in the north, and the inner hinterlands in southern Tuscany.

The centralities hierarchies' differences amongst local roads within the urbanized areas tend to be remarked in medium-high (yellow) and medium-low (green) NACH values. Despite that, the overall similarity between the distribution of these structures across different urban settlements does not bode for further assessments of their characteristics. As proposed by Yamu & Van Nes

(2017) NACH models can also inform properties and characterize hierarchical patterns amongst urban spaces. In that aspect, the size of the areas that concentrate road-elements with high values for local NACH, as well as their absolute number, can be compared to inform urban hierarchies and the overall weight of the urban systems in terms of *through movement*, while the *preferential routes'* structures, at the global scale, denote which connections that are responsible to associate the smaller urban spaces in-between larger urban settlements.

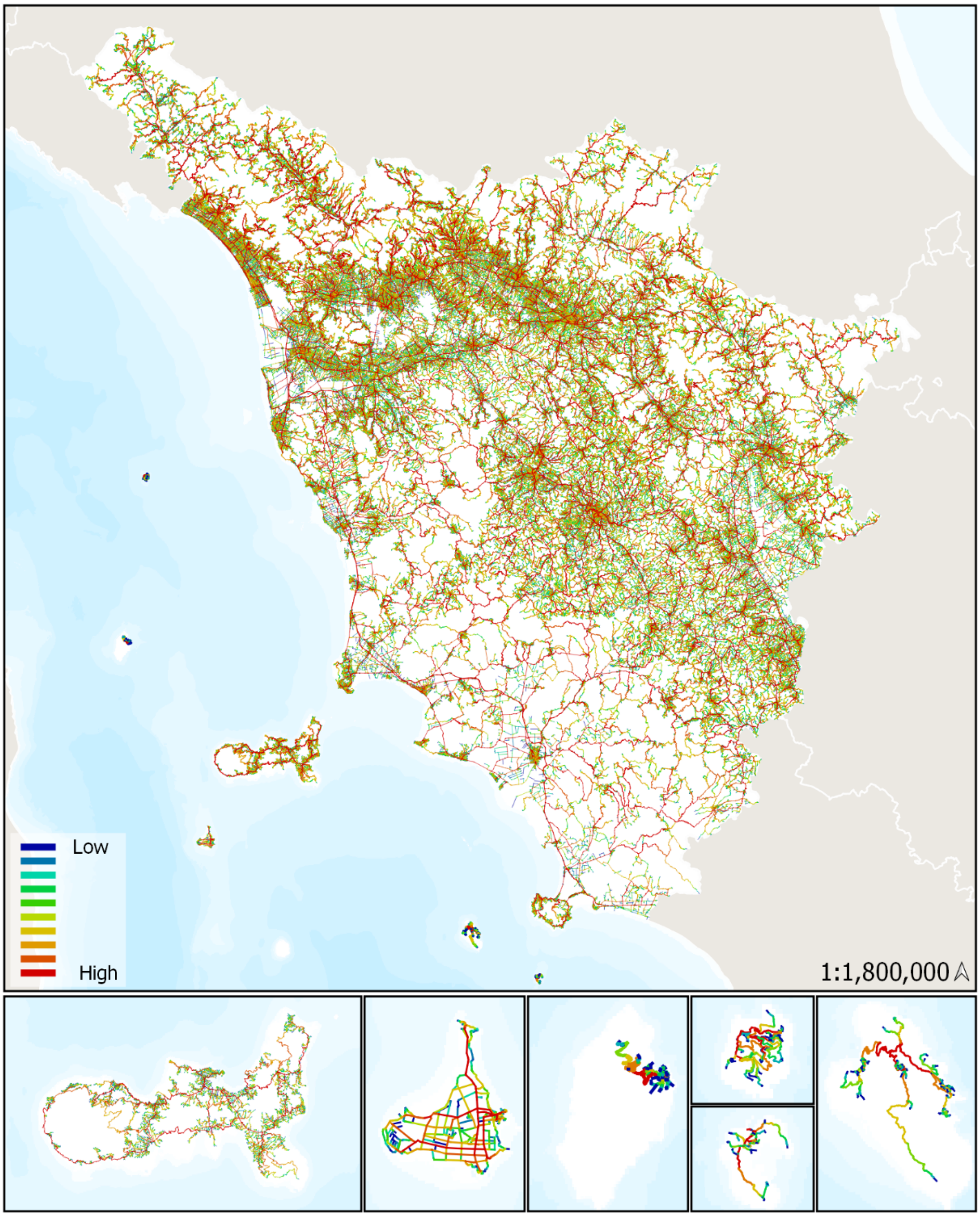

Figure 5: Normalized Angular Choice (NACH) - Tuscany regional road-circulation network

In quantitative terms, the NACH values for the regional model tend to be rather regular, as a result of the normalization process (Hillier et al., 2012), therefore set in a range between 0 and 1.5+ (Table 7). In the case of Tuscany, values slightly deviate from the 1.5+ values, ranging from

0 to 1.47. This is mostly due to the system's size – 1,225,140 road-elements – that renders the maximum (∨) value for angular *choice* quite significant, while also exhibiting a high value for Total Depth (Table 10). While the Tuscany's regional NACH model revealed interesting patterns regarding the road-circulation network structure and its *preferential routes'* distribution, the results' compared with the results attained for the provincial and municipal models revealed a remarkable property of normalized *betweenness* measures, that motivated further studies to understand the nature of its occurrence, as well as its uses to urban-regional analysis.

Table 7: NACH ranges and statistics Tuscany regional road-circulation network

NAIN - Value Ranges	Configurational Statistics			
0.000 - 0.438 (Low)	∨Total Depth		∨NATD	
0.438 - 0.777		548,400,000		27.12
0.777 - 0.815	∧Total Depth		∧NATD	
0.815 - 0.850		73,988,800		3.66
0.850 - 0.882	Total Depth Avg.		NATD Avg.	
0.882 - 0.915		130,905,000		6.47
0.915 - 0.952	∨Connectivity		∨Angular Choice	
0.952 - 0.999		12		369,808,380,000
0.999 - 1.067	Connectivity Avg.		Node Count	
1.067 - 1.470 (High)		2.56		1,225,140

The models Normalized Angular Choice (NACH) for the provincial and municipal scales (Figures 6, 7) revealed that there are outstanding recursive regularities in *betweenness centralities'* patterns.

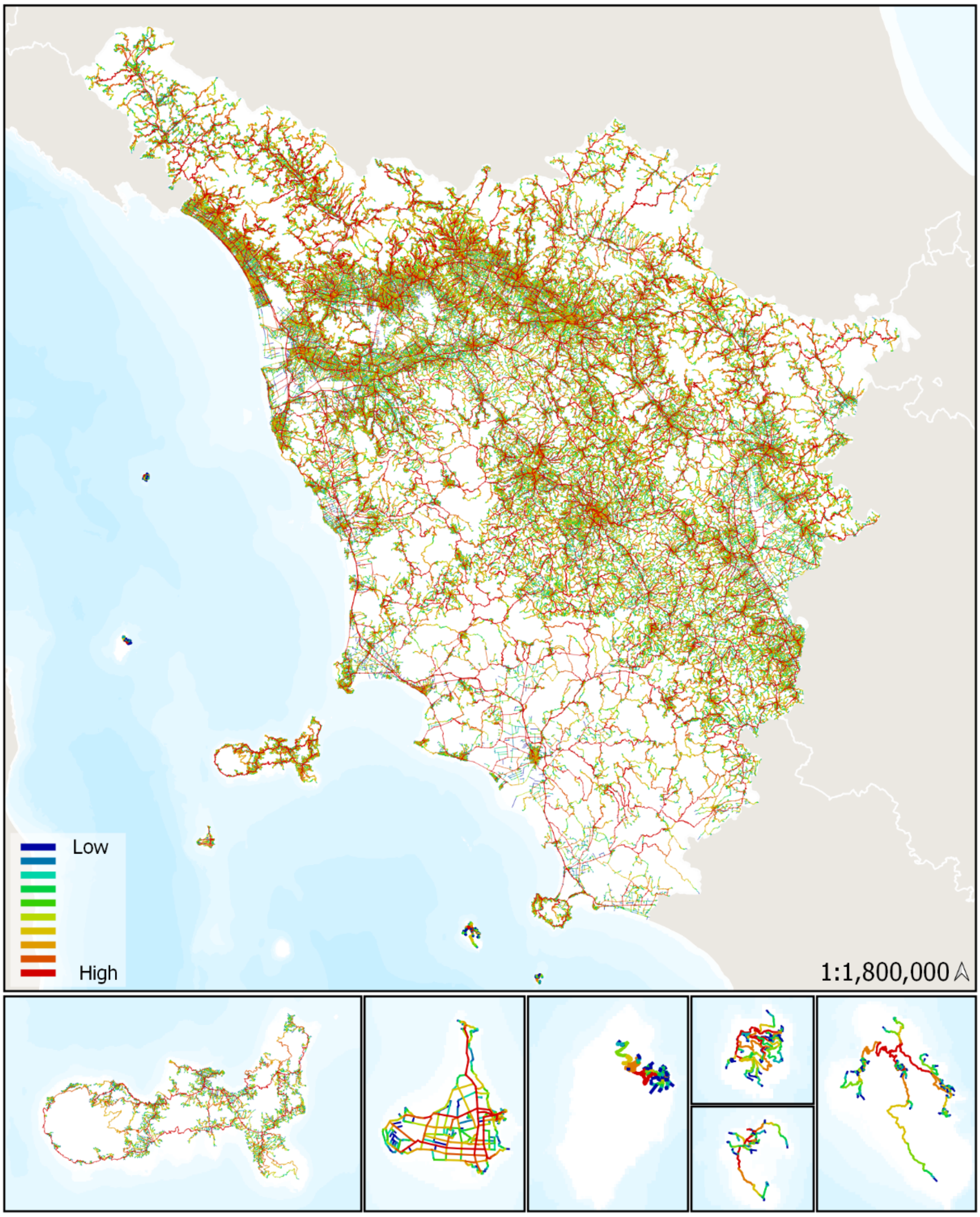

Figure 6: Normalized Angular Choice (NACH) - Tuscany provincial road-circulation network

Both provincial and municipal scale *preferential routes* tend to be set in the same road-elements as those from the regional scale model (Figure 5).

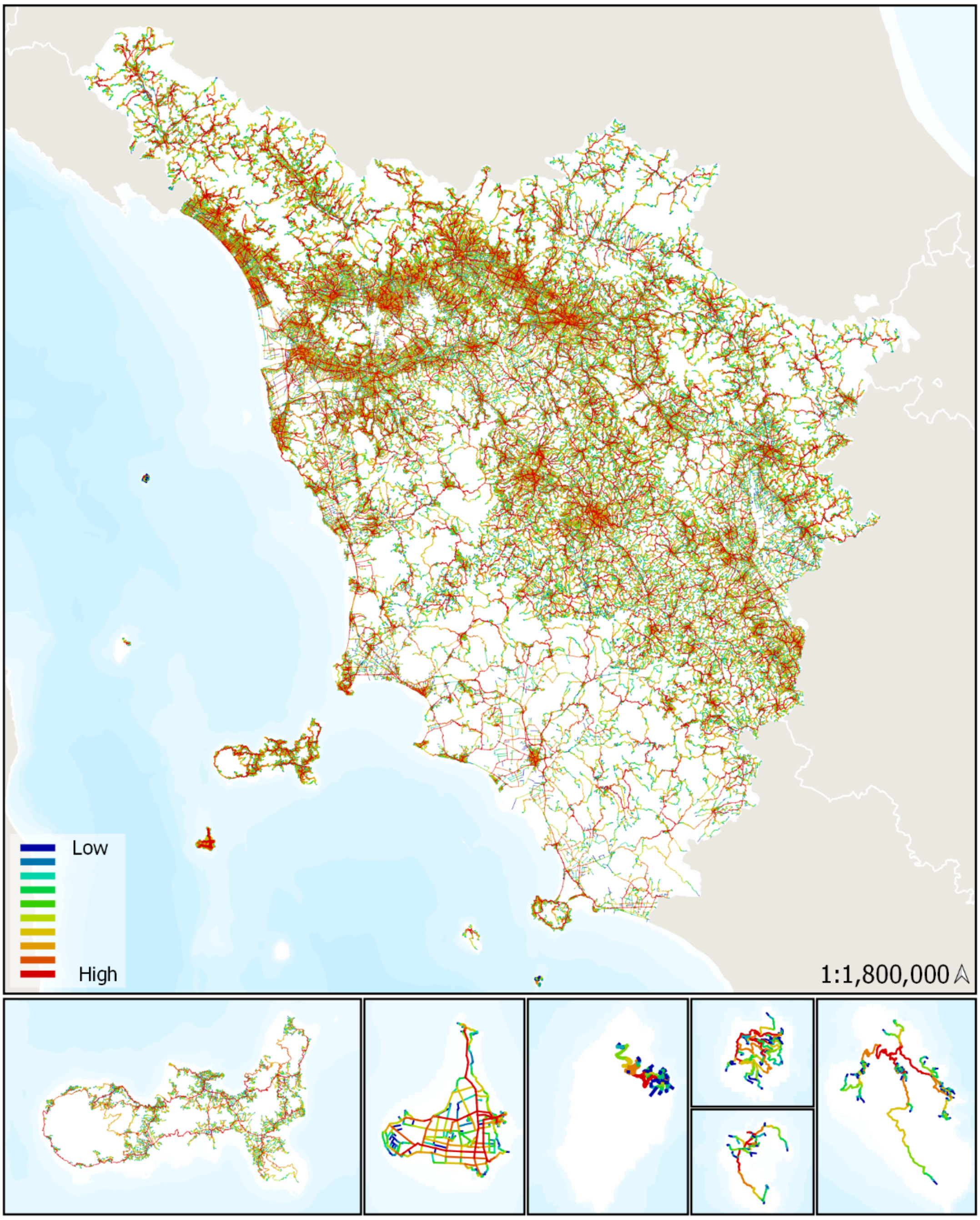

Figure 7: Normalized Angular Choice (NACH) - Tuscany municipal road-circulation network

When the quantitative aspect is addressed, it is attested that the provincial models tend to maintain a certain regularity also in terms of values (Table 8) being in ranges set between 0 and 1.5+. It was found, however, that NACH maximum (∨NACH) values are, on average, slightly lower (1.42 and 1.37) than in the regional model – 1.47 (Table 7).

Table 8: ∨NACH for the provincial models.

Maximum NACH values for the provincial models									
Arezzo	1.43	Firenze	1.42	Livorno	1.49	Lucca	1.43	Grosseto	1.38
Massa-Carrara	1.35	Pisa	1.43	Pistoia	1.42	Prato	1.41	Siena	1.46

These slight differences in values can be attributed to a smaller number of road-elements in these models that result in lesser values for maximum angular *choice* and Total Depth. Although regularities in values are expected due to the normalization process (Hillier, et al, 2012) – this indicates that the visual similitudes for the *betweenness centralities* might be beyond a simple spatial coincidence due to the equal count (quartile) division.

This logic is further tested in municipal models for NACH. Even if at this scale – which for NAIN models resulted in a rather distinct *quasi-fractal* centralities distribution – the *betweenness centralities* in NACH tend to present *preferential routes* set, essentially, in the same road-elements. While differences in quantitative terms exist, as the average NACH maximum (∨NACH) values for the municipal models are slightly lower (1.37) than those found for the larger scales – 1.47 (region) and 1.42 (provincial) – value discrepancies can be associated with the greater incidence of *edge effects* (Gil, 2017) as there are more network sections. Therefore, discrepancies in terms of centralities' spatial distribution can be traced mostly to system boundaries, where values tend to be reduced due to the absence of network continuities, that resulted from the road-graph section. As a general result, the NACH models for regional, provincial, and municipal scales (Figures 5, 6, 7) demonstrate that Tuscany's *preferential routes*' structure remains mostly unchanged across scales, as *through-movement* tends to be concentrated in the same groups of road-elements. Still, it is remarkable, and to a certain degree, unexpected, that all models exhibit a similar spatial distribution for centralities, a behaviour that merits being investigated from the network analysis standpoint. Our recursive regularities assessment restricts configurational models to deciles that comprise the 20% of the total number of road-elements with the highest value (Figure 8). This procedure emphasizes where the discrepancies in ∨NACH, which were attested in the quantitative analysis, are located, and if those are, as hypothesized, derived from *edge effects*. In that aspect, we verified that differences in centralities distributions for NACH tend to be rather restricted to boundaries, and when they are not, they are derived from boundaries decreasing in value. It is interesting to note that *homotheties* are less consistent for municipal models with predominant linear structures – such as those in southern Tuscany. At this point, it is important to summarize the *Angular Choice* and NACH measures definitions, as the underlying mathematical properties explain the reasons for these *homotheties* to occur.

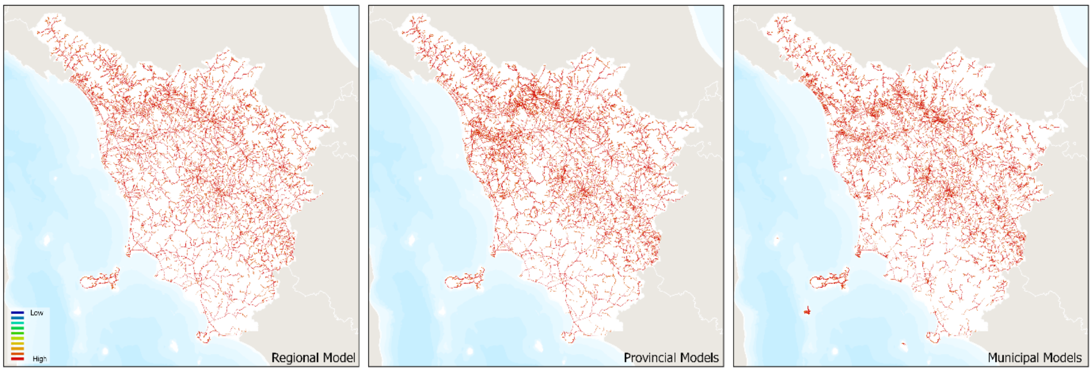

Figure 8: Comparison of Normalized Angular Choice (NACH) models - Tuscany road-circulation network restricted to the 20% of the highest valued road-elements.

Angular Choice (Turner, 2001) derives from mathematical *betweenness* and can be defined as the count (sum) of the number of times each individual road-element *i* is traversed when travelling, through the overall shortest path, from all possible origins, towards all potential destinations within the road-circulation network. The most travelled road-elements are deemed as central. As assumed on its expression (Table 3), *Angular Choice* does not consider the system's Total Depth, therefore, the maximum node count will always be dependent on network size. In that sense, *Angular Choice* has an intrinsic limitation that hinders the comparison of results in different sized networks, and the addition of road-elements causes exponential growth in *betweenness values*. In effect, what happens in this case is that *Angular Choice* establishes *betweenness* hierarchies that are mainly restricted in-between two points – that represent the shortest path – whereas the hierarchical distributions from the remainder traverse counts in the system become overshadowed, as their sum is insignificant in comparison to the shortest path sum values. This problem – the *paradox of depth* is known in *Space Syntax* and was the main reason for the NACH development (Hillier, et al, 2012), as a manner to consider the networks' Total Depth. *Angular Total Depth* establishes a positional reference to *Angular Choice* values, as the traverse count of each road-element will be related to the systems' general depth. In that regard, the road-elements will have – and maintain – the same hierarchical position in relation to the others, which depends on their individual ratio between the *Angular Choice* and the value of the network's *Angular Total Depth*. At the same time, those positional hierarchies are independent of the total size, and tend to not be altered at their cores if the system dimensions change since, as new road-elements are to be added, this proportionally increases both the *Angular Total Depth* and the *Angular Choice* values of the highest traversed paths, which maintains the overall hierarchies in the novel scale. The existence of this behaviour – where positional hierarchies are maintained – it's the principle that sustains the hypothesis that the normalized *betweenness centralities* in *Angular Choice* exhibit a *homothetic behaviour*.

Based on in order to better address this logic, we evaluate the recursive regularities also from a statistical standpoint. To that end, we developed a script in the R software (2017) to correlate the centralities distributions of regional, provincial, and municipal models. The established linear regressions (Pearson) compare the different systems' in pairs – reduced to equal territorial extents based on the municipal limits. R-squared values then indicate that models have the same variation both in numerical and positional terms. It is assumed that correlations in which the r-squared values surpass the established 0.8 (80% of correspondence) threshold attest that both network models have a significant likeness in their variation, therefore can be considered *homothetic* – if visual similitudes corroborate with the r-squared – as 0.2 differences are assumed to be attributed to *edge effects* distortions.

We then modelled 550 correlation analyses that compare the municipal road-circulation models to their provincial and regional counterparts. The results are aggregated according to municipalities' respective provinces and allow to visualize the average r-squared values obtained, and if they are within the established threshold. Comparisons between municipal-provincial and municipal-regional road-circulation network are organized according to their respective province. Results indicate that the average correlation values (r-squared) surpass the 0.8 (80%) threshold value in all cases, being no lower than 0.85 (85%) (Table 9) for the provincial-municipal, no lower than 0.81 (81%) for the regional-municipal correlations (Table 10). The result implies that, while outliers might exist – as emphasized in the standard deviations for *Lucca* and *Grosseto* – most of the systems present a general *homothetic behaviour* in their betweenness centralities distribution.

Table 9: Betweenness Centralities (NACH) average correlation values (r-squared) between Provinces and Municipalities road-circulation networks models, standard deviations, and standard errors.

Province x Municipalities - Correlation Data	Analyses	Averages	St. Dev	St. Error
Arezzo Province	38	0.8672	0.0443	0.0072
Firenze Province	42	0.8904	0.0441	0.0068
Grosseto Province	27	0.8514	0.0641	0.0123
Livorno Province	11	0.9003	0.0384	0.0116
Lucca Province	37	0.8685	0.1833	0.0301
Massa-Carrara Province	18	0.8905	0.0591	0.0139
Pisa Province	38	0.8948	0.0405	0.0066
Pistoia Province	22	0.9145	0.0253	0.0054
Prato Province	7	0.9156	0.0316	0.0119
Siena Province	35	0.9046	0.0392	0.0066
Total	275*	-	-	-

* Tuscany Archipelago models not considered

Table 10: Betweenness Centralities (NACH) average correlation values (r-squared) and statistics between the regional and the municipalities road-circulation networks models.

Region x Municipalities - Correlation Data	Analyses	Averages	St. Dev	St. Error
Arezzo Province	38	0.8423	0.0453	0.0074
Firenze Province	42	0.8685	0.0479	0.0074
Grosseto Province	27	0.8167	0.0750	0.0144
Livorno Province	11	0.8513	0.0470	0.0142
Lucca Province	37	0.8577	0.1616	0.0266
Massa-Carrara Province	18	0.8583	0.0605	0.0143
Pisa Province	38	0.8660	0.0539	0.0087
Pistoia Province	22	0.8905	0.0274	0.0058
Prato Province	7	0.8476	0.0514	0.0194
Siena Province	35	0.8862	0.0446	0.0075
Total	275*	-	-	-

* Tuscany Archipelago models not considered

Considering that the *homothetic behaviours* are regular, we can examine further aspects about what they can inform and their uses on urban analysis. For that purpose, we discuss the results for the municipal modes of *Grosseto* – lowest average correlation for municipal-provincial models –; and *Prato* – highest average correlation municipal-provincial models (Figures 9 and 10). Through the comparison of their respective regional *(regione)* provincial (*provincia*) and municipal (*comune*) road-circulation networks correlation graphs (Figure 9) and datamaps (Figure 10) we have a valuable overview to demonstrate how the urban-regional form can affect the propagation of NACH *homotheties* and their precision, which might give indications about its possible uses as an urban indicator.

The results for these two municipal models emphasize that the *homothetic behaviour* identified through r-squared values (Figure 9) can capture the differences in sprawl visible on the datamaps (Figure 10). It is verified that attained r-squared values tend to suffer a decrease when the road-circulation network becomes sparser or becomes more linear. In that aspect, *homotheties* indicate differences in their inner geography, addressing how much sprawled the urban system is in comparison to other systems within the same province or region. Urban settlements that have more compact structures, such as the example for *Prato* tend to present higher values for the *homotheties*, as *edge effects* will have a lower impact on the shorter road-elements near the borders, which denotes a cohesive urban network. Urban systems that, instead, possess a sprawled urban network, characterized by long linearities that are connected to a compact centre – such as the example for *Grosseto* – will present lower overall values for r-squared, therefore presenting a less consistent *homothetic behaviour* across the scales due to the major incidence of *edge effects*, which tend to have a greater effect on linearities that collect *betweenness*. In that aspect, the r-squared values for the *angular choice synergy* compared between scales and amongst urban settlements can be interpreted as an indicator that addresses the overall tendencies of urban sprawl, being useful for urban-regional analysis.

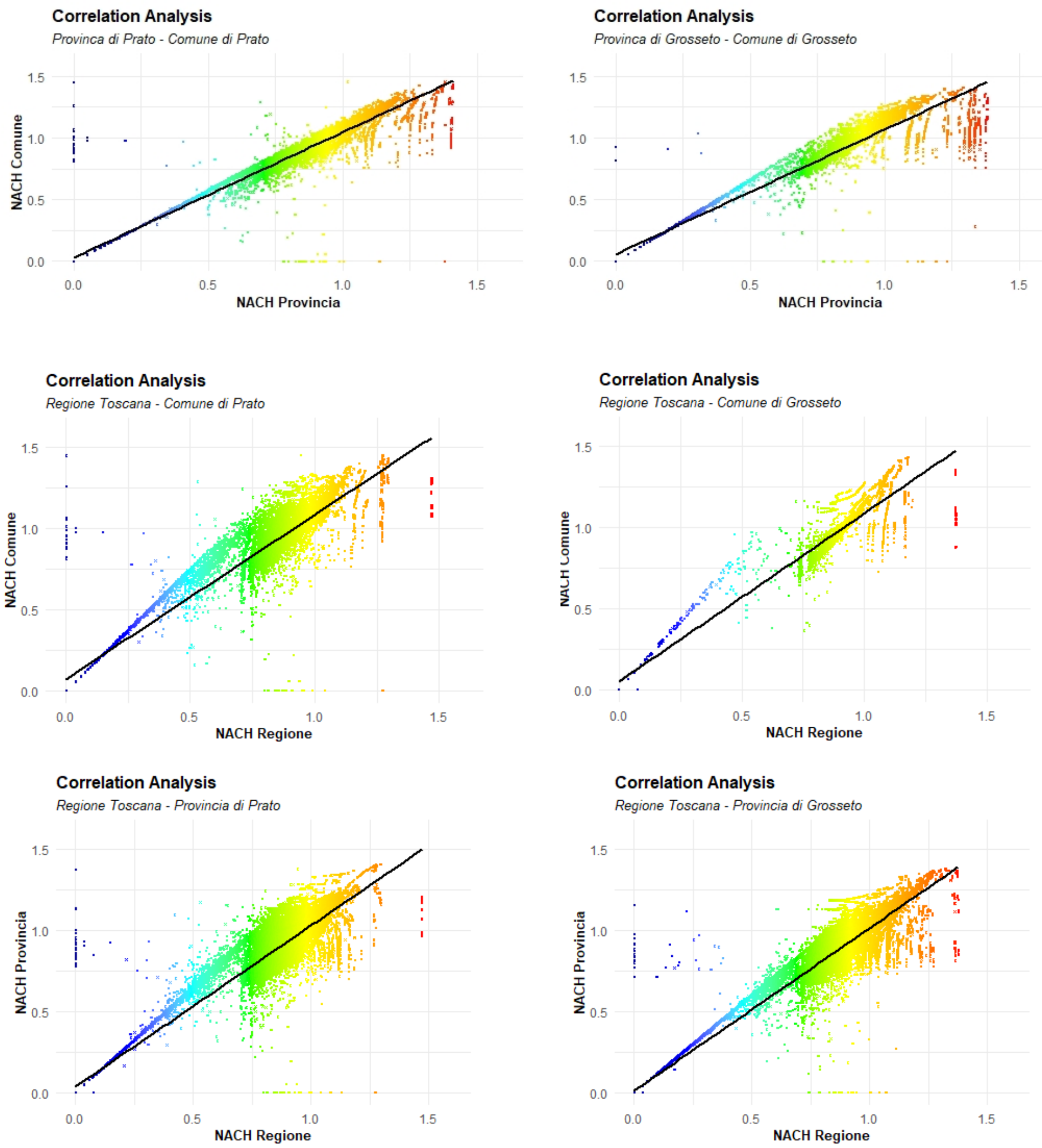

Figure 9: Normalized Angular Choice (NACH) models correlation for Prato (Highest Average) and Grosseto (Lowest Average) visual similitudes

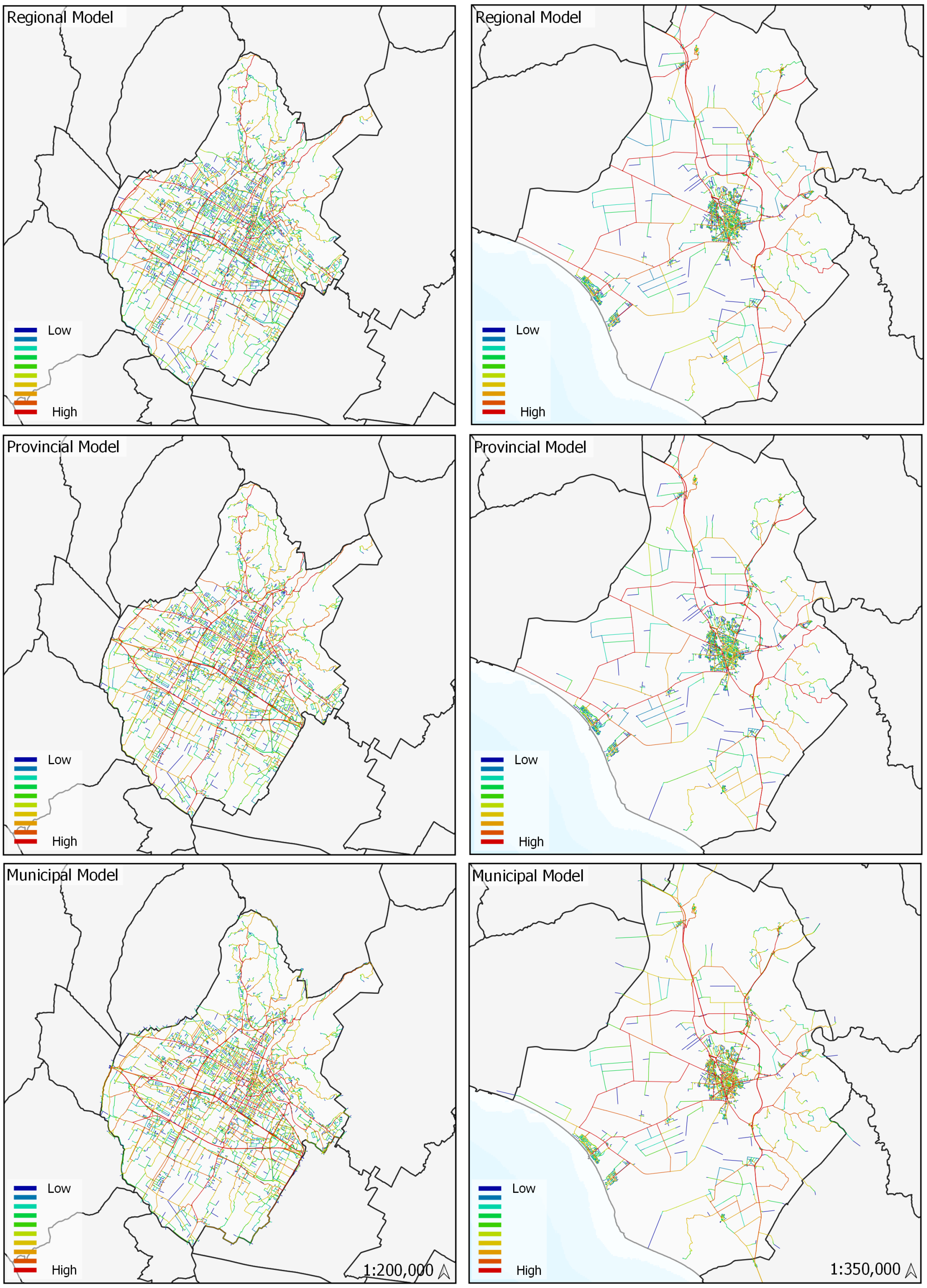

Figure 10: Normalized Angular Choice (NACH) models for Prato (Highest) and Grosseto (Lowest) visual similitude

5 CONCLUSIONS

A baseline condition for our experiments in configurational analysis, the construction of multiscale models for Tuscany revealed several aspects of the internal geography of urban-regional spaces, as well as interesting patterns regarding centralities distribution across scales. This approach provides a novel take when confronted with previous regional studies in Space Syntax, as it models multiscale networks with minimal generalization, which allows for an accurate comparison between different territories and reveals the linkages between urban and regional phenomena. Although this provides interesting original conceptions, we recognize that its novelty also represents a constraint, as no equivalent comparisons can be made to previous studies.

Beyond an original qualitative-configurational analysis of the relations between Tuscany's urban-regional structures, this paper proved to summarize recent findings of the underlying properties that centrality measures can assume when modelled across scales. One of these network properties consists of recursive regularities – or *homothetic behaviours* – found in *Space Syntax'* Normalized Angular Choice (NACH) measure, a mathematical *betweenness centrality* approximation. These *behaviours* demonstrate that *betweenness* is largely invariant across scales and that *edge effects* tend to determine the degree of inconsistency found by comparing larger models with their smaller components. This, further than leading to theoretical conclusions about the *fractal* nature of urban networks, is assumed to have its practical uses on urban analysis. It was verified that discrepancies in *homotheties* consistency are greater within certain urban forms, such as in linear-sprawled cities while being minor in compact urban settlements. In that aspect, *homotheties* can be used as an indicator to determine the degree of sprawl within the inner-geography of urban settlements, which has its uses for urban analysis. Further developments should be focused on formalizing this indicator into guided exploratory studies regarding urban sprawl.

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