The Spatial Morphology of Oporto's Urban Fringe

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Abstract We investigate the formation processes of suburban street networks, through the analysis of five study areas at Oporto's urban fringe, over a period of 55 years. We start by recreating their street grids on four different time periods through the common technique of map regression, extending it in order to make possible the identification of individual development operations (represented by their street layouts), occurring between sequential time periods within each study area. Space syntax is used to study the structural evolution of the complete street networks, while the individual morphologies of development operations are quantified and classified according to simple topological parameters. We observe different structural evolutions among the several study areas and also different frequencies for the morphological classes of development operations occurring therein. By crossing these two types of results, we show that the differences observed at the level of the entire networks may be explained by the also different morphologies of the individual developments constructing them through time. We conclude by suggesting that these findings offer some clues on how street networks could be planned from the bottom-up, by regulating street patterns at the very local level in order to achieve desired global outcomes.

1 Introduction

Worldwide, extensive metropolitan urbanization has produced new patterns of urban development, with physical and spatial characteristics that are utterly different from those of the historic, or traditional city (Levy 1999). Beyond their old urban cores, contemporary metropolitan regions extend far into the surrounding environment, assuming the peculiar forms of an 'urbanized landscape' or of a

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'landscaped city' – a mingling of urban spaces and built forms with natural and rural spaces, accompanied by a gradual disappearance of the traditional dichotomy between these two worlds (Sieverts 2003). From densely built, compact objects – easy to define by simple contrast with their surroundings – cities have now become porous and diffuse objects, sprawling across the landscape without clearly defined boundaries.

Even if no longer a novelty, metropolitan development was not followed by an objective conceptualization of its morphological characteristics. Instead, its novel non-orthodox morphology gave rise to a tide of theoretic criticism and repudiation, seeing in it the signs of a distressing and apparently unstoppable dismemberment of the city. The words of the influential American architectural critic, Lewis Mumford (Mumford 1961), provide a good example of such stance: "whilst the suburb served only a minority, it neither spoiled the country-side nor threatened the city. But now that the drift of the outer ring has become a mass movement, it tends to destroy the value of both environments without producing anything but a dreary substitute, *devoid of form* and even more devoid of the original suburban values" p. 506, our emphasis.

This theoretical state of denial, often more driven by aesthetical mistrust than by objective observation, has led to a general paucity of knowledge on the effective morphological nature of contemporary metropolitan and suburban environments. Indeed, the relevant question to ask is not if contemporary metropolitan form is aesthetically satisfactory or not, but rather what truly are its intrinsic morphological characteristics. As a recent paper (Prosperi et al. 2009) on the subject claims, "posing the concept of 'metropolitan form' as a question [...] is an absolute necessity at this stage of development of urbanized areas. [...] There is a persistent theme in the related literatures of architecture, urban design and urban and regional planning that the physical form of the contemporary metropolis is un-describable. [...] A new epistemology and a new language are needed for the question of metropolitan form" op. cit. pp. 1–2.

Yet, in a much older albeit brilliant paper, Friedman and Miller (Friedmann and Miller 1965) declare that in face of metropolitan contexts, "planners [...] are left in a quandary. Modern metropolitan trends have destroyed the traditional concept of urban structure, and there is no image to take its place. Yet none would question the need for such an image, if only to serve as the conceptual basis for organizing our strategies for urban development" op. cit. p. 313.

Forty-four years have passed between those two texts. Still, in view of their authors' claims, it seems that they were written just a few months apart. The truth is that further investigations on the subject of contemporary metropolitan and suburban morphologies are today more necessary than ever because, generally speaking, urban planning practice seems locked up in a kind of 'historical city syndrome': so bounded to the graspable and deeply interiorized image of the historical city (now obviously surpassed forever), that it seems unable to conceive any other type of urban morphological manifestation. In fact, as Michael Batty (Batty 2007) notes, this seems even to be a general condition: "if you were to ask the population at large to define a city, most would respond with an image much more akin to what a

medieval or industrial city looked like than anything that resembles the urban world [...] in which we live" op. cit. p. 18. Indeed, cities were more or less alike for millennia (Mumford 1961); our experience of the contemporary urban vastness and fuzziness is still rather unripe. But there seems no doubt that the extended city is here to stay and that urban planning needs to understand this new type of urban form and to learn how to tackle it.

The work described in this chapter seeks to make a contribution towards a more objective understanding of contemporary metropolitan and suburban morphologies. We will report the results of an on-going research project, some of which were already described elsewhere (Serra and Pinho 2011), so here we will just stick to the most relevant findings. We have conducted a comparative morphological study between five representative suburban areas of Oporto's metropolitan region, observing the development of their street systems along 55 years. We try, as much as possible, to confine our work to quantitative morphological descriptions and analytical procedures, in order to avoid the above mentioned subjectivity and aesthetical bias of some discursive approaches to contemporary urban form.

We take street systems as our sole object of study, for two fundamental reasons. Firstly, because street systems have for long been recognized by urban morphology as the most structuring of urban form's three basic elements[1] (namely street, plot and building systems). This is because streets have the greatest temporal inertia, being highly resilient to subsequent changes after their construction (by contrast, buildings have the least temporal inertia, changing quite frequently); therefore, streets are also the most conditioning of all elements, in what regards subsequent transformations to themselves or to the elements that change more quickly (Levy 1999; Case-Scheer 2001; Kropf 2009, 2011; Whitehand 1992, 2001). Secondly, because the available analytical techniques to model and analyse the morphology of urban street systems (namely space syntax's techniques) are purely quantitative and have attained a significative level of empirical and theoretical support (Hillier 1989, 1996a; Hillier et al. 2005; Hillier and Vaughan 2007; Penn et al. 1998; Read and Bruyns 2007).

We address our study object at two different levels. At the global, or macro level, studying the temporal evolution of the structure of each area's street network as a whole; and at the local, or micro level, investigating the individual morphologies of the incremental development operations occurring within each area through time. At the macro level we use space syntax (Hillier 1996b; Hillier and Hanson 1984) as main research tool; at the micro level we use several simple morphological quantitative parameters, adopted (and adapted) from Stephen Marshall's (Marshall 2005) work, which have the advantage of being comparable to space syntax's global structural descriptions (both techniques will be detailed in the next section). These two levels of research and the crossing of their results, are intended to produce insights on how the individual morphologies of urban development

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[1] See (Levy 1999) or (Kropf 2011) for details on the definitions and characteristics of urban form's basic elements.

operations give rise to global structures at the macro-level, through their progressive accumulation through time.

Contemporary metropolitan development is characterized by highly decentralized and uncoordinated growth processes, occurring in contexts of strong administrative and political fragmentation (EEA 2006). This is particularly true in the case under study. It seems difficult, given these factors and the territorial scope of metropolitan urbanization, to achieve substantial morphological control with top-down planning approaches. Instead, if we could find causal relationships between the individual morphologies that incrementally construct the city through time, and the global structural outcomes that they collectively produce at higher scales, the devising of bottom-up planning approaches to urban form would become possible (Marshall 2005, 2009). In other words, it would be possible to envision street pattern regulations for the very local level (which is liable of planning scrutiny and control), in order to achieve desired structural outcomes at the level of global street networks (which are difficult, if not impossible, to anticipate in detail today). As we will try to show, this work provides also some clues in that direction.

2 Methodology

In order to maximize the probability of observing significative morphological formation and transformation processes, we have selected as target areas the civil parishes[2] with highest urban growth rates over the last 50 years, belonging to the five municipalities that surround the city of Oporto. Because parishes' areas and their administrative limits are rather different, we considered a circular boundary of a 3 km radius for each study area (28.3 km^2, with centre on the centroid of the polygon formed by each parish's administrative limits). Figure 1 shows the location of these areas, as well as the limits of the chosen civil parishes and of the municipalities to which they belong. From now on, we will refer to these areas[3] as A, B, C, D and E, as shown in Fig. 1. These selection criteria produced some zones of overlap between study areas; but we accept this circumstance as natural, as these are excerpts of a larger and quite continuously urbanized zone. Therefore, the bordering context of each area (except case study E, the only to the south of the Douro river) is also part of the context of those which are nearer, because there are no abrupt urbanization discontinuities between them.

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[2] The Portuguese system of territorial administration is divided, at the local level, in two tiers: the municipal level, and the civil parish level.

[3] The Portuguese names of the parishes are Custoias, Vermoim, Ermesinde, Rio Tinto and Mafamude, respectively.
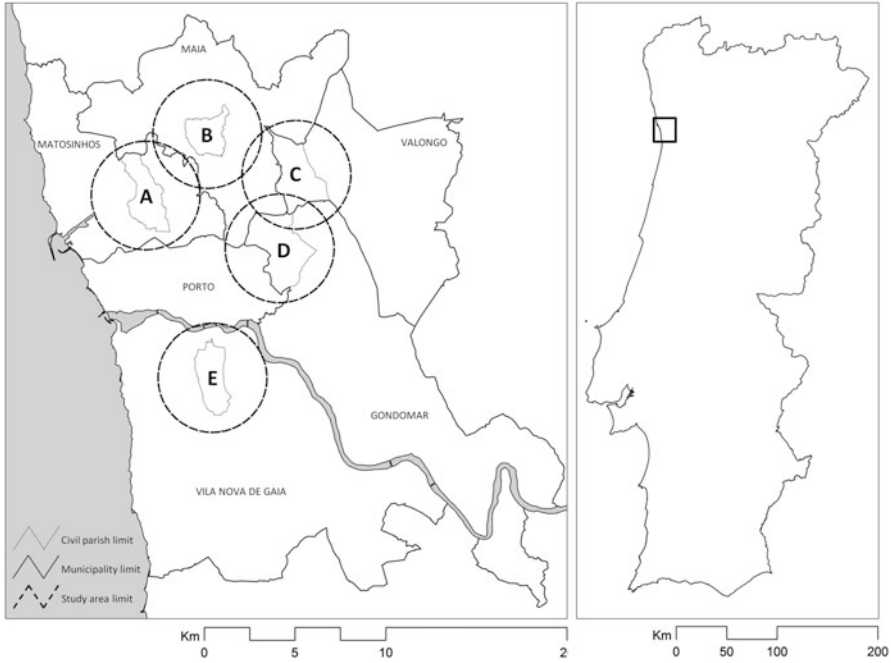
Fig. 1 Study areas location on Oporto's metropolitan region

Oporto's metropolitan region[4] is a dispersed, but continuously urbanized territory covering many cities and towns, most of them of ancient foundation. Unlike the typical metropolitan 'oil stain' pattern, produced by concentric growth from a dominant centre along a clear time-line, Oporto's metropolitan region has developed more by the densification of pre-existing and dispersed nuclei, with little differences in density or time of development. This polycentric urbanization pattern was fostered by a dispersed location of industry (starting late, well within the first half of the XX century) and thus also of employment, never generating the concentration of wealth and services at the central core, typical of early industrialized cities (Cardoso 2010).

However, prior to this industrial diffusion, a much older type of dispersed territorial occupation was already in place. The typical medieval land-division of the peninsular northwest, characterized by very small, family owned agricultural parcels, has generated a proliferation of small villages, hamlets and towns, and especially huge amounts of very old infrastructures (paths, roads, informal crossings), irrigating a former rural territory now thirsty for urbanization. The expansion of the built-up area has been supported in large part by this vast and labyrinthine

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[4] The total region known as Greater Oporto Metropolitan Area (or GAMP, in its Portuguese acronym), spans 75 km of the Portuguese northern coast over an area of 1.885 km^2 and has a population of approximately 1.673.000 inhabitants.

capillary road network (mostly of rural origin) and by an important network of long and sinuous radial and radio-concentric roads. Over this old matrix, the creation of an arterial system of metropolitan highways has gained importance over the last two decades, deeply changing regional and local accessibility patterns (Domingues 2008).

Figure 2 summarizes the research methodology. The first step concerns the diachronic modelling of each study area's street system at several time periods and the identification of individual development operations occurring between each period (see below). This step provides the data to be explored at the macro level using space syntax (i.e. the study areas' entire street systems at each time period, subsequently modelled as axial maps); and those to be explored at the micro level (i.e. the sub-sets of individual development operations occurring between each time period), using some of the techniques proposed by (Marshall 2005) to describe individual street patterns. The crossing of the results of these two types of analysis, will then allow exploring potential causal relationships between the morphologies occurring at the micro level and the structures indentified at the macro level.

Each of these research steps uses different analytical procedures that we must first introduce in order to make our results comprehensible. Besides providing the raw material to be explored by macro and micro-analysis, the data sets produced during the diachronic modelling phase have their own analytical interest and can be explored using simple density and spatial distribution parameters. Space syntax's analytical procedures and theoretical background are central in our work and need also to be previously introduced, as well as the techniques proposed by Stephen Marshall (Marshall 2005) to quantify and classify individual street patterns. In the next three subsections we provide these methodological and theoretical reviews, which will constitute the context for the findings presented further ahead.

2.1 Diachronic Modelling of Street Systems in GIS

Both space syntax and the methods proposed by Marshall (Marshall 2005) are static analytical techniques: time is not a dimension of analysis. However, time and temporal dynamics are central objects of urban morphology and of this study in particular. Therefore, in order to make use of both these techniques but also to integrate time in our study, the street system of each study area had to be recreated at several historical moments. This was done by the common method of map regression (Kropf 2011; Pinho and Oliveira 2009) widely used in urban morphology, but implemented here in a Geographical Information System[5] (GIS) environment, making use of the possibility of storing data both in spatial and tabular formats.
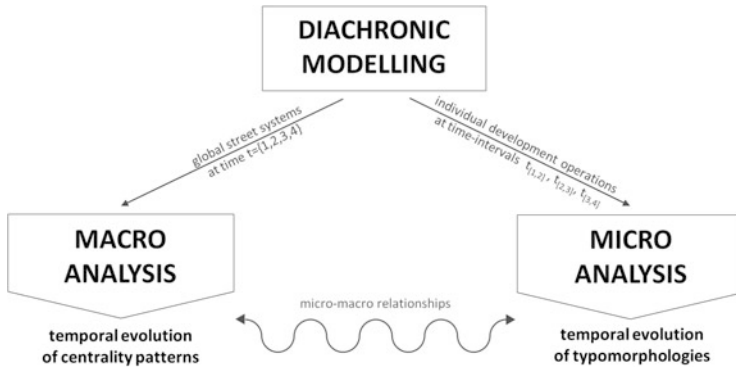
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[5] We used ESRI's ArcGIS 10.

Fig. 2 Research methodology

We start by importing into GIS several digitized historical maps[6] and current vector street layers,[7] describing the street systems at four different points in time, $t = \{1,2,3,4\}$, corresponding respectively to the years[8] 1950, 1975, 1990 and 2005. We note the time intervals between these temporal moments as $t_{[1, 2]}$, $t_{[2, 3]}$ and $t_{[3, 4]}$ (the first two intervals having a time-length of 25 years and the last of 15 years). The current vector layers ($t = 4$) are first used to georeference the digitized maps ($t = \{1,2,3\}$). Then, for each study area, we overlay the current vector layer over the most recent digitized map ($t = 3$) and tag all vector features that are not present on the digitized map. This is done through three binary attribute fields ([t3], [t2] and [t1], created on the vector layer's data table) describing the presence or absence of each vector feature at the periods $t = \{1,2,3\}$.

Initially, the [t3] field is entirely populated with 1 values; when a feature is identified as not present at $t = 3$, its value on the [t3] field is changed to 0; thus, recording its construction sometime during the time-interval $t_{[3,4]}$. We repeat this process until all features not present in the $t = 3$ map are indentified. Then, the values of the [t3] field are transposed to the [t2] field, the features where [t3] = 0 are excluded from the visualization, the digitized map corresponding to $t = 2$ is loaded and the process recommences (now changing the values of [t2] to 0, when-ever a vector feature is not present in $t = 2$ map). The process is repeated for all time periods on all study areas. This method allows storing all information on the development of the street systems in a single vector layer for each study area, encoding the time of occurrence of each vector feature in tabular format instead of simply deleting them.

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[6] Extracted from the Portuguese Military Map, covering the entire national territory at the 1:25.000 scale (edited by the Portuguese Military Geographic Institute, IGeoE).

[7] Extracted from urban digital cartographies, provided by the municipalities concerned in this study.

[8] The years 1950, 1975 and 1990 correspond to successive editions of the Portuguese Military Map; 2005 is the date of the municipal digital cartographies.

The extraction of the several temporal versions of each street system becomes a process of simple database querying. In the same way, we extract also the sub-sets of vector features created during each time interval.[9] The latter elements are subsequently visualized over current satellite imagery,[10] in order to further separate them into individual development operations. The large majority of these features occur as isolated clusters, usually corresponding to obviously different development operations. Whenever this is not the case (because several operations locate contiguously, or even intermingled), one can easily recognize their individuality through the visual inspection of the associated built structures, visible on the satellite imagery (e.g. the shape of buildings, type and colour of roofing, design style, pavements, etc). Besides providing the raw material for the macro and micro-analysis exercises, these data sets have their own analytical relevance. The simple visual inspection of the street systems at each t = {1,2,3,4} (as depicted on the upper row of Fig. 3), is enough to infer some characteristic aspects of their evolution, by comparing their initial and final states. But we have also studied the two types of data sets depicted on Fig. 3 quantitatively, using basic density and spatial distribution parameters.

We compute *road density* by simply taking the total length (in meters) of the street system[11] of each study area at each t = {1,2,3,4}; because the area remains constant through time and is equal for each case study, total road-length becomes a direct and comparable measure of road density. We have also introduced a simple index expressing urban growth's[12] *spatial distribution*. This index is calculated by counting the number of individual urban development operations occurring within a circle with half the radius[13] of the study areas and centred therein, expressed as a percentage of the total number of development operations occurring at each time interval. Because the centres of the study areas are defined by the centroids of the civil parishes' with highest growth rates in the last 50 years; and because, in all cases, the main urban nuclei are today located at those positions; it is expectable that, under normal conditions, the majority of development operations would occur near the centre of each study area. Therefore, we consider urban growth to be concentrated when this index yields values above 50 %; when it yields values below 50 %, we consider it to be dispersed.

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[9] For example, in order to extract the vector features created during $t_{[2,3]}$ we simply use the following SQL query condition: [t2] = 0 AND [t3] = 1.

[10] We used ESRI's 'World Imagery' layer, last updated in June 2013 and built-in ArcGIS 10. The layer features 0.3 m resolution imagery from DigitalGlobe, in the continental United States and parts of Western Europe (including Oporto's metropolitan region).

[11] We used the total length of axial lines in each street system after their conversion into axial maps (introduced further ahead), which is equivalent to total road-length.

[12] We take the previously individualized urban development operations as proxies of urban growth, more specifically of the growth of street systems.

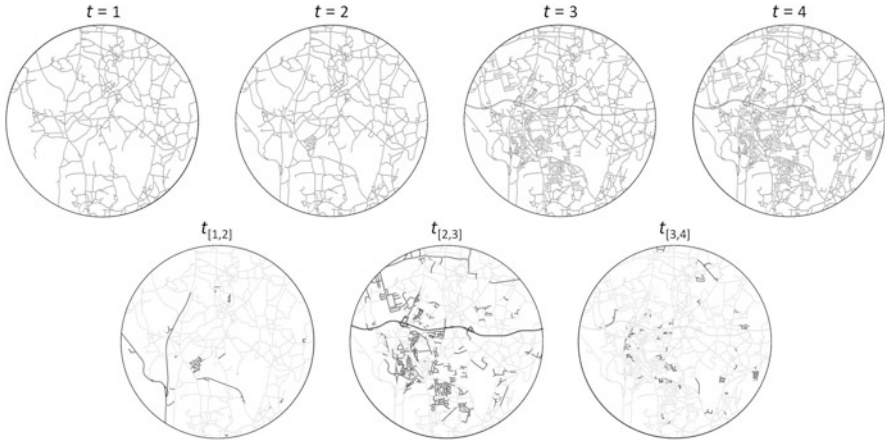[13] Thus, with 1.5 km radius and an area of 7.1 km^2.

Fig. 3 Diachronic modelling of street systems in GIS (study area B). The street system at each t = {1,2,3,4} (*upper row*) and the street layouts of urban development operations occurring between each time period (*lower row*)

2.2 Using Space Syntax to Study the Evolving Structure of Street Networks

The study of urban spatial networks underwent major breakthroughs in the last three decades. Among other things, it has revealed that the topological constitution of such networks plays a decisive role in urban functioning. We now have the tools to begin understanding the reasons for cities being physically and spatially like they are, and why some parts of them are vibrant and seemingly fit for living in, while others are lethargic and apparently inappropriate. Space syntax (Hillier 1996b; Hillier and Hanson 1984) is the most fertile and operative manifestation of this approach, with direct applications on the urban planning and design fields as well as providing the theoretical framework for a growing research community.

Unlike other analytical approaches to urban form, syntactic analysis ignores the information contained in the built elements and addresses only the form of the open space system defined by them. It adopts several methods to represent the morphology of spatial systems as networks of elementary spatial units (or spatial primitives), easily translatable into graphs,[14] thus allowing for the quantitative analysis of their topological structure. One of such methods – axial mapping – is particularly useful for describing urban space. Here, we will concern ourselves only with this kind of spatial representation.

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[14] A graph is a mathematical formalism, constituted by a set of nodes (or vertices) and a set of links (or edges), connecting those nodes. Graphs are used to represent any phenomenon in which there is a set of relations (the edges) between a number of objects (the vertices).
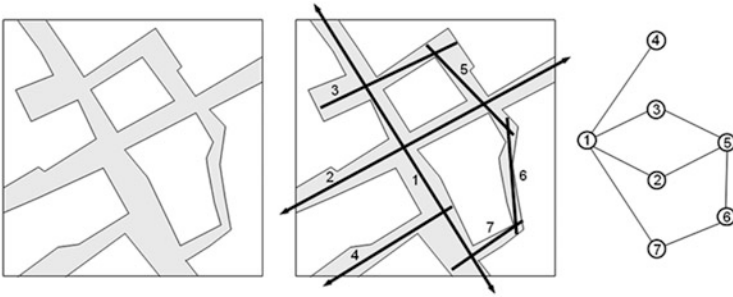
Fig. 4 A fragment of a hypothetical street system (*left*), its axial representation (*middle*) and the resulting axial graph (*right*). Numbers indicate axial lines and respective nodes in the axial graph

Axial maps aim at describing the spatial morphology of urban street systems by means of a very concise, skeletal representation. In an axial map, the convex geometry[15] of the planar representation of a given spatial system is approximately described by a set of interconnected straight lines (called axial lines) such that each line is extended as long as the geometry of the system allows, while ensuring that: i) any possible intersection with any other line is made; and ii) that the number of axial lines is minimal (thus, being also the longest lines meeting both conditions). Axial lines are translated into the nodes $V = \{1,...,n\}$ of an undirected graph $G = (V,E)$, henceforth called axial graph, in which any pair of axial lines encoded as nodes, $i \in V$ and $j \in V$, are held to be adjacent, $i \sim j$, when they intersect on the axial map. The adjacency relations between all lines are encoded by edges $(i,j) \in E$, if and only if $i \sim j$. Figure 4 illustrates the process of axial representation and its subsequent graph encoding.

Graphs have long been used in geographical analysis, including the analysis of transportation networks (Garrison 1960; Hargett and Chorley 1969). However, the way street networks are represented as graphs in geography and transport research, differs significatively from space syntax's axial graphs. In the former type of representation, junctions are interpreted as nodes and streets as edges linking those nodes. This is called a *primal graph* representation (Porta et al. 2006a) and it suits well the study of transportation networks where nodes are significant points of terminus and interchange (as airports in airway networks, or junctions in large-scale road networks). However, this convention is less effective when the *morphology* of streets is the main focus of attention. But if a street system is first described by an axial map and axial lines are subsequently encoded as the nodes of a *dual graph* (Porta et al. 2006b), morphological specificities become apparent. Figure 5 shows the differences between the two types of graph representation.

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[15] By convex geometry of a given polygonal shape we mean its decomposition into a minimal set of convex polygons (i.e. polygons in which any pair of points may be united by a line segment that remains entirely on the boundary or within the polygon itself). Circles, rectangles and triangles are convex polygons; however, any polygon with holes or dents is non-convex, because it has points that may only be united by segments that cross its boundary.
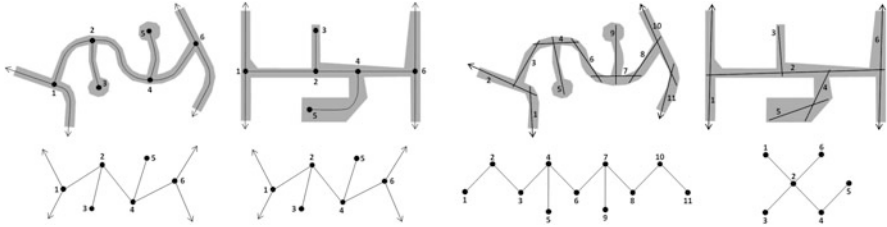
Fig. 5 Primal (*left*) and dual (*right*) graph representations of street networks

Although the two layouts show quite different morphologies, their primal graph representations (Fig. 5, left) have exactly the same topology (i.e. their graphs are homeomorphic). However, if both layouts are first represented as axial maps (Fig. 5, right), their different morphologies result in also different graphs. By using axial lines as nodes we are in fact encoding a morphological pattern into the graph, because axial lines are one-dimensional morphological descriptions of space (which are consistent insofar unobstructed sight and straight movement are possible along that line). Ultimately, what is being represented is the number of changes of visual axis, or the number of deviations from straight movement, that one must take to go from any point in the system to any other; both conditions are determined by the system's specific morphology. The correspondent axial graph is used to quantify the centrality (or accessibility) of each axial line in the system. Space syntax uses several graph measures for this purpose. We will only describe one of those, namely the measure of *integration*, which will be used for exploring the evolving centrality structures of our case studies.

Integration evaluates the relative proximity of each axial line to the overall spatial system. As a measure of proximity, it obviously deals with distances. However, the distance between two axial lines is of an unusual type (called topological distance, or *depth* within space syntax), measured in discrete units. If two axial lines are adjacent, the distance between them is 1 (independently of their actual metrical lengths); if they are not adjacent, the distance between them corresponds to the smaller number of edges separating their respective nodes in the axial graph (or geodesic distance). Therefore, the distance between two non-adjacent axial lines, can be seen as the fewest number of turns, or deviations from one visual axis to another, that one must take to move from one axial line to the other.

Integration is a normalized version of a simpler measure (which is actually equal to the *closeness centrality* of general network analysis), called *mean depth* within space syntax. In a connected and undirected axial graph $G = (V,E)$, the mean depth of a node $i \in V$ is given by the equation below, where k is the number of nodes in the graph and d_{ij} the length of each geodesic between i and any other node j (Hillier and Hanson 1984).

$$MD_i = \frac{1}{k-1} \sum d_{ij}$$

The mean depth of a node is highly dependent on the order of the graph (i.e. the number of its nodes, k) making impossible the comparison of values produced by different-sized graphs. This is only relevant in systems varying greatly in size and structure, but it constitutes a problem for the comparative analysis of cities and therefore a hindrance for research. In order to tackle this problem, mean depth values must be normalized according to some general 'yardstick'. Within space syntax, this is done by comparing the centrality of each node in a graph with k nodes, with the so-called D-value[16] for a special graph of the same order, or D_k, which is given by the following expression (Krüger 1989),

$$D_k = 2 \frac{k\left[\left(\log_2 \frac{k+2}{3} - 1\right) + 1\right]}{(k-1)(k-2)}$$

Finally, the integration value of a node i (which is a standardized measure, comparable between graphs of different orders) is calculated by the equation below (Hillier and Hanson 1984) in which the numerator $(2MD_i - 2)/(k - 2)$ corresponds to MD_i rescaled[17] to vary only within the [0,1] interval.

$$integration\ (i) = \left(\frac{\frac{2MD_i - 2}{k-2}}{D_k}\right)^{-1}$$

The correspondence between the axial graph and the axial map allows centrality values to be represented also graphically. Figure 6 shows the global integration values of study area B at each time period, represented on the axial map according to a chromatic scale ranging from light-grey (low values) to black (high values). Such graphic representation is called 'integration pattern' and it makes visually evident the centrality structure of a given street network.

Like the generality of space syntax's graph measures, the integration value of each axial line may be calculated over the entire system (global integration) or over a restricted topological neighbourhood – or *radius* – around each line (local integration). For instance, for a given line, radius 1 includes all the lines directly connected to it; radius 2 includes also those lines, but still all other lines directly connected to them; and so on, regarding any desired topological radius around each line (Fig. 7). Thus, the centrality of each axial line may be assessed at different radii, or spatial scales, from the local level (e.g. the scale of a urban neighbourhood)

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[16] The D-value of a node i in a graph with k nodes, corresponds to the mean depth of the 'root' node of a special type of graph with the same number of nodes (a so-called 'diamond graph'), in which depth values follow a strict normal distribution.

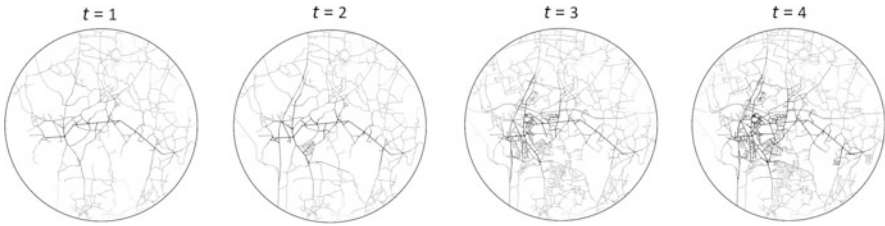[17] This rescaled version of mean depth is called relative asymmetry (RA).

Fig. 6 Example of integration values represented on the axial map according to a chromatic scale (study area B)
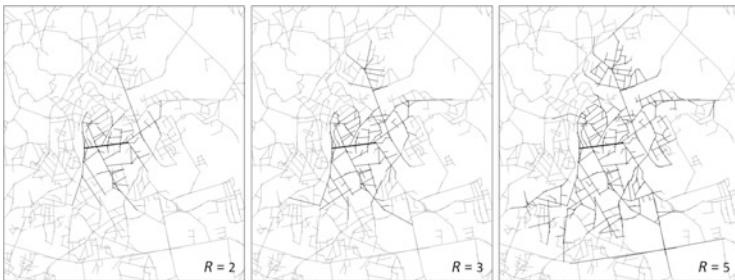

Fig. 7 Three radii (2, 3 and 5), or topological neighbourhoods (*black lines*), of an axial line of study area C (represented in *thick black*)

up to the scale of the entire spatial system under analysis (e.g. the scale of a city or even of an entire metropolitan region).

However, local and global centralities are not mutually exclusive: a given axial line may be central both at the local and global levels. This brings us to the last space syntax concept to be introduced, namely that of spatial *intelligibility*. For a given spatial network, this parameter is expressed by the correlation coefficient (R^2), between the values of local[18] and global integration (Hillier 1996b). When such correlation is high, it means that spaces that are locally integrated are also integrated at the global level, and that segregated spaces tend to be segregated at all scales. By contrast, when the correlation is low, it means that integration is more or less randomly distributed at the local and global scales, without any particular relation between locally and globally integrated (or segregated) spaces. Thus, this parameter can reveal deep centrality regularities in urban spatial networks, namely the presence (or absence) of a structural unity between the local parts and the wholes of those networks. As we will see in a moment, such structural unity can have significative impacts in the way we perceive and use urban spatial systems. In this work we studied both integration and intelligibility, finding clear differences

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[18] Besides local integration, intelligibility is also quantified by the correlation between global integration and connectivity (i.e. the number of direct links each axial line has). Connectivity is the most local type of centrality (called degree centrality, in general network analysis).

between the several study areas and the way they have evolved through time. However, our findings may have relevance only at the light of the empirical validity of such properties; these are quickly reviewed in the following paragraphs.

The fundamental finding of space syntax, over which its theoretical *corpus* has been constructed, was the discovery of an intimate relationship between urban movement and spatial centrality. Movement (vehicular or pedestrian, from every origin to every destination) is the most basic and common use of urban space. However, urban movement does not distribute itself uniformly (or randomly) within urban street systems; quite the contrary, in every city one can always find bustling thoroughfares and also secluded streets. These inequalities in urban movement rates correlate strongly[19] with spatial centrality, as described by the above mentioned methods (Hillier et al. 2005; Penn et al. 1998). Because certain urban functions (like tertiary functions) thrive on the presence of urban movement (searching locations of high visibility and accessibility), while others are indifferent or even averse to high movement rates (like the residential function), it is a small step to conclude that urban functional patterns may also be explainable by urban spatial centrality patterns. And in fact they are, as several works (Chiaradia et al. 2009; Kim and Sohn 2002; Ortiz-Chao and Hillier 2007) have clearly demonstrated. Attracted to movement-rich locations, tertiary functions act then as additional movement destinations, creating a multiplying effect over the basic movement pattern induced by the street network itself (Hillier 1996a).

Spatial intelligibility, or the lack of it, has another type of structural significance. Firstly, from a purely morphological point of view, this parameter is capable of capturing the degree of structural order (or disorder) of a given spatial system (Hillier 1996b, 1999), if we understand 'order' in the sense of spatial linearity or axial continuity (which is not the same as pure geometric regularity). This type of spatial order seems to be closely related with some morphological regularities characteristic of naturally evolved urban street systems, as the seemingly universal Zipf distributions of axial line's lengths (Carvalho and Penn 2004), or the ubiquitous pattern of a foreground network made up of a few, quasi-linear main urban routes, set against a much more vast (and much less linear) background network of secondary streets (Hillier and Vaughan 2007; Hillier 1996b, 2002). Secondly, several studies have shown that, in unintelligible systems, the predictability of urban movement rates from spatial centrality decreases (Read 1999; Hillier et al. 1987, 1993; Park 2009). This seems to indicate that in such systems, movement (as an aggregated phenomenon) loses structure and becomes diffused, or with highly individualized patterns. And thirdly, other studies have also empirically shown that the property of intelligibility is indeed a relevant descriptor of a system's propensity for facilitating or for hindering spatial orientation (Conroy 2000; Haq 2003; Haq et al. 2005; Long et al. 2007; Tuncer 2007). For all these

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[19] For example, (Penn et al. 1998) reports correlations of R2 ~ 0.8 for a very large sample of movement observations in London. Other studies have found similar correlations in many cities around the world.

reasons, syntactic intelligibility is also particularly relevant to this work, because suburban contemporary areas are usually qualified not only as 'labyrinthine' but also as 'structurally flawed' (at least when compared to the traditional city); therefore, this parameter may capture these characteristics.

2.3 Classifying and Quantifying the Morphology of Urban Development Operations

The last analysis technique was used to explore the morphology of urban growth at the micro level, as represented by the sets of individual development operations, identified before. We used some of the analytical tools proposed by Stephen Marshall (Marshall 2005) to classify and quantify these elements. Marshall's work is mainly concerned with two fundamental questions: how to classify street layouts in a consistent and systematic way and how to quantify their particular morphological characteristics. The analytical tools proposed by this author adopt a topological approach to street pattern classification, producing results that are consistent with those of space syntax.

Given the formal diversity of the development operations, the typomorphological classification criteria would have to be simple, yet sufficiently discriminant. We used two basic properties of street patterns mentioned in (Marshall 2005): the *internal structure* of street layouts; and the *external relationships* they establish with the surrounding grid. These two properties were assessed by inspecting the axial descriptions of the development operations (selecting the axial lines corresponding to their street layouts, extracted from each period's axial map), and how they were articulated with the existing street network (Fig. 8).

Internally, development operations were classified under two basic types, reflecting the presence or absence of urban blocks *within* their street layouts. In topological terms, these correspond respectively to axial sub-graphs with internal cycles[20] and to acyclic (or tree-like) sub-graphs. Throughout the first phase of this work (i.e. the recreation of the street systems at several temporal periods), we observed that the majority of new developments were small and simply composed by a few street segments, but that a minority were larger and commonly corresponded to layouts with internal blocks. As this is a basic difference between networks (i.e. cyclic or acyclic), moreover also indentified by (Marshall 2005) as a fundamental distinction between street layout morphologies, we classified the internal structure of development operations according to this criterion, defining

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[20] In graph theory, a cycle is a closed path starting and ending at the same node and passing at least by two other nodes. In street networks, cycles correspond to urban blocks (or to islands of private space, completely surrounded by streets). A graph without cycles is called a 'tree' because, as trees, it has 'branches' but those branches never intersect.
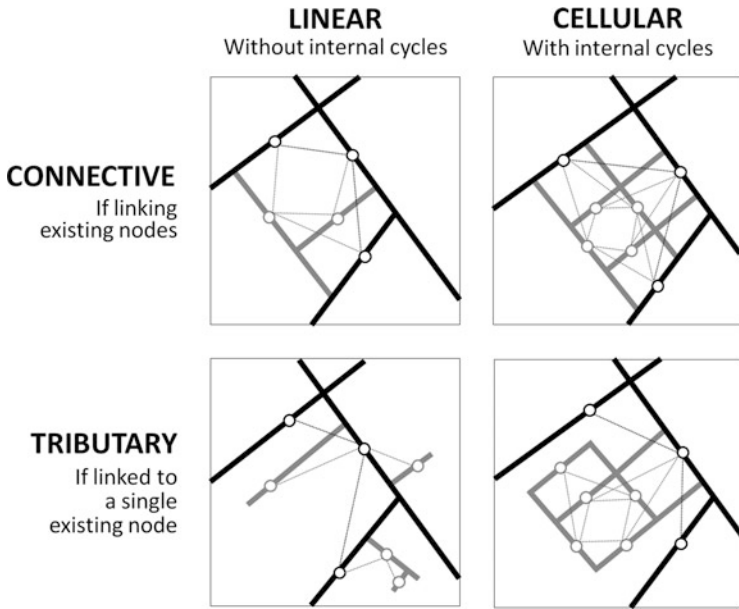
Fig. 8 The typomorphological classification system of the individual development operations

two morphological classes – cellular and linear – corresponding respectively to layouts with and without internal blocks.

   We have also identified two recurrent types of external linkage, quite independent of the above mentioned internal properties. We have observed that some development operations had very few linkage points to the existing grid (usually just one, but sometimes two or three in the larger exemplars), thus not creating (or creating very few) connections between existing streets; conversely, other development operations (independently of their sizes) linked to several points of the existing grid, thus always creating new connections between existing streets (and also new potential circulation alternatives). In other words, the former type very rarely sub-divides existing spatial islands (or existing network cycles), while the latter type always creates new sub-divisions of existing spatial islands. These basic external connection possibilities are also mentioned in (Marshall 2005), where they are called respectively *connective* and *tributary*, designations that we have kept to characterize the external connectivities of the identified development operations. These types of internal structures and external linkages make a total of four possible typomorphological combinations (linear → connective/tributary, cellular → connective/tributary), summarized in Fig. 8. For each time interval, we classified as such each development operation and made an accounting of their relative quantities, as percentages of the total number of occurrences in each study area at each time interval.

   The internal characteristics of each development operation (linear or cellular) are rather easy to establish. Externally, however, most developments are not so

purely connective or tributary, although this criterion has shown to be effective if used with some degree of freedom.[21] But to cope with possible classification bias we used also two simple morphological parameters introduced in (Marshall 2005). Given the number of internal cells (graph cycles) and culs-de-sac (end-nodes of the graph, linked by cut-edges[22]) in a graph representation of a street network, it is possible to establish a 'cell ratio' and a 'cul ratio', as proportions of the total number of 'cells' and 'culs-de-sac'. Let C be the total number of cycles and D the total number of end-nodes in a street layout; then, the cell ratio (C_R) and the cul ratio (D_R) of that street layout will be given by,

$$C_R = \frac{C}{C+D} \quad and \quad D_R = \frac{D}{D+C}$$

In a pure tributary layout (a tree, without cycles) D_R will be one and the C_R will be zero. Conversely, in a pure cellular layout the D_R will be zero and the C_R will be one. More generally, in real-life mixed situations the values will vary, with the sum of both being one (Marshall 2005). We used these two basic quantifications, but for slightly different purposes. In an axial map, rings made by sequences of intersected lines correspond to cycles in the graph. In the same way, axial lines that do not lead to other lines (i.e. whose connectivity is 1), correspond to end-nodes. Thus, counting cycles and end-nodes in the axial representation becomes a rather simple task. However, we were not interested in quantifying the morphology of each development operation, but rather the morphological nature of urban growth at each time interval and in each study area; the idea was to obtain global morphological values, characterizing the extent to which urban growth was 'connective' or 'tributary'. These values would serve as morphological indicators *per se*, but also as benchmark values to control the typomorphological classification explained before. Thus, for the set of urban development operations of each time interval, we counted the total number of new cycles[23] and new end-nodes; with these values, we calculated the two ratios mentioned above, only now reflecting the global morphological composition of urban growth at each moment in time on each study area.

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[21] For instance, some cellular developments have an extremely tributary character (and as such were classified), showing many cycles isolated from the surrounding network, even though they are externally connected with two existing streets and not just one. In the same way, although creating new links in the existing network, connective developments can come with some tributary appendices.

[22] In graph theory, a cut-edge (or bridge) is an edge which, if suppressed, divides the graph in two connected components.

[23] We did not count cycles of length 3, because on axial maps these are almost always trivial cycles, created by the simple intersection of axial lines in open space and not because there is anything built in the middle. Also, when counting new cycles, we took the care of discounting existing cycles; for instance, if a connective development operation divides a former single cycle into three cycles, the count of the new cycles will be two.
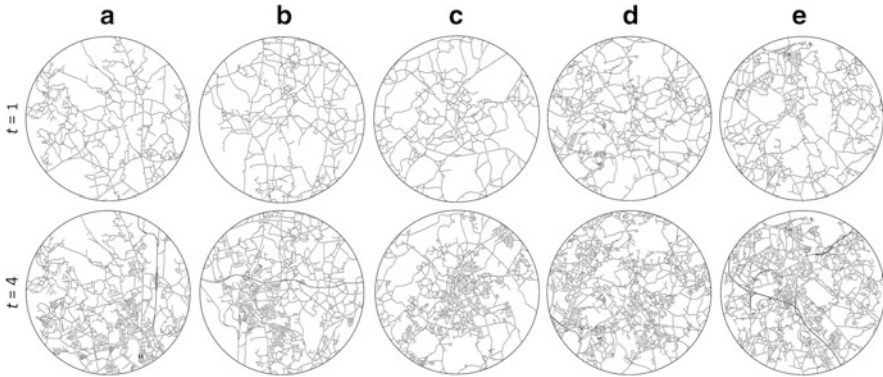
Fig. 9 The initial (t = 1, *upper row*) and final street systems (t = 4, *lower row*) of all study areas

3   Results

Our general result is in recognition of patterns of morphological change that are characteristic for each of the five study areas. This is despite all these areas being located within a 10 km radius from the centre of Oporto and considered as similar Oporto's suburbs. The street systems of t = 1 (before 1950), which are the initial spatial matrices over which urban growth will occur (Fig. 9, upper row), are visually describable as showing low street densities and a prevalent pattern of sinuous and narrow roads, with large undeveloped spatial islands, characteristic of local rural road networks (except study areas D and E,[24] which already show at t = 1 some small grid condensations of urban characteristics, i.e. smaller and more regular spatial islands and greater road density).

However, it is possible to visually discern on the final street systems differentiated morphological patterns (Fig. 9, lower row). Case studies B and C (and, to a certain degree, also A), evolved towards grids characterized by a dense, central urban core, surrounded by a sparser grid still with rural characteristics. In these cases, the distinction between urban and rural morphologies is rather clear. However, case studies D and E evolved into a kind of hybrid grid, with no clear spatial distinction between rural and urban components.

Even if all study areas show the same growth rates, their different final states may be explained (at least in part) by the evolution of urban growth's spatial distribution. The intensity rate of urban growth may be assessed by comparing the values of road density of each study area at all time periods (Fig. 10, left). Starting from different density levels (with density decreasing with increasing distance from the central city), all study areas show the same growth rate (i.e. their curves are approximately parallel), with a maximum intensity phase[25]

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[24] These case studies are the nearest to the central city, and thus had an earlier urban development.

[25] Corresponding to the urban boom that Portuguese cities suffered between the 70' and the 90'.
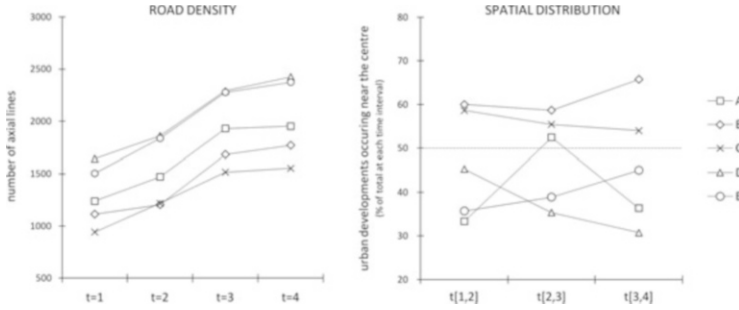
Fig. 10 Road density (*left*) and urban growth's spatial distribution (*right*), for all study areas at all time periods

during $t_{[2, 3]}$. Most of the transformations that the grids have undergone happen during this time interval. However, the spatial distribution of urban growth (measured according to the method described in Sect. 2.1) shows clear variations, both among study areas and across time (Fig. 10, right). Urban growth is always concentrated (>50 %) on study areas B and C, and always dispersed (<50 %) on study areas D and E. There are also periods of concentration and others of dispersion in the same study area, namely at A. However, during the time interval when urban growth is more intense ($t_{[2,3]}$), study areas A, B and C show a concentrated distribution, while D and E a dispersed distribution.

The space syntax results showed that differences were also present at the configurational level. Figure 11 (upper row) shows the integration patterns of all study areas at t = 1. Visual inspection of these patterns reveals few hierarchical differentiations between network spaces (i.e. patterns characterized by generally low integration values and very few dominant structures, with clear higher values or complex organization). This is general at all study areas except E, which shows a centre with some structure at this phase. But the other initial networks show just a few integrated long lines, being (for the most part) segments of old radial roads linking other towns to Oporto. These centrality patterns suggest that rural street systems do not favour any particular route structure, apart from a few more integrated spaces with distinct morphological characteristics (more linear). In contrast, urban spatial networks are in general characterized by highly heterogeneous centrality hierarchies.

The visualization of the final (t = 4) global integration patterns (Fig. 11, lower row) reveals different structural outcomes among the several study areas. Those in which concentrated growth was dominant (B, C and to a lesser extent also A), produced cohesive urban zones with clear centrality hierarchies. While in the cases were dispersed growth prevailed (D and E) we observe the stagnation, or even the dilution, of previous spatial hierarchies and a loss of structural differentiation between grid spaces. In spite of the intense grid transformations, and even if mean integration values kept increasing along time in all cases, in case studies D
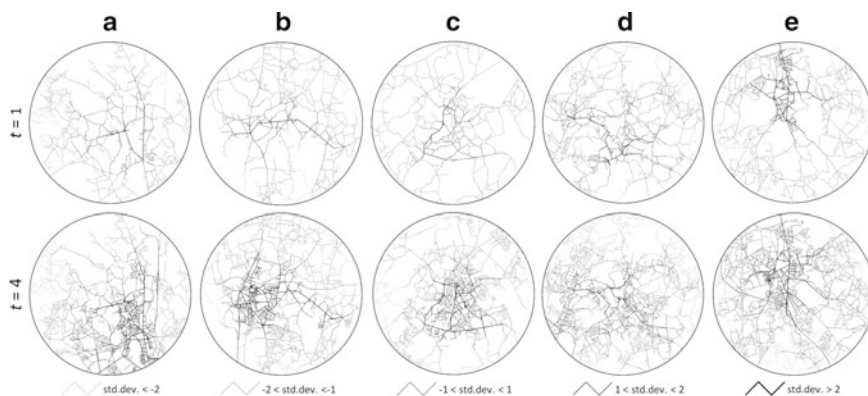
Fig. 11 The initial (t = 1, *upper row*) and final global integration patterns (t = 4, *lower row*) of all study areas

and E the dispersed growth pattern was not able to alter significantly the undifferentiated spatial character of the initial rural grids.

The evolution of the intelligibility values of the study areas (for both correlations of local integration and connectivity against global integration) showed an unexpected, yet quite relevant result, expressed in the charts of Fig. 12 (the yy axis represents R^2). A profound difference regarding the evolution of these parameters is noticeable, as case studies A, B, and C present ever increasing intelligibility values, while case studies D and E, show a sharp decrease during the period of most intense growth. The initial values are all low and close to each other, adding low intelligibility to the characteristics of rural street systems identified before. However, in case studies A, B and C, urban development manages to invert this situation and to raise intelligibility values considerably. However, in case studies D and E, in spite of an initial increase and of the similar urban growth rates, the values end up at the initial level.

Such a differentiated behaviour means that there are qualitative differences in the morphogenetic processes constructing the street systems throughout time. If suburban contemporary areas are marked by their labyrinthine character, these results show that some of the study areas diverged from that character, while others remained as unintelligible as they were initially, even if much more denser and developed. It is important to stress that these results refer to global structural properties of street networks emerging from urban growth, which is fundamentally a local process. In other words, such results describe emergent global effects, arising from discrete urban development events, operating at the local scale. The causes for such effects must therefore be sought at a lower level, that of the individual development operations constructing the networks over time.

Figure 13 (upper row) shows the frequencies of the typomorphological classes of urban development operations, as percentages of the total number of operations occurring during each time interval, for each study area. Again, the division in two
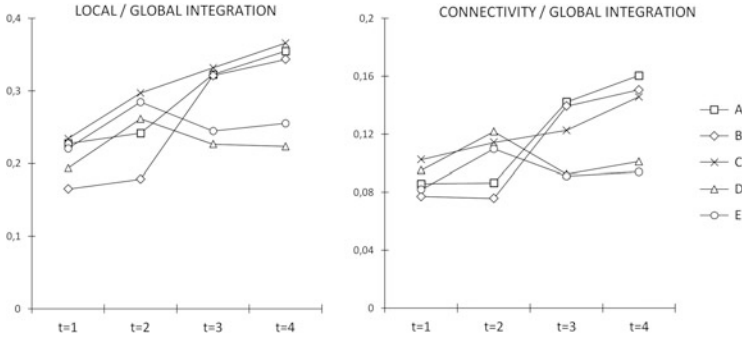
Fig. 12 Evolution of intelligibility values

groups is rather evident. In the first group (study areas A, B and C), connective typomorphologies are always prevalent over the tributary ones (both linear or cellular). However, in the second group (D and E) during $t_{[2,3]}$ (the time interval when growth is more intense) and regarding linear types (which are much more frequent than cellular types), tributary morphologies overcome connective ones. Thus, it is possible to say that the first group has a permanent connective grid construction; while in the second group, grid construction becomes predominantly tributary when most of the street system is produced.

The values of C_R ratio (Fig. 13, middle row), measuring the proportion of new cycles created at each time interval relatively to the creation of new end-nodes, is consentaneous with the previous result. At study areas A, B and C the creation of new cycles is always prevalent over the creation of new end-nodes (i.e. C_R values are always higher than 0.5); while at D and E, during the period of most intense growth, the creation of new cycles is surpassed by the creation of new end-nodes. These results show that the study areas of the first group were getting more cyclic (or more grid-like) along time; while the second group suffered a strong decrease in the creation of new cycles during $t_{[2,3]}$ (i.e. these areas got more acyclic, or more tree-like, during that time interval).

But in addition of being mutually supportive, these two results provide significant insights into the reasons behind the different evolution of intelligibility values, described previously. The charts in the lower row of Fig. 13 describe the variation of these values (Δ intelligibility) during each time interval (i.e. the intelligibility value of each time period subtracted by the value of the previous period). The relation between the former two parameters and intelligibility variation is rather evident: it is exactly during the period of most intense growth, when tributary forms overcome connective ones and new end-nodes surpass new cycles, that the intelligibility values of case studies D and E plunge. In other words, there seems to be a direct correspondence between the prevalence of tributary forms and intelligibility decrease. Indeed, this can be formally demonstrated by correlating the values of the C_R ratio at all time intervals and for all study areas, with the values of Δ intelligibility (Fig. 14). The correlation coefficients with both types of intelligibility
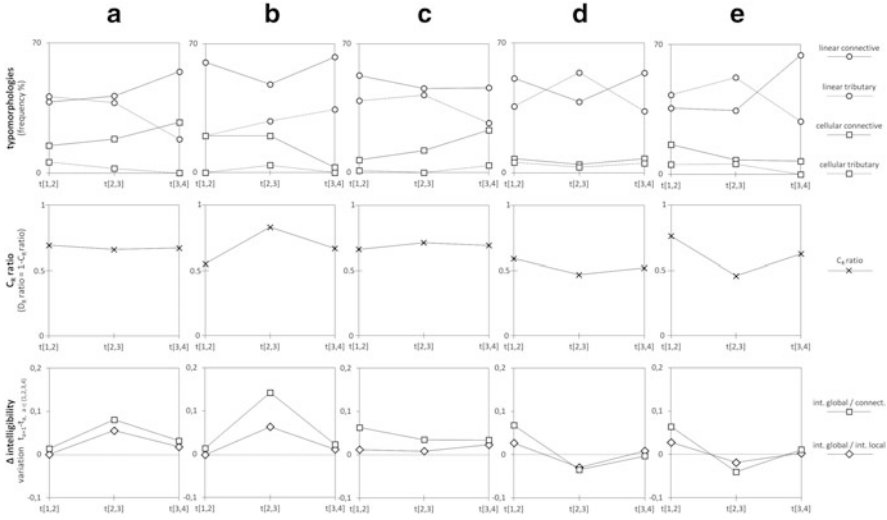
Fig. 13 The relation between frequencies of individual typomorphologies and intelligibility variation

quantification are quite significative ($R^2 = 0.55$ and $R^2 = 0.66$), showing that the more cyclic a street system gets the more intelligible it becomes. We only show the positive correlations with C_R, because C_R and D_R ratios are complementary (i.e. $C_R = 1 - D_R$) and thus the correlations with the D_R ratio are symmetric (i.e. same values, only negative).

It is important to stress that the new cycles taken into account in the calculation of both C_R and D_R ratios, are not just the internal cycles present only in cellular typomorphologies. New cycles created by the sub-division of previous ones (i.e. by the subdivision of existing spatial islands) are also accounted for and are much more frequent, being created both by linear and cellular typomorphologies (providing that they are externally connective). In fact, and besides the fact that they can also be tributary, cellular types are rather sporadic and could never explain the drastic variation of intelligibility values; what is determinant is not the distinction between cellular and linear internal structures, but between connective and tributary external linkages. What fosters the positive evolution of intelligibility, is the prevalence of urban development operations that sub-divide the existing grid and enhance its local connectivity; and what dictates its negative evolution, is the prevalence of urban developments that simply colonize existing streets to gain public access to their own layouts, but that do not create new connections between existing streets.

It seems unavoidable to conclude that the morphology of individual development operations, together with their spatial distributions (concentrated or dispersed), have been determinant to the evolution of the street networks' global structures. Such causal relationships are important; however, not because they are unlikely. In fact, with hindsight, one could say that they were expectable. Still, one
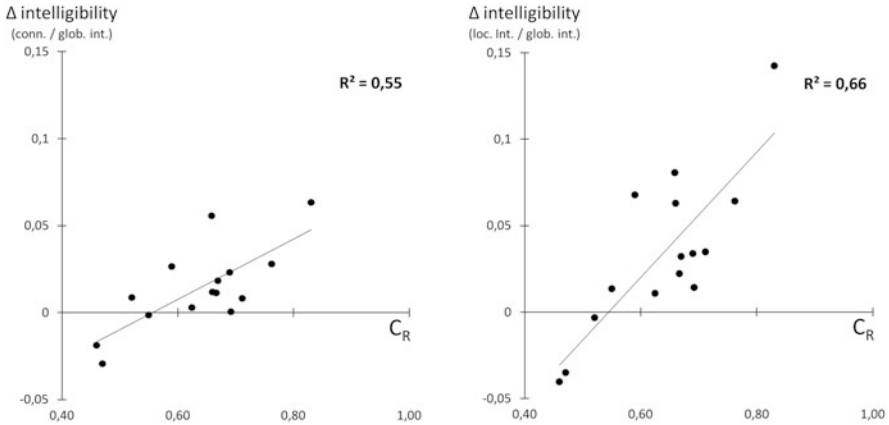
Fig. 14 Correlation between C_R ratio and the variation of intelligibility values

thing is to say that something is plausible; another is to show that such thing is factual and to measure its effects. Even if not claiming any generality for our results beyond the geographical context under study, we believe that they demonstrate that it possible to explore objectively contemporary suburban morphology and to understand how it arises from individual urban development events. Those seem to be nowadays the only possible targets for steering urban form. From the bottom up, in the same decentralized and uncoordinated way the contemporary city is produced, but with increasing knowledge on the aggregated consequences of individual morphological options.

4 Conclusions

Contemporary suburban areas present an analytic challenge to urban morphology. When approached at the level of their superficial characteristics they may seem a perversion of 'good city form', hopelessly disjointed and nonsensical. However, such morphological intractability seems to be avoidable by more quantitative approaches, capable of probing the deep structural characteristics of suburban street systems. The methodology adopted in this study was able to produce a different morphological picture of suburban development, not based on its odd superficial looks but rather on its underlying spatio-structural organization.

We provided evidence of different development patterns of suburban street systems, with also different structural outcomes. The study areas where urban growth was predominantly dispersed and led by non-connective typomorphologies, evolved into structurally flawed street networks characterized by low intelligibility values. In contrast, the study areas where urban growth was predominantly concentrated and composed by connective typomorphologies, evolved into better

structured and intelligible street networks. Syntactic intelligibility is an indicator of the overall structural cohesion of a street network, something that accumulated evidence points as a relevant characteristic of well-functioning urban areas. It seems thus possible to say that our results provide also clues on how suburban street systems could be steered at the very local level, by creating morphological guidance and prescriptions that would lead to desired global structural outcomes.

Both growth concentration and street pattern prescriptions are parameters liable of being introduced in urban policies or planning instruments. The former aspect is already currently pursued in many situations. The latter not so much, because morphological prescriptions tend to focus more on the ephemeral elements of urban form (as buildings' architectural aspects) than on its more structuring and perennial elements (as street systems). However, the latter ought to be the main objects of morphological concern, because once laid out they will endure for long time lengths and will condition future urban form and functioning. Moreover, the establishment of basic morphological prescriptions for the street layouts of incremental urban development operations, seems quite feasible. Such prescriptions could be defined at the most basic morphological level, that of the internal and external connectivities of street layouts. This type of basic formulation would avoid the implementation difficulties that highly detailed or specific morphological prescriptions obviously entail. To promote a predominantly connective grid construction, shunning the tributary types, would not be difficult, both through planning instruments or through direct collaboration with agents of urban change. We would thus recommend that urban policies should add to their current concerns on urban dispersion, a further focus on street connectivity at the micro-scale.

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