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ANATOMY OF AN EMERGING METROPOLITAN TERRITORY

Towards an Integrated Analytical Framework for Metropolitan Morphology

MIGUEL LUIS LAGE ALVIM SERRA

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Supervisor: Paulo Manuel Neto da Costa Pinho, Professor PhD

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DEPARTAMENTO DE ENGENHARIA CIVIL

Tel. +351-22-508 1901

Fax +351-22-508 1446

✉ prodec@fe.up.pt

Editado por

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Rua Dr. Roberto Frias

4200-465 PORTO

Portugal

Tel. +351-22-508 1400

Fax +351-22-508 1440

✉ feup@fe.up.pt

http://www.fe.up.pt

To Ana, Inês and Clara

Thinking is skilled work. It is not true that we are naturally endowed with the ability to think clearly and logically – without learning how, or without practicing

A. E. Mander

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ABSTRACT

This work addresses contemporary metropolitan regions as morphological problems. It identifies in the methodological and analytical fragmentation of urban morphology as a discipline, one of the main causes for the current paucity of knowledge on metropolitan form. Drawing on this conjecture, the work proposes a set of analytical methods, integrated within a coherent framework for metropolitan morphological analysis. It approaches metropolitan form at the macro-scale, through the conjoint use of space syntax and data mining techniques; and at the micro-scale, proposing a method based on quantitative morphological descriptions and unsupervised classification techniques. It makes wide use of GIS technologies, for integrating these methods into a common platform for data gathering, analysis and visualization. Using Oporto's metropolitan region as study area, the work studies its morphological evolution along the last sixty years, in order to demonstrate how the proposed analytical framework is capable of probing, describing and systematizing the complex spatial structure of contemporary metropolitan form.

KEYWORDS: metropolitan, morphology, macro-analysis, micro-analysis, diachronic.

RESUMÉE

Ce travail traite les régions métropolitaines contemporaines comme des problèmes morphologiques. Il identifie dans la fragmentation méthodologique et analytique de la morphologie urbaine en tant que discipline, l'une des principales causes de l'insuffisance des connaissances actuelles sur la forme métropolitaine. S'appuyant sur cette hypothèse, le travail propose un ensemble de méthodes analytiques, intégré dans un cadre cohérent pour l'analyse morphologique métropolitaine. Il approche la forme urbaine à la macro-échelle, grâce à l'utilisation conjointe de la syntaxe de l'espace et des techniques d'exploration de données ; et à la micro-échelle, en proposant une méthode basée sur des descriptions morphologiques quantitatifs et des techniques de classification non supervisée. Il fait une large utilisation des technologies SIG pour l'intégration de ces méthodes dans une plate-forme commune pour la collecte de données, d'analyse et de visualisation. En utilisant la région métropolitaine de Porto comme zone d'étude, le travail étudie son évolution morphologique sur les des dernières soixante années, afin de démontrer comment le cadre d'analyse proposée est capable de sonder, décrire et systématiser la structure spatiale complexe de la forme urbaine contemporaine.

MOTS-CLÉS: metropolitaine, morphologie, macro-analyse, micro-analyse, diachronique.

RESUMO

Este estudo aborda as regiões metropolitanas contemporâneas como um problema morfologico. Identifica na fragmentação metodologica e analítica da morfologia urbana como disciplina, uma das pricipais causas da actual escassez de conhecimento sobre a forma metropolitana. Apoiando-se nesta conjectura, o trabalho propõe um conjunto de métodos analíticos, integrados num quadro coerente para a análise morfologica metropolitana. Aborda a forma metropolitana à escala macro, através da utilização conjunta da sintaxe espacial e de técnicas de mineração de dados; e à escala micro, propondo um método baseado em descrições morfológicas quantitativas e em técnicas de classificação não supervisionadas. Faz um uso alargado de técnologias SIG, para integrar estes métodos numa plataforma comum para a recolha de dados, análise e visualização. Usando a região metropolitana do Porto como área de estudo, o trabalho analisa a sua evolução morfológica ao longo dos últimos sessenta anos, de forma a demonstrar como o quadro analítico proposto é capaz de sondar, descrever e sistematizar a estrutar espacial complexa da forma metroplitana contemporânea.

PALAVRAS-CHAVE: metropolitana, morfologia, macro-análise, micro-análise, diacrónico.

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INTRODUCTION

1.1. THE RISE OF THE METROPOLITAN URBAN SCALE

More than a century ago, in a book entitled "Anticipations of the Reaction of Mechanical and Scientific Progress upon Human Life and Thought", the great British author H. G. Wells foresaw, with astonishing prescience, the dramatic changes that cities would undergo in the future. He dedicated the second chapter of his book - "The Probable Diffusion of Great Cities" - entirely to that matter; weaving, paragraph after paragraph, arguments that today seem almost prophetical.

Not only did he predicted that the most important world cities would growth to unprecedented dimensions (both in population as in extent), but also that they would become more and more diffused and rarefied, as the result of ubiquitous fast transportation infrastructures and of the consequent weakening of traditional urban centripetal forces. In his own words, "indeed it is not too much to say that the London citizen of the year 2000 may have a choice of nearly all England and Wales south of Nottingham and east of Exeter as his suburb, and that the vast stretch of country from Washington to Albany will be all of it 'available' to the active citizen of New York and Philadelphia before that date." (Wells 1902); p. 46.

For Wells, these "cities of tomorrow", were "destined to such a process of dissection and diffusion as to amount almost to obliteration, so far, at least, as the blot on the map goes. […] These coming cities will not be, in the old sense, cities at all; *they will present a new and entirely different phase of human distribution*. […] The city will diffuse itself until has taken up considerable areas and many of the characteristics of what is now country, [leading] us to suppose that the country will take to itself many of the qualities of the city. The old antithesis will indeed cease, the boundary lines will altogether disappear; it will become, indeed, merely a question of more or less populous" Op. cit.; pp. 39-40, 63-64; our emphasis.

Wells coined a term for his inspired urban vision[1]. Such a term is common today, but in the first years of the twentieth century it surely must have seemed an improbable conflation of words, indeed of antithetical concepts. Towards the end of his text, he declares that "enough has been said to demonstrate that old 'town' and 'city' will be, in truth, terms as obsolete as 'mail coach'. For these

[1] The term and the concept of "urban region" is sometimes erroneously attributed to Patrick Geddes (1915), who dwelt on the issue in his famous essay "Cities in Evolution: an introduction to the town planning movement and to the study of civics". However, on the same essay, Geddes used for the first time a shorter form of the same term, today also very common: "city-region".

new areas that will grow out of them we want a term […]. We may for our present purposes call these coming town provinces ‘*urban regions*’.” (Wells 1902); p. 61, our emphasis.

These urban regions are today a world-wide reality. In all continents and on all geographic contexts, the most important cities of almost every nation, coalesced with their hinterlands and surrounding towns into *metropolitan*[2] *regions*: continuously urbanized whole sections of countries (sometimes of several countries), encompassing many previously existing and newly created urban areas, functionally and economically united into single entities, which have become the nodes of a globalized and interdependent *world network of cities* (Hall and Pain 2006; Castells 2000, 2010; Taylor 2007, 2010). Together with this global trend urban densities in metropolitan regions all around the globe seem to be inexorably decreasing over time . A 2005 World Bank report, shows that even if densities were still three times higher in developing countries than in industrialized countries, they all decreased at an average annual rate of 1.7% in the decade previous to the report’s publication (Angel et al. 2005).

This process seems to have begun in the U.S., where fast suburbanization and functional redistribution processes were already in action at the beginning of the twentieth century: in 1900 a third of all manufacturing jobs were located outside the central cities; by 1950 this figure was already close to 50% (Bruegmann 2005). In Australia, metropolization of the largest cities began also early; by the 1950s Sydney, Melbourne and Canberra were already the subjects of metropolitan planning tentatives (Bunker 1971). In all western European countries, since World War Two, cities have also undergone decentralization processes. First in Britain and the Benelux countries in the 1950s, next in Germany and Scandinavia in the 1960s and then finally in the countries formerly thought immune to such processes - France, Italy, Spain and Portugal - in the 1970s and 1980s (Hall 1996). But during the last decades of the twentieth century, closely following the inexorable globalization of economy, metropolization has truly become a global process, equally present in developed and developing countries of all continents; today reaching unprecedented scales in Asia, where the urban region of the Pearl River Delta boasts a population of approximately 50 million people (Castells 2010).

Indeed, just as Wells anticipated, contemporary metropolitan regions are not only much larger but also very different from cities ‘in the old sense’. Manuel Castells, one of the most influent theorists of contemporary network society, has recurrently stressed that metropolitan areas are indeed an entirely new type of urban manifestation (Castells 1989, 2010). According to Castells “the metropolitan region is not just a spatial form of unprecedented size in terms of concentration of population and activities. It is a new form because it includes in the same spatial unit urbanised areas and agricultural land, open space and highly dense residential areas: there are multiple cities in a discontinuous country side. […] The metropolitan region is constituted by a multicentred structure, a decentralization of activities, residence and services with mixed land uses, and an undefined boundary of functionality that extends the territory of this nameless city to wherever its networks go. In this early 21st century the metropolitan regions are a universal urban form. ” (Castells 2010); p. 2739.

Also Peter Hall (2006), who has extensively studied and theorized the metropolitanisation of western Europe, claims that the metropolitan region (or *poly-centric metropolis*, as the author call it) is indeed “a new form, including anything between ten and fifteen cities and towns, physically separated but functionally networked, clustered around one or more larger cities, […] drawing enormous economical strength from a new functional division of labour. These places exist, both as separate entities […] and

[2] Etymologically, the term *metropolis* (whence the adjective *metropolitan* derives) is a Greek word, originating from the agglutination of the words “méter” and “polis”, meaning respectively “mother” and “city”. In antiquity, that was the name that inhabitants of Greek colonies would give to their city of origin in mainland Greece: their mother-city, or ‘metropolis’.

as a functional region that is connected by networks of transport and communication processing flows of people, goods, services and information." Op. cit.; p.3.

What drives the development of these new extensive urban bodies, is still not absolutely clear. But it seems that at least two basic, intertwined processes are present at their genesis: on one hand an extended decentralization (of population, functions and employment) from large cities to their adjacent areas and, on the other hand, the interconnection of pre-existing surrounding towns whose territories have become integrated by new (physical and non-physical) infrastructural communication capabilities. The transport and the digital communication infrastructures are the nervous system of the contemporary metropolitan region (Castells 2010).

Thus, metropolitan development is, at least in part, fostered by technological and infrastructural innovation. Namely, by a new and highly augmented mobility induced by individual motorized transportation and by high-speed road and rail infrastructures, leading to wider and stronger territorial interconnections and to new functional logics and location opportunities; and also by powerful and efficient digital communication infrastructures, further enabling the spatial redistribution of specific functional sectors of economical activities (e.g. managing, producing, storage, selling) and therefore also of employment.

But metropolitan regions are also fostered by social and economical transformations. Worldwide, a profound and seemingly irreversible economical shift has occurred, from a predominantly production and manufacturing economy (characteristic of pre-war societies), towards a predominantly tertiary mode of economical development, based on the trading and sharing of information and knowledge: the *advanced services economy* (Hall 2001). Hall and Pain (2006) identify four key groups of advanced services: finance and business services; power and influence (related to the previous, but also existing as individualized services, e.g. lobbying and law services); creative and cultural industries; and tourism. Primarily processing information and tending to by highly synergistic and symbiotic, these advanced services have become the new dynamos of growth, wealth and power in the contemporary society of knowledge and information.

The fundamental difference between advanced services and traditional tertiary activities, is that they are *globally oriented and organized*, representing a novel and more complex division of labour, whose *raison d'être* is no longer local. They do not cater only for their immediate surroundings, they cater for the entire world. However, they *locate in geographical space*, namely in places that are well connected in terms of transport and telecommunication and possess a strong basis in terms of knowledge generation and professional labour. The key spatial features of the global networked society are its *nodes*, i.e. its points of connection between the global *space of flows* and the local *space of places* (Castells 2000).

Thus, a new globalized economy and a new networked division of labour, based on increasingly specialized and information-hungry service industries, are identified; but also their grounding and concentration in particular geographical spaces. In order to be able to process the value and information flowing along its immaterial rhizome, the globalized network economy needs nodes from where to operate. And from these nodal landing places, through the operation of advanced services, expands the economical and infrastructural foundation of the metropolitan region (Hall and Pain 2006; Castells 2010; Taylor et al 2010).

Therefore, rather than local phenomena, metropolitan regions are, in their essence, local manifestations of global processes. As Castells (2010) stresses, "for these places to become nodes of the global networks, they need to rely on a multidimensional infrastructure of connectivity: multimodal transport on air, land and sea; telecommunication networks; advanced information systems; and the whole infrastructure of ancillary services (from accounting and security to hotels and entertainment) required for the functioning of the node. Every one of these infrastructures needs to be served by highly skilled personnel, whose needs have to be catered to by service workers. These are the ingredients for the growth of the metropolitan region." Op. cit.; p.2741.

However, these are rather broad phenomenological explanations, even if substantively supported by empirical research. The abovementioned authors have produced large contributions to the understanding of the emergence of the new metropolitan urban scale; but they approach the issue from sociological, economical and geographical points of view, because their aim is to explain the *global dimension* of the process and not so much the details of its *individual local manifestations*. Moreover, they focus mainly on *external urban relational processes* (Taylor et al 2010), which may indeed be the main forces behind the ubiquitous formation of metropolitan regions around the world, but tell us little about their intrinsic, individual physical and spatial natures.

Metropolitan regions are conceptualized as the nodes of a new, networked global economy; and their physical development is believed to be fuelled by also new socio-economical global forces, fundamentally unspecific in local terms. But nodes are, after all, zero-dimensional abstract entities; and global socio-economical forces are, by definition, non-local factors. Thus, in epistemological but also in psychological terms, we are still far from having appropriated the *physical and spatial structures* of the new urban realities we inhabit. Beyond the usual baffled descriptions of dystopic and incredibly vast new urban territories, and as far as urban planning theories go, metropolitan regions remain amazingly weird and ungraspable physical objects.

If we step down from the abstract level of global city networks and land somewhere in the middle of, say, Oporto's metropolitan region - do we still have any available explanatory or descriptive model for what we see? Do we know how to describe, physically and spatially, that which we call 'metropolitan regions'? Are they - in truth - describable or cognoscible objects at those detailed levels? And, consequently, are metropolitan regions appropriable by urban planning? Do we know how to steer their evolving spatial and physical structures?

1.2. THE PROBLEM OF METROPOLITAN FORM

The answers to the questions enunciated above are, I believe, in all cases 'no'. We do not have satisfactory morphological descriptions of contemporary metropolitan form, let alone of its morphogenetic processes. And, largely because of that, we do not have substantive planning methodologies for dealing with metropolitan development. In part, because the phenomenon is recent. Furthermore, because metropolitan morphologies are so utterly different from traditional urban form. But also, and not least, because their territorial scale is so vast that it escapes the scope of traditional methods of morphological analysis.

In a recent paper by David Prosperi, Anne Vernez Moudon and François Claessens (2009), the two first authors moreover being long-time researchers of contemporary suburban morphologies, is stated that "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. p.1-2.

Yet, in a much older albeit brilliant paper, Friedman and Miller (1965) declare that in face of the new metropolitan landscape, "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 we are so bounded to the graspable and deeply interiorized image of the compact, historical city (now obviously surpassed forever), that we seem unable to conceive any other mental representation for the urban object. As Michael Batty (2005, p.18) puts it, "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." After all, cities were more or less alike for millennia; our experience of the contemporary urban vastness and fuzziness is still rather unripe. But there seems no doubt that the new extended urban reality is here to stay and that we must learn how to tackle it.

In the last few decades, baffled by the awkward guise of the contemporary metropolitan environment, urban researchers have produced a plethora of neologisms in an attempt to coin descriptive terms for it. A short list, compiled in (Vaughan, Griffiths et al 2009), includes: 'outtowns', 'technoburbs', 'superburbs', 'edgeless cities', 'zoomburbs' and 'boomburbs'. Others could be pointed out, like 'città diffusa', 'splintered city' or 'fractured metropolis', only to highlight how the profusion and the negativity of such new terms is by itself indicative of the difficulty of the problem and of the need for more research into contemporary metropolitan and suburban forms.

From a purely phenomenological point view, the best analysis of the new metropolitan landscape was, in my opinion, achieved by Thomas Sieverts (2003, first published in 1997) on his amazing essay "Cities without Cities: an interpretation of the Zwischenstadt". He recognizes in the new urbanized areas *in between* the historical nuclei within metropolitan regions a completely different and novel type of humanized landscape, neither rural nor urban, to which he called the *zwischenstadt*[3]. More than just a distinct settlement pattern, such term is actually a *phenomenological concept*, capable of embodying the state of psycho-socio-political limbo, into which metropolitan territories are still immersed today. Sieverts defines the *zwischenstadt* as "the type of built-up area that lies between the old historical city centres and the open countryside, between the place as a living place and the non-places of movement, between small local economical cycles and the dependency on the world market" (op. cit., p.xi).

In spatial terms, the *zwischenstadt* is described as a "structure composed of completely different environments, which at first sight is diffused and disorganized, […] a structure without a clear centre, but therefore with many more or less sharply functionally specialized areas, networks and nodes. […] In the *zwischenstadt* the ratio of open landscape and built-up areas has frequently been reversed; the landscape has changed from being an all-inclusive 'background' to being a contained 'figure'. Conversely, the settlement surface has increased […] and has acquired something of the character of a surrounding landscape. The *zwischenstadt* is a field of living which, depending on one's interest and perspective, can be interpreted either as city or as country. Although these diffuse forms may differ, they share the fact that the historical city-forming forces and the limits imposed by them have reached their end." (op. cit., p.3).

Sieverts' clairvoyant approach to the odd sprawling tissue of today's metropolitan regions, so difficult to conceptualize because so different from our traditional image of what a city should be, is able to pinpoint some of the drawbacks that hamper its appropriation by urban planning. He argues that "when confronted with the *zwischenstadt* as a political and design-task, all cultures find it a problem that so far appears to be insoluble and lack of any strategy, [because]: i) the *zwischenstadt* does not

[3] *Zwischenstadt* is a German word, a single concept not literally translatable into English, but that can be conveyed by the expression 'in-between-city', after the German terms [*zwischen* → between] and [*stadt* → city].

have an independent identity either in the imagination of its occupants or as a subject for politics; ii) the shaping of the *zwischenstadt* can no longer be achieved by the traditional resources of town planning, urban design and architecture - new ways must be explored, which are yet unclear; [and] iii) the fascination of the myth of the Old City clouds our view of the reality of the periphery." (op. cit., p.12).

In fact, what seems to be happening today, is the inescapable progression and consolidation of entirely new urban morphological phenomena, whose rules we are still not aware. They seem unpredictable, incomprehensibly random and disordered, or at least with an order that is not at all evident to classical analytical devices. Our incapacity to find in contemporary metropolitan form obvious and graspable structures, turns it into a very problematic issue for urban morphology (Levy 1999). As a result, urban planning and design practices, are left without reliable morphological models for action, oscillating between the appealing image of the traditional city and an intractable urban reality that is totally at odds with it. As Nicolas Falk (2006, p.225) so boldly says, "despite talk of poly-centric city regions, most planners and politicians seem stuck in a kind of pre-Galileo model of how cities work. They think of cities as revolving around their historic centres, and so long as these centres provide bread and games, […] all should be right in the world."

Morphologically, therefore, underlying the collective idea of the urban contemporary state, we could say that there are in fact not one but rather *two cities*, coexisting in precarious equilibrium, perhaps even in artificial but nonetheless exhausting rivalry (Figure 1). There is a city that we know: *the city of traditional urban form*, consisting in the historical cores of any settlement of ancient foundation and in their immediate expansions, built up roughly until the first decades of the twentieth century; and another city that is strange to us, although much vaster and actually much more relevant in economical and social terms: *the city of extensive metropolitan urbanization*, sprawling fast around the former and extending far into the surrounding environment, assuming the peculiar forms of a uncanny mixture of urban, natural and rural land-uses, where built forms and landscape interpenetrate freely and unpredictably. However, because we do not recognize this new city as something clearly 'urban', we tend to characterize it always by opposition to the old city that we know: 'the city with good form' versus 'the city without form', so to speak.

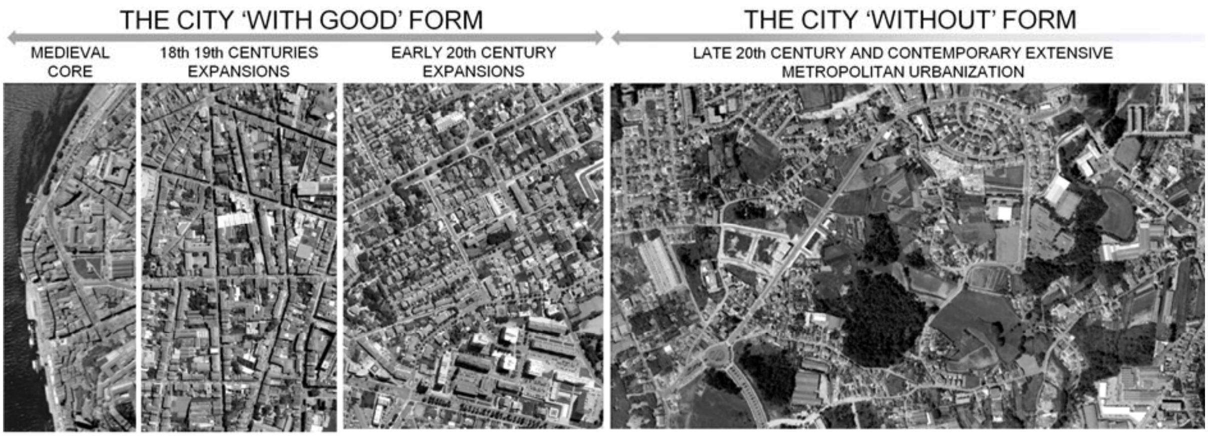


Fig. 1 – The city we know and the city we do not (excerpts from Oporto's metropolitan region).

Obviously, considerable research efforts have been made to cope with this situation: as we will see, many authors have previously identified the problem and have struggled to fill the huge epistemological gap, dividing the available urban planning procedures and the new forms of metropolitan development. Further ahead some of these studies will be reviewed, in order to systematize their findings but also to show that their very different analytical approaches are hardly compatible, and therefore difficult to incorporate into an integrated analytical framework capable of informing urban planning and design practices. However, before that I should try to make clear why urban morphological knowledge is important in the first place, and why it may constitute a way out of that current state of affairs.

1.3. URBAN MORPHOLOGY AND URBAN PLANNING

The term "morphology" was invented by the German polymath Johann Wolfgang von Goethe (1749-1832). Among his many interests, Goethe was a dedicated botanist, having written (along with many papers and essays) an entire treaty on the subject[4]. In his day, the undisputed botanical theory was Carl Linnæus (1707-1778) taxonomic system, in which plants were classified according to their external characteristics. For Goethe, although effective as classification schema, Linnæus method had a fundamental drawback: by focusing solely on external characteristics, it ignored the inner development and transformation processes of living things in general and, therefore, it failed in distinguishing *a priori* organic from inorganic natural objects (IEP 2013).

Developmental aspects were for Goethe as important as the external attributes of organisms. He termed the study of the transformations of organisms' forms throughout their development *morphology*, basing his investigations on this new concept: "when, having something before me that has grown, I inquire after its genesis and measure the process as far back as I can, I become aware of a series of stages, which, though I cannot actually see them in succession, I can present to myself in memory as a kind of ideal whole"; thus, for Goethe, morphology reveals "the laws of transformation according to which nature produces one part through another and achieves the most diversified forms through the modification of a single organ" (translated transcriptions of Goethe's works, taken from the "Internet Encyclopaedia of Philosophy", IEP 2013).

This diversion from contemporary metropolitan regions to a XIX century polymath may seem laboured, but it is important for our subject. Because Goethe's ideas were far-reaching; so far-reaching in fact, that such a trite reference as the current Wikipedia's entry[5] on "urban morphology" states that it "is the study of the form of human settlements and the process of their transformation […] by examining the patterns of its component parts and the process of its development". Not very far indeed from what Goethe had in mind when he looked at "something that has grown".

The term *morphology* has found application in disciplines as diverse as biology, medicine, geology, geography or linguistics, meaning in each case the study of the form (and of its eventual developmental processes) of the objects of the field in question. In the same way, *urban morphology* is the study of the *physical and spatial form of cities and of its processes of development*. The importance of the developmental, or processual, dimension of urban form is crucial. As Karl Kropf (2011) notes, urban form "is the result of a process. Forms are not given, but generated. More specifically, the process of [urban] formation, which is to say, the sequence of more or less deliberate acts undertaken by groups and individual people, is fundamentally a social and cultural process" op. cit., p. 394. Thus, urban morphologists study the city's physical and spatial forms and their evolution, but always bearing in mind that the meaning and cause of such forms must, ultimately, be sought within the cultural and socio-economical contexts, either in a general (i.e. universal) or local-specific perspective. As Goethe found, it makes little sense to study the form of growing things obliviously of their developmental causes.

[4] Published in 1790 and entitled "Versuch die Metamorphose der Pflanzen zu erklären", know in English as "Metamorphosis of Plants". In this work, Goethe exposed is discovery of the homologous nature of leaf organs in plants, from cotyledons (a part of the embryo present in the seed, that gives origin to leafs), to photosynthetic leaves themselves, to the petals of a flower. Homology, i.e. the same organ in different organisms for the same function, is a fundamental concept of comparative biology.

[5] en.wikipedia.org/wiki/Urban_morphology. Accessed on 22/06/2013.

As any other analytical method, urban morphology tries to break its object of analysis down to its elemental constituent parts, in order to better understand the whole and how that whole may result from the gradual aggregation of those parts. In other words, urban morphology seeks to identify the basic (and ultimately invariant) elements of urban form that, through their incremental aggregation through time, construct the urban object. These are commonly[6] acknowledged as the *street*, the *plot* and the *building*. The aggregation of these three types of morphological elements *generate patterns* (i.e. streets, plots and buildings patterns), organized under a *nested hierarchy* of spatial relations (Figure 2): "plot patterns nest within street patters and building patterns nest within plot patterns. An individual street, taken as a whole, contains plots and plots contain buildings" (Kropf 2011), p.394.

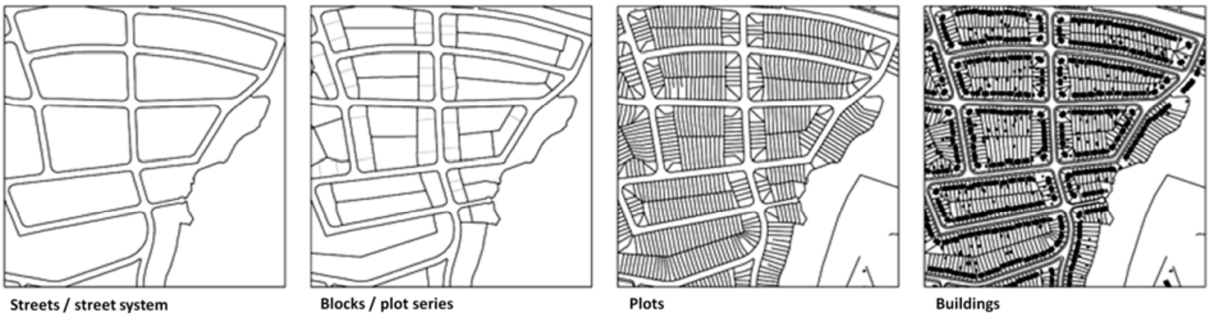


Fig. 2 – The basic elements of urban form and their hierarchically nested spatial relations. Source: (Kropf 2011).

To this simple hierarchy of spatial relations between the basic urban form components, corresponds yet another hierarchical scale, expressing the *resilience to change* (or temporal inertia) that each of those components has. The acknowledgment of that resilience scale elegantly introduces the *temporal dimension* into urban morphological analysis, because it explains several characteristics of cities and, at the same time, illuminates important aspects of their development processes (Whitehand 1992, Moudon 1997, Sheer 2001).

In fact, like living organisms, cities are essentially dynamic systems, characterized by permanent processes of change; this is noticeable to any city dweller, but also quite clear in the urban archaeological record, showing always many layers of construction, demolition and re-construction. Yet, again like living organisms, cities manage to maintain their overall *morphological structures intact*, in spite of being permanently renewed. This happens because the elements of urban form indeed change, only they do so at *different rates*: some of them quite often, others more episodically, while others hardly ever. Buildings change frequently; plots are more resilient, but aggregations or further sub-divisions are common through time; streets and street systems, however, can endure for millennia once laid-out, being utterly resilient to change.

A direct consequence of this, is that each element's propensity for change is *inversely proportional* to its structural importance, in morphological terms: the elements that change the least (namely street systems) are those responsible for holding the overall form of the city stable, in spite of the constant alterations within the building and plot systems. But besides explaining why cities are able to maintain their morphological integrity while being dynamic in nature, the different resiliencies of urban form elements have also obvious consequences to way cities evolve; because the more resilient an element is, the more it conditions subsequent transformations to itself and to the elements that change more quickly - either with positive or with negative, long-term impacts.

[6] We say 'commonly', because there are variants of these terms and also of the extent to which they are taken as elemental units. For instance, American authors commonly use the term 'lot' instead of 'plot'; the structure of land-subdivision (i.e. the plot pattern), as well as the street system, are sometimes considered as elemental as their constituent units (i.e. plot and street), and the dwelling unit (which is not necessarily a building) may be occasionally considered an elemental morphological unit. Also, land-uses are sometimes considered as elemental aspects of urban form. But, in any case, the street, the plot and the building, are consensually considered the most irreducible of all urban form elements.

Urban morphology, as a systematic field of research, has produced these important generic findings and also many others, which will be exposed throughout this work as they become relevant. Moreover, there are also several other analytical approaches to urban form; some of them quite different from the one described above, but whose use will be crucial to this work. However, my purpose now is just to make clear why urban morphology can be crucial for the urban planning and design fields and, most of all, for resolving the *metropolitan morphological problem* enunciated in the previous section.

Because urban design has for main purpose the creation of urban form, and because urban planning is in large part dedicated to the management and guidance of urban form, one would expect that both disciplines were significantly informed by urban morphology (Whitehand 2005). However, the reality is quite different. Urban morphology is a recent research field, still struggling to harmonize its different analytical approaches (Kropf 2009). Whilst urban design, at least in its most archaic manifestations, is as old as urban civilization. Moreover, as a practice, urban design is essentially a craft, highly driven by intuitive methods and not so much by systematic reflection[7]. Urban morphology, on its side, has until now been largely the preserve of academia, more prone to pure research than to translating its findings into operational knowledge. Thus, examples of cooperation and knowledge exchange between the urban morphology field and urban planning and design practices -even if not absolutely absent - have up till now always been the exceptions, not the rule (Whitehand 2005).

However, the contributions that urban morphology can offer to urban planning and design seem obvious, and are recurrently recalled (Whitehand 2005, Kropf 2011). Karl Kropf (2005), with great wit and accuracy, has made this issue particularly clear through a very precise metaphor, which describes the relation between urban morphology and the basic goals of urban planning and design. So I will simply use his inspired words to support my argument.

Comparing urban form to the 'material' that a skilled craftsman 'manipulates' (i.e. the urban planner/designer), he says that "different materials have their own 'handling characteristics'. […] Those with skill and experience understand that a material has a bias. It has strengths and weaknesses, limits and potentials depending on the way it is cut or joined and the forces or stresses applied to it, in relation to the bias of its internal structure. The primary concern of urban morphology is urban form. So, if an understanding of internal structure is essential to successful 'manipulation' of a material, urban morphology is essential to urbanism and to urban design. […] The only way to understand the handling characteristics of a material is to examine and experiment with it, test it to destruction. […] In this context, the built environment is a vast record of previous experiments." op. cit., p.17.

Then, using the example of suburban street grids with "classic culs-de-sac tree layouts due to the over reliance on T-junctions and ninety degree speed reduction bends to achieve what is laughingly called 'natural' traffic calming", he concludes: "there is no appreciation of the handling characteristics of the material being distorted. No attention is paid to the knock on effects, either on the overall structure, legilibility and visual hierarchy of the town as a whole. […] The damage is enormous and, for all intents and purposes, irreversible. More effective and, in the long run, more successful urbanism and urban design will only come from a better understanding of urban form as a material with a range of handling characteristics." op. cit., p.18.

Stephen Marshal and Olgu Çalişkan (2012), also drawing on the obvious beneficial links between urban design and urban morphology, have identified three key operational applications for the latter: "(i) as an investigative or explanatory technique, where the intention is to help find out 'what happened', and where change in form is studied better to understand urban change more generally; (ii) as a diagnostic or evaluative tool, a means of studying successful or unsuccessful kinds of urban

[7] I speak here only on my behalf, based on my personal and professional experience and without reference to any literature whatsoever.

fabric; and (iii) as a means of identifying exemplars, types or elements of urban form which could be used as units of design" (Op. cit. p. 413). All these possible applications have an obvious interest for our matter. The first, because the problem enunciated in the previous section lies primarily in the lack of basic understanding of the objective morphological properties of metropolitan regions; that is, we need to understand, in morphological terms, 'what happened' during the shift from traditional to metropolitan urban forms. The second, because we also need to understand what went wrong and what went right on that process, in order to know what to keep and what to transform, or to do differently henceforth. And the third, because without learning how to look positively and without prejudice at the new morphologies occurring today within metropolitan regions, we will not be able to separate the wheat from the chaff, so as to define new urban policies capable of fostering desirable morphologies and/or discouraging undesirable ones.

We do have now some acquired knowledge on the causes behind the worldwide proliferation of metropolitan regions and we know that they have become economically crucial; indeed the very sources from where each nation may draw its share of the wealth flowing in the ethereal networks of a globalized economy. But still we do not feel comfortable or at home therein. We do not control the metropolitan territory because we do not have a full mental image of it. Metropolitan regions do not have yet a fixed psychological identity, either in the mind of its inhabitants or in the mind of those with political responsibilities over them (Sieverts 2003). And thus we long for the old city: small, compact, graspable, controllable; but today, no more than a small section of what the 'urban' has become. To overcome the longing for the *city that we know* and to boldly face *the city that we don't*, we have no other choice but to explore it. Patiently, thoroughly, with amazed but not biased eyes. And the only way to do this is through the objective and systematic reconnaissance of the new urban terrain, in order to start disclosing its apparently untameable morphology.

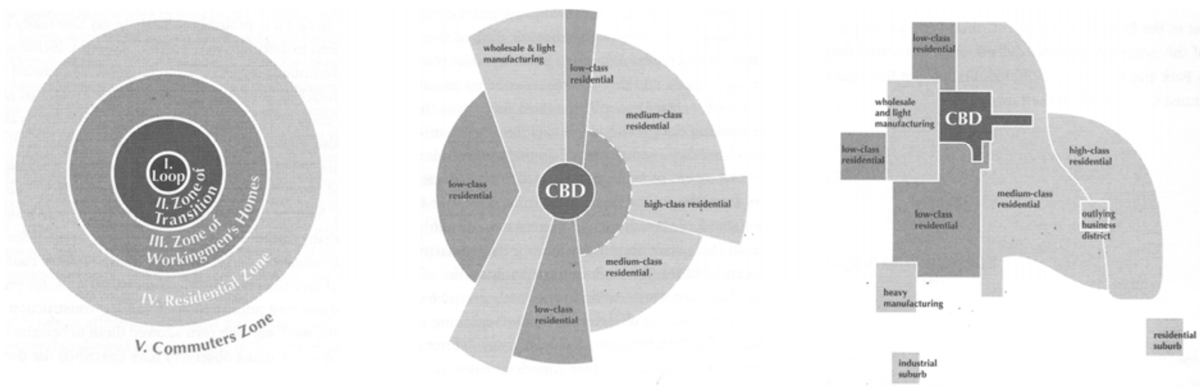
1.4. THE NEED FOR AN INTEGRATED ANALYTICAL FRAMEWORK FOR METROPOLITAN MORPHOLOGY: A LITERATURE REVIEW

This section will constitute the main exercise on literature review of this work. However, whenever pertinent, all the subsequent chapters will introduce further analytical procedures which, because of their specificity, are not discussed here. The reason for this option is due to the fact that more than simply reviewing literature, this section aims at showing that in its current disciplinary state, urban morphology is far from constituting an *integrated analytical framework*. Actually, several and quite different approaches to the study of urban form may be identified, whose research outputs are hardly comparable (Kropf 2009). This methodological fragmentation is, in my opinion, the main reason why a clearer understanding of contemporary metropolitan form was not yet achieved. In order to advance towards substantive knowledge, with sound operational outputs, on the form of the contemporary city, one needs to devise an *integrated analytical framework for metropolitan morphology*. Such is the objective of this work.

These several analytical approaches address quite different territorial scopes, using either quantitative or qualitative methods and their results are, to a large extent, simply incompatible. Furthermore, when used separately, each analytical approach is not sufficient to overcome the morphological quandary that the metropolitan city poses. Not because they are not equally worthy, neither because some of them miss the point, but mainly because they speak very different analytical 'languages'. The current panorama of metropolitan morphological research is a bit like an improbable scientific meeting, where researchers coming from all corners of the world would insist in making their presentations in their native languages: even if all of their papers would hold critical findings, which together might solve all their research problems, no one would ever figure that out[8].

Such an integrated analytical framework would not be a bundle of new techniques, neither a patchwork of those existing today. Rather, it should result from the acknowledgment of the current methodological hindrances, from an assessment of the capabilities and scopes of application of each analytical approach and, most of all, from a judicious identification of the most relevant, or structural, aspects of urban form. Cities are very complex objects and metropolitan regions are even more complex, if nothing else because they are much larger. Trying to envision some revolutionary analytical device or technique, capable of exhausting or of encompassing their overwhelming morphologic diversity, would be anecdotic. Instead, we need to be selective, searching for the *structural* aspects of metropolitan form and deliberately avoiding its *epidermal*, or superficial aspects. Metropolitan form is so variable and so vast, that any other stance would lead to quick capitulation.

Starting from the beginning, let us look at the first models of metropolitan spatial structure, conceived in the United States during the first half of the twentieth century (Figure 3). Even if not yet formally stated as ‘metropolitan’ models, the American cities that inspired them had already become enormous multinucleated regions, well before the on-set of World War II (Bruegman 2005). Those are also geographical urban models, thus only very remotely concerned with morphological issues; but, as we will see, they are quite relevant for understanding the evolution of the concept of the city as a physical object, and how such concept has been knocked down by the rise of the metropolitan urban scale.



Concentric model, Park-Burgess (1925) **Sector model, Hoyt (1942)** **Multinucleated model, Harris-Ulman (1945)**

Fig. 3 – The three first models of metropolitan spatial structure. Source: (Brueggman 2005).

The very first of these models is the Robert Park and Ernest Burgess concentric, or “ecological” model, proposed in 1925 (so called because it drew on analogies between urban social dynamics and some botanic ecological processes; Figure 3, left). Using Chicago as their prototype, these authors tried to create a conceptual diagram that could explain the general form and growth process of the city. Park and Burgess observed that residents, as they become more affluent, tend to move constantly outward in the urban area, being also constantly replaced by newer, less affluent residents; this process expanded the city outwards continuously. Even if simplistic and actually failing in capturing the social and functional complexity that American cities already showed at the time (not to mention the complexity they show today), the diagrammatic clarity of the Park-Burgess model continues to influence the way many people think of urban development (Bruegmann 2005).

It was clear from the beginning that the neat, concentric rings of the Park-Burgess model failed to account for many of the things that could be observed in Chicago or many other American cities at the time. But only twenty years later (in 1942) another model was proposed (Figure 3, middle). Homer Hoyt observed that social classes, functions and development did not expand in tidy rings around the

[8] I am imagining an uncanny scientific meeting with very few researchers with English as their native language, of course.

urban core, but rather as distinct sectors, each with its own dynamic and progression rate. His revised, “sector” model corrected some of the shortcomings of the original, but it did so at the expense of diagrammatic and graphic clarity. Moreover, it was still unable to incorporate other metropolitan characteristics, already noticeable in the years between the wars; the most crucial being the fact that urban development did not occur concentrically, but neither *unidirectionally* (i.e. from the centre to the periphery, with the most affluent residents always on the vanguard).

Shortly after that (in 1945), Chauncey Harris and Edward Ullman proposed their “multinucleated” model (Figure 3, right): an attempt to incorporate the clearly non-concentric, multidirectional and, above all, spatially non-regular, functional distributions of large American cities. But the Harris-Ullman model still assumes that each city (with all its peripheral development) is a single, discrete entity. However, by that time entire urban regions had already emerged, in the U.S. and elsewhere; the ‘industrial belt’ stretching between Cleveland and Pittsburgh (encompassing two different states) or the coal-mining region of the Ruhr Valley in Germany, are just two examples. These places were clearly single urban systems, but without a single dominant centre around which functions would gravitate. They were already much more complex than anything the models of Figure 3 could describe (Bruegmann 2005).

Even if outdated and describing only very truncated aspects of the reality, these three initial metropolitan models are quite informative; in particular when one looks at them sequentially (as shown in Figure 3), as the stages of *the temporal evolution of a concept*. Then, several things become apparent.

The first is the progressive *loss of diagrammatic clarity*: starting from a regular, geometrically pure, concentric shape - visually quite strong and immediately graspable - we notice an evolution towards an irregular, geometrically non-classifiable and hybrid shape - visually complicated and much less graspable. We could see in this the progressive *erosion of the idea of the city as a compact and unified object*: from a very clear, sharply defined and unsuspecting notion of a circle (the most compact of all geometric shapes); towards a less confident and halting notion of a geometrically elusive shape - difficult to define and no longer self-contained, but rather discontinuous and fragmented.

The second thing that becomes apparent, and which follows from the previous, is the progressive *loss of regularity of the diagrams’ external limits.* The diagram on the left could not be more regular and the limit more sharply defined; whatever the actual territorial scale that it may represent, this is still a very traditional city. However, the second diagram starts to question its limits, which are no longer regular and have their own inner differences; the centre is not challenged though, still occupying the middle of the diagram, whence everything emanates. But when we look at the last model, we see that the external limit has become highly unstable and contingent; the ‘urban centre’ (i.e. the CBD) is not even at the actual geometrical centre of the diagram and has no obvious relation with the other functional ‘sectors’; and, quite remarkably, the diagram no longer depicts an unified shape, but has fragments scattered beyond its main area - in other words, the city has no longer a single boundary, but *several disconnected boundaries*. Again, we may see in this the *progressive dilution of the dichotomic concepts of centre and periphery*. Such differentiation is intrinsic to traditional or historical urban form; cities grew from the centre and halted at the countryside (if not actually bounded by some kind of natural or artificial barrier), with a short transition zone between these two antagonistic worlds: the urban fringe, or periphery. But the progressive questioning of this very old truth (today completely obliterated) is quite apparent on the three diagrams of Figure 3.

And finally, a third aspect may also be noted: the fact that, from the first to the last diagram, a *progressive awareness* that the mono-centric concept must give place to a *poly-centric idea of the city* (not least, of course, because the last model is termed ‘multinucleated’). However, as mentioned before, the rupture is not complete, as even the Harris-Ullman model still sees the city as an individualized thing - a single entity - and not as a truly composite urban territory, made of interdependent and interconnected centres with complementary weights.

We would have to wait for the end of World War II and for the full impact of Christaller's (1933) central place theory, conceiving for the first time cities as inter-dependent entities rather than individualized objects. Then, for the systems theory to contaminate urban studies in the '60s and '70s, revealing that "cities are systems within systems of cities" (Berry 1964): nodes in networks of interdependent urban spaces, of which metropolitan regions are the most obvious examples. And, finally, for the polycentricity theories of the '90s (Faludi 2004; Healey 2004), warning us that not to fully recognize the polycentric nature of metropolitan regions and their inner networks as definitive facts, would jeopardize urban, regional and national economies at the same time. A long way has been covered, since the Harris-Ullman multinucleated model to the current systemic and polycentric views on metropolitan regions. Figure 4 illustrates this with three images taken from a very recent article (Burger et al 2013), depicting inter-cities movement flows and economic relationships within the Randstadt urban-region, in the Netherlands.

Fig. 4 – Flows between cities of the Randstadt urban-region, the Netherlands. Source: (Burger et al 2013).

But what about *metropolitan morphology*? We went back to the '20s and '40s, only to say that the metropolitan models of the time were wrong; and we have returned to the present day, only to find again the same abstract networks of metropolitan flows, from which we had separated at the end of Section 1.1. However, two main reasons justify such detour, making it important for my argument.

Firstly, because it has made clear the extent to which the image of the historical city has continuously clouded our view and hindered our understanding of the new extended urban reality: metropolitan development was already unquestionable at the time the models of Figure 3 were devised, but all of them seem to insist on the idea of the city as single entity (even if also showing a progressive but reluctant abandonment of that concept). The psychological inertia of the historical city's image is so great, that it took us almost a century to start understanding the workings of the new extended city. Still, the historical city remains as *morphological ideal* in the minds of urban dwellers, designers and planners alike, even though its operability as a model outside historical urban areas is very reduced, or even null. We need to imagine new morphological ideals, if we are to find our way in the contemporary urban environment (Sieverts 2003).

And secondly, because that detour also showed the *temporal evolution of the concept of the city as physical object*: from the deep-rooted but obsolete historic city's image, to the still unripe but factual metropolitan vision. On that process, the progressive abandonment of the dichotomic notion of centre *versus* periphery and an increasing awareness of the polycentric and networked nature of the metropolis, were crucial. Indeed, the refusal of the hierarchical relation between city and suburb (i.e. between centre and periphery), together with the recognition of the very diverse and multiple centrality structures of urban-regions, are today the most consensual aspects, in what regards metropolitan spatial structure (Sieverts 2003, Healey 2004, Hall and Pain 2006, Castells 2010); and thus also from where we should depart.

But having established that, we will now delve specifically some of the research that has been made in the last two decades to understand metropolitan morphology. As stated before, there is a variety of analytical approaches to urban form. Urban morphology was only recently systematized as an independent scientific field of enquire, with clearly defined objectives and research subjects (Moudon 1997, Kropf 2009). In fact, it was 'invented' several times by several authors, working on different countries and using different approaches, not obviously aware of each other's works, even if all dwelling on the same subject.

One of these founding authors comes from the Geography field - M.R.G. Conzen (1907-2000) - other from the Architecture field - Saverio Muratori (1910-1973). The works of these two authors and of their followers have constructed what we may now call the *classical approach to urban form*. Analysis (specially in the Conzenian case) uses deductive methods based mainly on *map regression* (or comparative diachronic analysis): a sequence of available historic maps and plans of given settlement is collected, reproduced at the same scale and compared visually. The method facilitates identifying both the growth and the internal transformations of the settlement, such as the modification of the street and plot systems, or the replacement and demolition of buildings (Kropf 2011).

Even if rigorous and systematic, classical methods of urban morphological analysis are mainly descriptive and deductive, and their results are seldom quantitative. However, they have produced some of the most important findings of urban morphology, already touched upon in section 1.3. And their final objective, as in all the other approaches to urban form, is the eventual identification of generalisable morphological processes and regularities, underlying the physical and spatial development of urban settlements.

In the meantime other approaches to urban form have appeared, again without clear connections to the work of Conzen or Muratori. Some were influenced by the work and by the mathematical *ethos* of Lionel March (b. 1934), a visionary British mathematician and architect, who produced in the '60s the first mathematical and computer-aided investigations in architecture and urbanism. While others result from proficuous cross-pollinations between complexity science and urban studies since the early '70s (Batty 1971, 1991; Couclelis 1985). Unlike those mentioned previously, these more recent analytical approaches have a strong mathematical component and make wide use of computers, either for calculations or for the development of numeric models of urban morphogenesis.

Of these, we may identify three main trends: one, founded on discrete geometry and graph theory, which has found in the recent epistemological paradigm of networks (Barábasi 2003) a powerful and innovative way to analyze urban form; another, founded on the concept of self-similarity (Mandelbrot 1975), which uses fractal geometries to describe urban form at large scales; and still another, founded on the concepts of self-organization and emergence (Bak et al 1987), using numerical modelling techniques borrowed from complexity science to simulate the dynamics of urban growth and change. We could perhaps identify yet another quantitative approach, in the use of geographic information systems (GIS) and their spatio-analytical capabilities in urban morphology. However, the use of GIS is also transversal to the three previous analytical trends. In fact, the utility of GIS in any field addressing spatial and geographical issues so obvious, that to classify its use in urban morphology as an independent analytical approach is somewhat trivial.

Karl Kropf (2009) has made an effort to organize the rather untidy landscape of the urban morphology field, producing a quite successful classification of its several research trends. He divides all the above mentioned analytical approaches into four classes, namely:

- *the historico-geographical approach* - encompassing the Conzenian tradition of town-plan analysis (Conzen 1969), continued by Jeremy Whitehand (1974, 1992, 2001) and others, within the Urban Morphology Research Group (UMRG), based at the University of Birmingham . This approach was already quickly characterized on the previous page.
- *the process typological approach* - represented by the work of Muratori and Gianfranco Caniggia (2001), his former student and collaborator who further developed his ideas. Urbanization is seen as process, and urban form and structure as the product of the operation of that process over time. The process works from the bottom-up, according to a hierarchy of scales: starting with the individual building, then groups of buildings (or urban tissues), then the city and finally the territory. The forms found at each scale are identified with *types* and seen as their variable, concrete manifestations. The *type* is an archetypal morphological unit, which embodies both form, function and cultural values, and which change through time as society and culture also change. The way the types at each scale aggregate to form higher-scale objects is called the *typological process,* giving rise to urban form and structure through time. Such process may only be understood historically, through the chronological analysis and deductive deconstruction of its built outcomes (Moudon 1994).
- *the spatial analytical approach* - includes all the works stemming from complexity science, revolving around the ideas of *emergence* and *self-organization*. The main hypothesis is that the morphological complexity that we see at the scale of the city, may be just the dynamic by-product of very simple processes acting at the local scale, but whose dynamic interactions through time give rise to the emergent structures that we find at upper-scales. In other words, that we may be able to reproduce the global form of the city from the bottom-up, in the same way that cities actually grow and change; and that, ultimately, cities may only be understood that way. The tools used for these ends are two types of numeric models, known as cellular automata (CA) and agent-based models (AMB), which will be discussed later. Examples of this approach may be found in the work of Mike Batty (2007) and of his colleagues at the Centre for Advanced Spatial Analysis (CASA), based at University College London. Kropf (2009) includes in this approach also the pioneering work of Batty with fractal geometries (Batty and Longley 1994, Batty 2007) and the wide use of GIS technologies at CASA; but these are not dynamic morphological models based on emergence and self-organization, as those mentioned before.
- *the configurational approach* - includes all urban morphological research based on the paradigm of *networks*, or graphs. Since the '60s, networks have become paramount for describing and analyzing the phenomenologies of many scientific fields (e.g. sociology, ecology or computer science). Several authors have used graphs for representing urban form (Krugger 1979, Marshal 2005), but the most successful example of this approach (which has become an independent field on its own) is known as *space syntax* (Hillier and Hanson 1984, Hillier 1996). Space syntax is set of analytical techniques based on graphs, for representing and studying architectonic or urban spaces, that has evolved significatively since its beginnings. But beyond space syntax's analytical dimension, the writings of Bill Hillier[9] (1987, 1989, 1996, 2002, 2007) may also be said to constitute a quite comprehensive *morphological theory of the city*, which has been able to link city-form and city-function in a way that was never achieved by any of the other approaches. The epistemological breakthrough of the syntactic approach, was to understand that the most critical object of the city, in what regards its functioning, is *not material* (in the sense of built mass) but *spatial*: it is the system of open space, including all streets, squares, or any other public spaces; and that that spatial object may be easily represented and analyzed quantitatively as a *network*.

[9] Bill Hillier is the founder of space syntax and its most prominent theorist.

Moreover, space syntax has developed several ways of representing urban spatial systems (e.g. axial and convex representations) which encode the *morphology* of those systems in the topology, or *configuration*, of the resulting spatial networks. Thus, unlike all the other approaches, space syntax focus only on urban spatial systems and ignores built-forms, even if these are indirectly taken into account as the objects bounding urban space, and therefore endowing it with form. Using these basic notions, space syntax was able to show that the flows of people and vehicles running through urban space, plus their locally variable rates, are strongly modulated and determined by the configuration of the urban spatial network. Drawing on this relation between spatial configuration and urban movement, space syntax was also able to show that a large extent of the city's functional formatting, and therefore of its functioning, is caused by the morphology of the city's spatial network. This type of *cause-effect relationship* between urban form and urban function, is almost exclusive of the space syntax's approach. This has granted it a huge success and an immediate operability on actual urban design and planning situations, placing it on a different level of the other approaches to the analysis of urban form.

All these analytical methodologies have produced contributions to the study of metropolitan form. We will start by looking at those coming from the first two classes, the *historical-geographic* and the *process typological* approaches, for these are (as mentioned before) liable of being aggregated more broadly as *classical approaches*, today united under the umbrella of the Internal Seminar on Urban Form (ISUF)[10] and of the journal "Urban Morphology", published by that organism. Next, we will proceed to the *spatial analytical* and *configurational* approaches. However, my aim in reviewing the following works is not of being exhaustive; surely many more studies could be cited, even if those described here were found to be the most relevant. The objective is just to illustrate the advantages and shortcomings of each approach, in order to show why and how they are currently disarticulated. Such review will provide the background for the formal statement of a set of necessary premises to achieve an 'integrated analytical framework for metropolitan morphology', which will be made in the last section of this Chapter (1.5).

1.4.1. CLASSICAL URBAN MORPHOLOGY AND METROPOLITAN FORM

Even if the historical city has always been the main object of interest of the classical approaches to urban form, some authors have dwelled on the form of the contemporary city and tried to apply the their analytical techniques on that context. Albert Levy (1999) has opened this debate, with his path breaking paper "Urban morphology and the problem of the modern urban fabric: some questions for research". Besides being a call to arms for urban morphologists to start looking at the contemporary city, the paper provides initial considerations about the intrinsic differences between historical and contemporary urban forms. The author notes that the basic elements (street, plot, building) remain the same and hold the same relevance for studying contemporary urban morphologies; what has profoundly changed are the spatial relations that those elements establish between themselves.

In the historic city, streets, plots and buildings form a system whose structure is coherent and easy to systematize. Topologically, each element is strongly related to the others. Lots aggregate in blocks, forming discrete 'islands' of private built space. These islands (and the lots composing them) are made accessible to each other through the continuous system of open space, where the streets (or other public spaces, as squares and gardens) are spatial units clearly defined by built forms. Buildings are densely packed, usually filling completely the side of the plot in contact with the street. A strong

[10] See www.urbanform.org for more information on the International Seminar on Urban Form.

correspondence between building, plot and street is thus produced, endowing the overall system with great continuity and legibility.

However, outside historical centres, contemporary metropolitan development is characterized by profound alterations to that kind of morphological structuring. First, the overall texture of the urban fabric has become much more loose and fragmented, through the mutual interpenetration of rural and urban landscapes and by the disappearance of a more or less continuous border between the two. Second, the previous relationship between buildings, lots and streets is much weaker or even null. The street system is now composed of regional roads whose borders have become progressively urbanized, narrow and labyrinthine rural paths, patches of denser urban grids, all without a clear structural hierarchy. New heavy-duty transportation infrastructures (highways and motorways) following regional transportation logics, criss-cross this incipient local street network, changing drastically its accessibility patterns. The structure of land tenure, with a strong rural matrix and great variety of lot sizes, no longer has the organizing role that the traditional urban lot had over the built form system. Accordingly, built forms are now free from the usual inhibitions of lot boundaries and no longer relate clearly to the street, many times not even to each other, sharing only the same access road. Summing to all these transformations, the scale of urban expansions (thus, also their impact) and the speed of landscape transformation have greatly increased (Levy 1999).

But even before Levy's paper, at the U.S. the analysis of local morphologies of metropolitan regions had already begun. Michael Southworth and Peter Owens (1993) studied the morphological evolution of several local areas of San Francisco's metropolitan region, from 1900 to 1990. The work of these authors is particularly interesting because of the attention they devote to the morphological structure of the street system, which is not usual among classical morphological studies. Analysis is carried out at several spatial scales (community[11], neighbourhood[12] and individual street levels), which is something also seldom done. At the community level, the authors identify four types of street patterns, characterized by their connectivity degree and geometric shape (Figure 5).

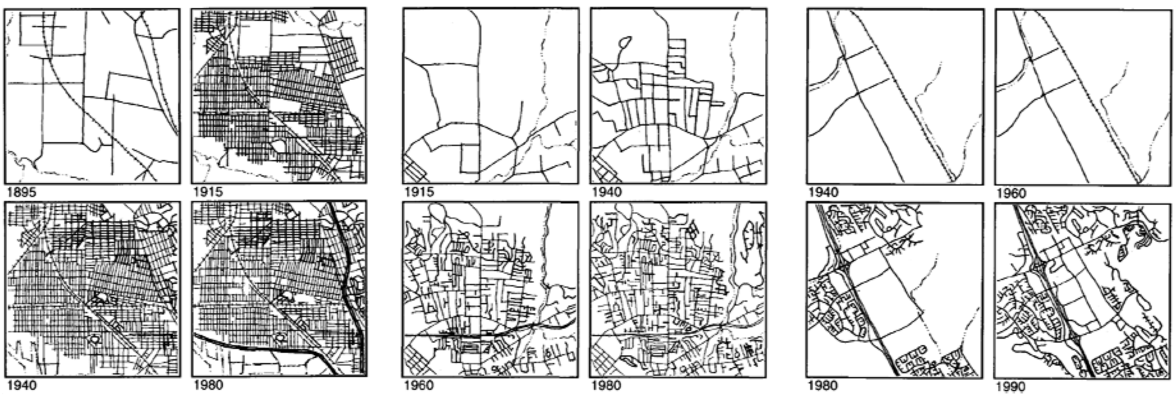


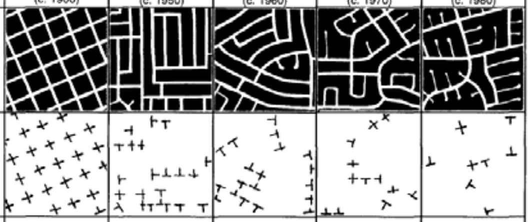
Fig. 5 – Three of the several types of street patterns identified by Southworth & Owens and their development through time: 'speculative gridiron' (left), 'incremental infill' (middle) and 'loops & lollipops' (right). Source: (Southworth and Owens 1993).

These range from the 'speculative gridiron' (characteristic of early developments) to the 'loops and lollipops' type (the typical 'cul-de-sac' pattern of bedroom communities from the 60's and 70's). The former type seems to produce a rather fine-grained, well-connected and diverse urban fabric; the latter results in twisted, non-directional and inwardly focused street lay-outs. At the neighbourhood level, the authors go further into the analysis of the topological composition of street pattern types. Five types are identified, again accordingly to their connectivity and shape. These range from the pure

[11] 600 acres; 2,4 Km2

[12] 100 acres; 0,4 Km2

gridiron to the 'lollipops on a stick' type (an extreme version of the type mentioned before, but without loops, only cul-de-sacs branching off some through streets). Here, the authors actually quantify some topological and geometrical parameters of the several patterns, as the number and type[13] of intersections, total street length, number of blocks and number of loops and cul-de-sacs (Figure 6).



	Gridiron (c. 1900)	Fragmented Parallel (c. 1950)	Warped Parallel (c. 1960)	Loops and Lollipops (c. 1970)	Lollipops on a Stick (c. 1980)
Street Patterns					
Intersections					
Lineal Feet of Streets	20,800	19,000	16,500	15,300	15,600
# of Blocks	28	19	14	12	8
# of Intersections	26	22	14	12	8
# of Access Points	19	10	7	6	4
# of Loops & Cul-de- Sacs	0	1	2	8	24

Fig. 6 – Comparative analysis of neighbourhood street patterns. Source: (Southworth and Owens 1993).

The authors draw several interesting conclusions from their findings. First, looking at the parameters' values for each morphological type, they show how the gridiron offers the shortest trip lengths and the largest number of route choices (highest total street length and number of intersections), even if it maximizes infrastructure cost. It is, therefore, also the most walkable pattern, which is also the reason for this to be the pattern of the oldest case studies, when pedestrian travel was high. At the other end of the morphological spectrum, the 'loops and lollipops' and the 'lollipops on a stick' types, are the more recent. They are characterized by non-directional patterns, where interconnection is limited to several through streets not readily apparent on the plan, creating a disorienting maze-like pattern. In the extreme type, inter-accessibility and route choices are very limited, as the pattern is almost only composed by cul-de-sacs. As the authors note, "the residents of this limited-access maze [...] are hard put to find a block around which to walk the dog." (op. cit., p.281). However, this pattern also minimizes infrastructure cost (minimum value for total street length) while maximizing the number of lots, which is economically advantageous for developers. The authors conclude by claiming that street patterns, as the basic skeletal structure of communities, affect environmental interaction, by determining where residents can go and interact along the way. "The clarity, orientation and topographic sensitivity of street patterns significantly shape a community's self-image and sense of space. [...] Urban designers need to build a visible public structure, a visible public spatial framework that in time can nurture civic life". (op. cit., p.286).

Brenda Case Scheer (2001) studied the morphological evolution of Hudson (an area of Cleveland's metropolitan region, Ohio) from 1800 to 1995, using a more traditional approach. However, she proposes an innovative model of urban form evolution, based on five layers of morphological components, organized in terms of their resilience to transformation (Figure 7, next page). These layers are the 'site' (landform and natural features), the 'superstructure' (paths and land boundaries prior to urban development or others with structural impact on the settlement), 'the infill' (fine-grained paths and plots nestled within the superstructure), 'buildings' and 'objects' (surfaces, signs, etc). Looking at change along time on the several layers, the author concludes that urban form on that specific metropolitan context has been directly conditioned by the size and shape of the pre-urban superstructure (rural roads and the division of land into farms and fields) and its subsequent developments. This is "checkerboard on which the real estate game is to be played. Once development begins, the road structure is more or less fixed, whether it is adequate or not. Intervention at the

[13] 'X' or 'T' intersections, i.e. with four or three incident streets.

earliest stages of development [...] could most productively take the form of rethinking rural networks for suburban growth." (op. cit., p.36).

Regarding the 'infill' layer, three generic types of non-traditional morphological patterns are identified: the 'static', the 'elastic' and the 'campus' tissues (Figure 7). 'Static' tissues are mainly residential, composed of allotments of different types and sizes which are consistent with the typologies identified by Southworth and Owens (1993). These tissues are the less prone to subsequent structural change, as they are composed by small-sized lots, with a much dived form of ownership, highly resistant to wholesale lot aggregations. 'Campus' tissues are composed of large tracts of land that are developed with several buildings but not subdivided into distinct properties (e.g. large institutional functions, like universities, medical centres, industrial complexes, etc). The 'Elastic' tissue is the least stable of the three types of infill. It appears usually aggregated to pre-urban paths. "This tissue is not pre-planned; it evolves over time and has a rapid change rate compared to static tissues. Lots tend to be highly varied in size, though they are generally larger than lots in static tissues and generally contain a single major structure. [...] Elastic tissue areas are structurally disordered at the level of lots and paths, and deeply conditioned by their relationship to the superstructure." (op. cit., p.34,36).

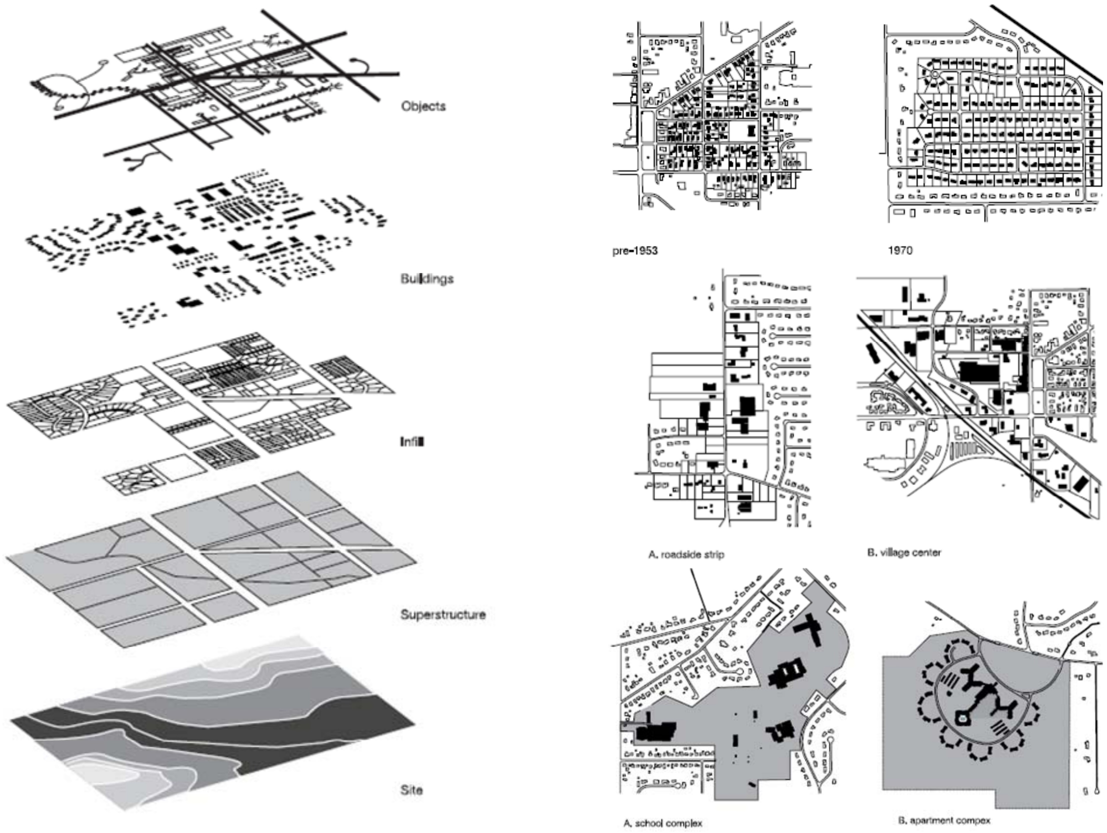


Fig. 7 – Scheer's layered model of urban form (left). The three types of urban tissues identified by Scheer (right): static tissue (top), elastic tissue (middle) and 'campus' tissue (bottom). Source: (Scheer 2001).

Brenda Case Scheer concludes with important recommendations for urban planning. "Suburban growth develops in patterns that are strongly conditioned by the pre-urban fabric, such as farm roads and fields. These patterns can generate extremely scattered and disordered suburban environments, which are difficult to plan or change because they are structurally flawed. [...] Modern regulatory processes do not address some of the most influential and long-lasting layers of the city, tending instead to intervene in transitory conditions such as specific land use and building details. Such transitory conditions should be lightly regulated to provide more leeway for growth and change, while the urban framework should be more controlled than current practice allows." (op. cit., p.37).

Still in the U.S. geographical context, Stephen Wheeler (2008) provides perhaps the most detailed and exhaustive account of “The Evolution of Built Landscapes in Metropolitan Regions” (the paper’s title), using classical techniques of morphological analysis. The author studied the development of six *entire* metropolitan regions[14], along the period comprised between 1860 and 2005 (divided in sub-periods of 20 years), with the support of GIS. The territorial comprehensiveness of this work is unparalleled within classic morphologic studies. In general, as we have seen through the previous examples, works using classical techniques of morphological analysis cover only local areas (at the neighbourhood or municipality levels) and not the integrity of metropolitan territories. But in this case the restrictions to small-scale territorial samples are completely overcome. In fact, as Figure 8 illustrates, the method is capable of covering all scales, from the level of the neighbourhood to the level of the whole metropolitan region.

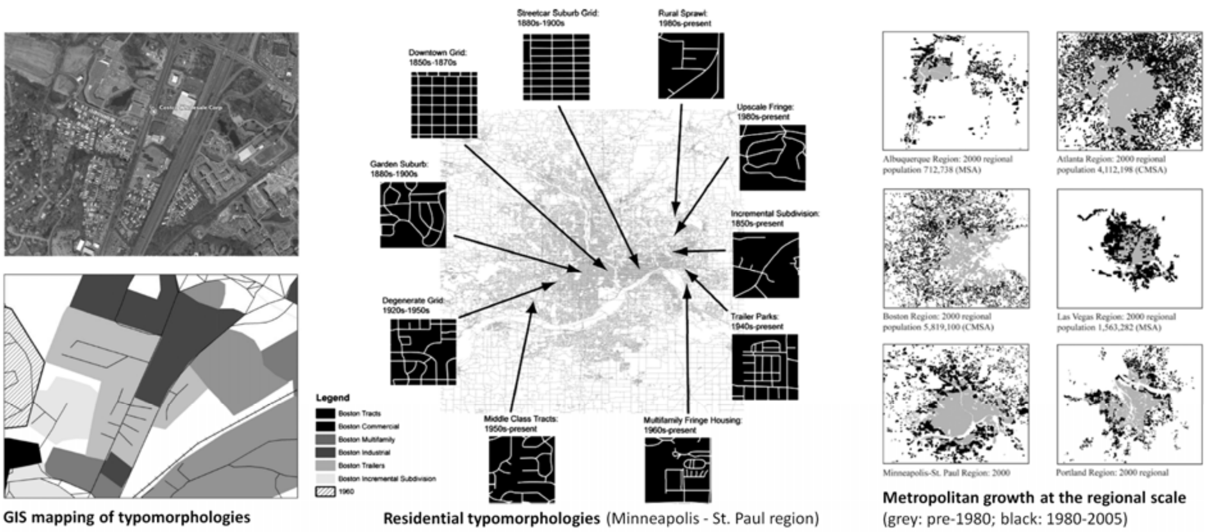


Fig. 8 – Wheeler’s GIS method for mapping metropolitan development and typomorphologies (left); several residential typomorphologies and their location on Minneapolis - St. Paul metropolitan region (middle); metropolitan growth at the regional scale in the six studied metropolitan regions (right). Source: (Wheeler 2008).

The territorial comprehensiveness of Wheeler’s work is of course made possible by GIS, whose scant use in (albeit recent) studies adopting classical analytical approaches is rather surprising. In fact, Wheeler’s objective is unpretentious and straightforward, although of the utmost importance: “I have sought to document the growth of selected metropolitan areas; […] the aim was to map the extent and types of built landscapes created.” (Wheeler 2008), p.402. Moreover, because this was done at the level of the *entire* territories of *several* metropolitan regions, his work has a degree of empirical validity which is not comparable to that of the previous works, independently of the relevance and soundness of their results. Furthermore, because analysis was done and recorded on GIS (even if based only on methods of visual identification), simple but relevant quantifications of metropolitan typomorphologies and of their frequencies through time were made possible, which is also a very significative advance (even with some epistemological caveats, mentioned below). The method used in this work is the simple visual inspection of overlayered old cartographies (the common map-regression technique) together with current aerial photographs, providing the contemporary state of each metropolitan region. However, the recording of the differences observed among the several maps and aerial photographs (i.e. of the areas identified as having been developed at each period), was done on a GIS base-map (a TIGER[15] vector file containing the road-centre lines of the current metropolitan

[14] The concerned metropolitan regions were: Boston, Atlanta, Minneapolis, Albuquerque, Las Vegas and Portland.

[15] TIGER stands for “Topologically Integrated Geographic Encoding and Referencing”, a free GIS file format used U.S. Census Bureau to describe land attributes.

street networks), by manually drawing polygons around each new neighbourhood or substantial increment of development, observed at each time period; a surprisingly simple but very efficient research methodology.

On those hand-drawn polygons two attributes were encoded: the period of construction and a given *morphological class*, or type, to which each development area supposedly belonged. And that is the point where this work, otherwise so relevant and innovative, looses objectiveness and even some scientific validity. The period of construction is a rather reliable parameter, because it is based on the dates of maps and easy to confirm through the architectonic characteristics visible on aerial photographs. However, the morphological types identified are much less reliable. Wheeler claims to have indentified seven classes, or types, of *historical urban tissues*, which are present at all sub-periods with varying frequencies; and still more seven types of *new urban tissues*, which occur *only* during the last period, from 1980 to 2005. Thus, just seven historic typomorphologies for more than a century, and then seven new typomorphologies appearing in only 25 years: not impossible, but hardly probable.

Even if the first seven types of historical tissues are supported by the findings of others (namely those of Southworth and Owens, discussed before) and are referred as widely recognized American urbanization patterns, they remain difficult to accept as *objective realities* because no truly objective proof of their substantiality is provided. However, the seven new urban types are actually *only* supported by Wheeler's observations, by the eloquence of his descriptions and by a few aerial photographs of some examples. This is a major limitation, not only of this work but of all urban typomorphological studies in general. Such limitation does not arise from insidious doubts about the good faith or intellectual honesty, of this or of any other author. But, as anyone knows, sometimes things exist only 'in the eye of the beholder'.

It is a well acquired fact that even though the human brain is very good at identifying patterns, it is also very prone to see patterns were there are none - a common psychological bias known as *apophenia*, that all of us have experienced when looking at clouds[16]. Or, in the more well-defined field of statistics, something known as *Type I error* - a false rejection of a true null hypothesis, i.e. the assertion of something that is absent or not true. And that is the reason why findings like the urban typomorphologies asserted by Wheeler may never be regarded as *scientific evidence*, because they are ill-defined, non-reproducible and impossible to falsify. This is a very important issue, to which we will return later.

But, notwithstanding these limitations (moreover general and not specific of this case) Wheeler's (2008) paper is undoubtedly one of the most relevant contributions of the classical morphological approach to the study of contemporary metropolitan morphology. If for nothing else, because it definitively shows that large comparative studies of metropolitan typomorphologies are feasible, based not on restricted territorial samples but on entire metropolitan regions.

These works stem from North American contexts and their results should not be seen as literally transposable to other geographical settings. Still, the same general morphogenetic processes - like those identified by Sheer (2001) - may been seen in action also in Europe, as the work of Jaqueline Tatom (2004) demonstrates. This author analyzed diachronically (1812-1994) two suburban municipalities from the Lyons metropolitan region (Bron and Chassieu), coming to results very akin to those mentioned before. She concludes that, even if this is not visually obvious on the sites, the *rural landscape structure* (developed prior to the successive periods of urbanization) has largely persisted, with urban transformations taking place within the continuity of rural parcels and rural roads. She also

[16] Shakespeare made our proneness for apophenia famous on *Hamlet*: act 3, scene 2. While discussing the form of a cloud with Hamlet, Polonius sees in the cloud what Hamlet suggests him: "Do you see that cloud up there that looks like a camel?", "By God, it does look like a camel", "To me it looks like a weasel", "It does have a back like a weasel's ...", "Or like a whale", "Yes, very much like a whale ...".

draws attention to the fact that parcel size and tenure play a significant role in the nature and extent of subsequent development, for they correspond to different time frames and space-making strategies. On the whole, the role of what Brenda Case Sheer (2001) has called the 'superstructure', is again highlighted as a main determinant of the emerging morphologies in metropolitan contexts. Pre-metropolitan morphological elements are highly conditioning, especially those with *structural importance* (as roads and rural land-tenure structures). And this morphological *path-dependency* is not geographically specific, but a potentially generalisable fact.

These few studies by no means exhaust the literature of classical morphological analysis applied to metropolitan development patterns. Several other relevant works could be described here (some of them being actually books and not journal papers) as, for example (Moundon and Hess 2000; Carr and Whitehand 2001; Stanilov 2002; Stanilov and Case-Sheer 2004; Gospodini 2006; Çaliskan 2009; Bosselmann 2011; Tisma et al 2012). But, as stated before, my aim is to selectively illustrate analytical methods and not to simply list the work of others which, in any case and regarding this study's specific subject, are not very numerous.

In summary, the contributions of classical urban morphology approaches to the study of metropolitan form are not only relevant as they have produced several important insights into the subject. Those are:

- The identification of urban form's basic elements (street, plot, building) and of their traditional spatial relationships; and, through that, the characterization and the listing of the general *morphological differences* between *traditional* (i.e. pre-metropolitan) and contemporary *metropolitan morphological patterns*.
- The identification of the *impacts and constrains* that pre-metropolitan morphological elements inflict on subsequent metropolitan morphology (especially in previously non-urban areas, most commonly ex-rural). Such impacts are variable and proportional to *the structural importance* of those existing elements, stemming from their *different temporal inertias* (or resilience to change). S*treets and streets systems* are the most resilient (and therefore the most structuring) of all morphological elements. Thus, existing *roads, streets or paths have the greatest impact of all*: being capable of *perpetuating flawed urban structures*, if originally inappropriate for urban ends but eventually consolidated by urban development.
- The acknowledgement that urbanization is an incremental *process*, in which the morphology of the basic components is not randomly or continuously reinvented, but rather *restricted to a finite set of types*, or *typomorphologies*; which evolve through time but may be present for long periods, because they are also socio-cultural products. Knowledge of those typomorphologies is the first step for the understanding of the 'urban materials'[17] being produced at each historical period, for understanding their qualities or flaws, and therefore to devise empirically-based urban policies, aiming at their promotions or demotion.

However, the classic morphological approaches also have several limitations, which become especially noticeable when they are used in contemporary metropolitan contexts. Such limitations should likewise be summarized and made clear.

- The identification of urban form's basic elements is robust and apparently definitive. The same may be said about the scale of their different temporal inertias, and of the logic consequences those differences have to the formation and maintenance of urban structure. However, the *identification of the morphological characteristics* of pre and post-metropolitan morphologies is the *product of little explicit visual assessments* and their enunciation is made in purely *verbal and semantic terms*. Thus, as they are, such findings are difficult to

[17] Following Karl Kropf's (2005) inspired metaphor.

reproduce, hardly generalisable and cannot claim the status of truly reliable evidence. They ought to be formally defined, either through numerical or geometrical means, or through exhaustive empirical proof.

- Visual analysis, by itself, is not a problem in any way: it is as valid as any other observation method, as long as it is rigorous, systematic and controlled, and the observation method and criteria explicitly stated. The problem lays in *the format the results are conveyed*, using only discursive and semantic resources; even if eloquently exposed, their are quite laconic regarding how they were obtained and, more importantly, regarding the how they might be *reproduced* elsewhere and/or by others (the systematic use of GIS could dramatically reduce this problem and is difficult to understand why its use is not more widespread). This lack of formality in the results implies still another problem: the difficulty of using those results in *conjugation with those of other approaches to urban form* using numerical methods (or even with the results other scientific disciplines), which could lead to unsuspected and important discoveries (e.g. regarding urban form and energy consumption).
- The *territorial and sampling scopes* are usually small and restricted to the *urban micro-scale* (i.e. to the local scales of neighbour or municipality). Also in this aspect, *the use of GIS* may be invaluable for *expanding* both the size and the territorial extent of samples, which would produce large gains in terms of finding's empirical validity. However, not the scale of analysis: the characteristic minutia of the classical approach make the *urban micro-scale its natural object of analysis*. Classical morphological approaches are efficient for the study of *local structures*, but apparently do not have analytical methods or concepts for studying the *regional-scaled structures*, which today are also part of the metropolitan city.
- Typomorphology and *the definition of urban types* (be them buildings, street layouts or urban tissues) is, as mentioned before, very important and with obvious potential operational outputs. However, the way types are defined suffers from the same abovementioned problems: one must *rely not on hard evidence, but on the author's discourse*. Unlike the validity of visual analysis, this is simply non-acceptable in scientific terms. Urban typomorphologies *must be defined either by geometrical or by numerical means*. Something not so difficult to accomplish, when one thinks of it: the mean values of a few *quantifiable and judiciously chosen morphological attributes,* describing the objects of sufficiently large samples, would probably be enough.

1.4.2. THE 'SPATIAL ANALYTICAL' APPROACH AND METROPOLITAN FORM

If the methods of classical urban morphology have in the local urban scale their natural 'analytical environment', the techniques constituting the *spatial analytic approach* occupy the opposite end of the spectrum of urban scales, studying the global form of entire metropolitan territories. And, in the same way, they have little vocation for the smaller scales, losing their meaning below a certain spatial threshold. In other words, these techniques have a *limited spatial resolution*. For example, cellular automata (one of the techniques described ahead) can achieve amazing results when simulating metropolitan development at large scales, based only on dynamic interactions between relatively small spatial units (of the order of 100x100 meters) through artificial (or iterative) 'time'; but if we zoom in the model, we will basically find 100x100 meters *pixels*; not streets, plots or buildings.

Thus, more than analytical, these are *modelling techniques*. They aim at understanding the process of urbanization by numerically modelling it; i.e. by conjecturing some very initial and local premises of that process, encoding them into an iterative algorithm, and then running it *in silico* to see what comes out. The objective is *purely theoretical*, something close to 'fundamental research' in urban morphology; but little operative from the point of view of its direct applications in urban planning and design practices (at least at the current state of the models). But because our aim is to produce an operational, ‘integrated analytical framework for metropolitan morphology’, relevant for research but also for planning support purposes, we will not use these techniques. Nevertheless, the endeavor behind them is very compelling and the seminal concepts on which they are rooted - *complexity*, *emergent order* and *self-organization* - will also be central to this work. Therefore, the ‘spatial analytic approach’ will be briefly described; but the current section will be deliberately used to expose the seminal ideas underpinning that approach, and to explain how they will be conceptually integrated in this work.

Cities are typical examples or *self-organized complexity*, as Jane Jacobs (1961) first stated in such a prescient way. At that time, few could grasp the implications of what she was actually saying. Systems’ theory was then starting to contaminate urban planning theory, but cities were seen as rather *stable and predictable systems* tending naturally towards *equilibrium*, as the visible long-lasting urban structures suggested (Batty 2007). But what Jacobs was saying was a different thing: she was claiming for a planning culture “where individuals are in touch with the problems of the city and know best how to tackle them: a planning and design that is highly decentralized, in tune with the way cities grow and change - from the bottom up.” (Batty 2007), p.2. Something that the analytical approaches described in this section seek to support, in trying to find the underlying organizational principles that could inform a novel *bottom-up planning*, that would use local actions for achieving desired global results (Marshall 2009).

She distilled her ideas from a famous Warren Weaver’s (1948) paper[18], in which he proposed that all systems could be classified as describing three kinds of phenomenologies: problems of *simplicity*, problems of *disorganized complexity* and problems of *organized complexity*. The first type corresponds to the kind of phenomena addressed by classical Newtonian physics. The second type, to the kind of phenomena addressed by statistical physics, as thermodynamics. But the last type, Weaver argued, would be at the core of future scientific discoveries: “The really important characteristic of these problems lies in the fact that [...], as contrasted with the disorganized situations with which statistics can cope, [they] show the essential feature of *organization*. [...] These new problems, and the future of the world depends on many of them, requires science to make [...] an advance that must be even greater than the nineteenth-century conquest of problems of simplicity or the twentieth-century victory over problems of disorganized complexity. Science must, over the next 50 years, learn to deal with these problems of *organized complexity*.” Op. cit. p. 539-540.

In other words, problems of the first type are *simple*, of the second type *complicated*, but those of the third type are something different: they are *complex*. Unlike the randomness characterizing the movement of atoms in a hot gas, which may be reduced to a general statistical behaviour, the dynamic interactions between the ‘particles’ of a complex system are probabilistic but not intrinsically random, they cannot be reduced to a general statistical description and, most importantly, they give rise to *ordered emergent structures* at higher-scales.

The possibility of *emergent order* is magnificently retracted in many natural systems. Indeed, life itself is an emergent phenomenon: arising from unfathomably improbable chemical interactions between inanimate organic compounds, but which have become possible - at least on Earth - throughout the billions of years in which geological eras are measured; and, perhaps, not only possible but even probable elsewhere in the universe, where the favorable conditions for its emergence may be present. Time (allowing emergence), and not the Deity, is the best explanation for the fact that we are here (Dawkins 1986).

[18] Warren Weaver (1894-1978) was an American scientist and mathematician that founded, together with Claude Shannon (1916-2001), the *mathematical theory of communication*, latter extended to the more general field of *information theory*; one of the pillars of contemporary science, with implications ranging from computer science to cosmology and fundamental physics.

But many other examples of natural *self-organization*, perhaps less cosmic but not less baffling, may be pointed out. Stephen Marshal (2009, 2009a), who has dwelled on the importance of such issues for urban planning, provides two examples with uncanny similarities with cities and even with one of the most common planning procedures: land-use zoning (Figure 9). Common domestic bees construct their hives using regular hexagonal lattices, made of wax: the honeycombs. Such neatly regular structures - used by the bees to store honey, pollen and larvae - are already amazing enough. However, honey, pollen and larvae are not randomly arranged on the honeycomb; instead, the industrious bees organize them into well defined 'functional' areas, highly evocative of the patterns formed by urban land-uses. While termites, on their part, are very good at constructing gigantic 'cities', or termite mounds: huge structures, surpassing any human construction in relative size and with such sophisticated features as natural ventilation or sun-exposure optimization. Termite mounds - whose visible part (above the ground) may reach 10 meters in height, while underground may extend for areas larger than 30 meters in diameter - are built by the tiny termites piece-by piece, each one carrying no more than an bit of mud or of chewed wood; but being millions in each colony and acting like a disciplined army, they are able to produce such amazing constructions. Of course, such natural structures are not the work of any bee or termite 'master-planners'. Rather, they *emerge from the local interactions* of legions of small insects, doing very simple individual actions without any centralized control whatsoever, besides the protein-production instructions that natural selection has encoded over the ages in their *individual* DNAs. Their works are pure examples of the power and infinite creativity that *self-organizing dynamic processes* are capable.

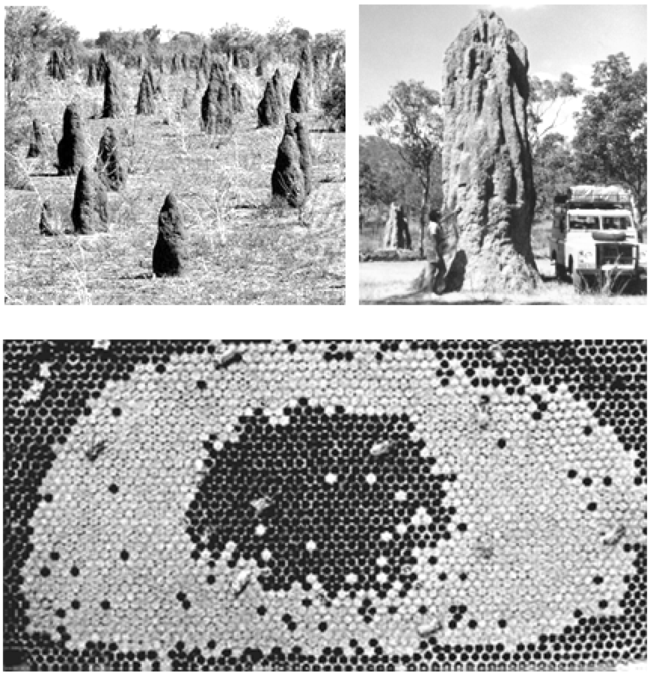


Fig. 9 – **Top**: Australian termite mounds; note the scale of the exemplar on the right. **Bottom**: the concentric pattern of 'land-uses' in a hive comb; larvae cells in the middle, then a concentric ring of pollen, then honey on the outside. Images taken from the internet (original sources lost).

Given that these natural structures are made by insects, it is not very difficult to imagine that cities may also be the product of self-organizing processes. Indeed, analogies between cities and anthills or beehives can go much further than the mere social metaphor. Like those natural 'constructions', the urban object is also the product of the actions of innumerous agents (albeit not insects), acting in a highly non-coordinated manner, incrementally building and renewing the city through time. And instead of being stable systems tending towards equilibrium, cities are actually highly *dynamic systems*, always out of equilibrium (Batty 2007)

It is the relatively slow pace of urban change that give us the illusion that they are static objects; but they are not, as we have seen before: *change* is the hallmark of the urban process. In order to function, cities need to constantly exchange energy and matter with their surrounding environment: drawing resources from it, using them to renew themselves and exhaling the resulting residual materials; in short, like living organisms, cities also have a metabolism: a feature typical of *dissipative structures* that achieve a *far-from-equilibrium* steady state, through *self-organization* (Prigogine and Stengers 1984, Bak et al 1987).

Michael Batty (1971, 2007) was one of the first authors to bring these ideas to the urban field. In his own words, “The challenge is to dig below the surface and detect the processes that generate what we see. [...] The physics of far-from-equilibrium structures is important, as it is the notion of decentralized decision-making. Processes that lead to surprising events, to emergent structures not directly obvious from the elements of their process but hidden within their mechanism, new forms of geometry associated with fractal patterns and chaotic dynamics - all are combining to provide theories that are applicable to highly complex systems such as cities.” (Batty 2007), p.4-5.

Three types of analytical formalisms support this endeavor. The first is *fractal geometry*, used to describe and to measure urban form at large scales (usually at the metropolitan or regional scale). The second, is a type of discrete numeric models called *cellular automata* (CA), which are used to simulate and understand the underlying dynamics that give rise to the spatial, physical and functional structures of cities. And the third, is another type of numeric simulations called *agent-based models* (ABM), used for the same purposes of CAs, but having different characteristics. Both CAs and ABMs also study urban functional and morphological structures at significatively large scales.

A *fractal* is an object that scales with respect to its various attributes, usually its size. If an object scales, it appears the same (or at least similar) at different levels of resolution. This is why fractals are said to be *self-similar*: the form of the whole object is repeated, again and again, along its structure down to its smallest parts. Many living organisms exhibit this type of morphological structuring; for instance: the recursive branching pattern of trees, of bronchi (in lungs) or of arteries and capillaries (in circulatory systems), or the intricate self-similar forms of broccoli and cauliflowers (Figure 10).

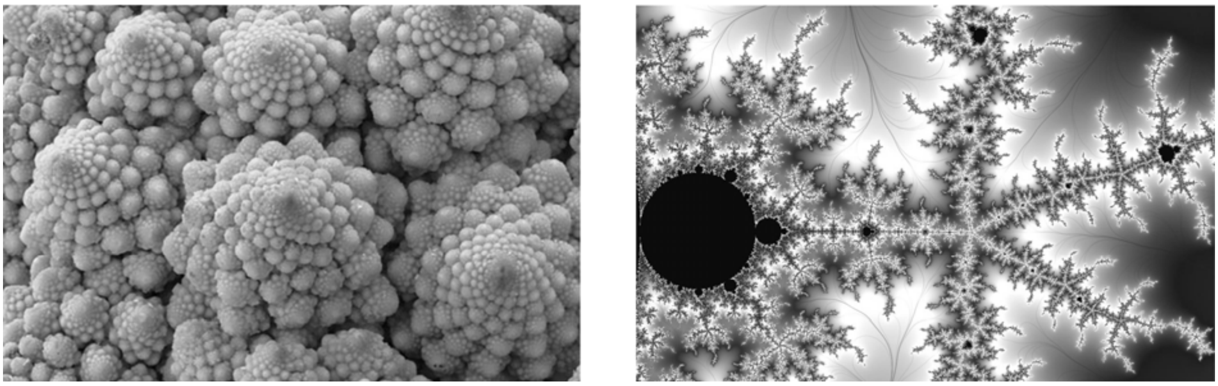


Fig. 10 – Natural and artificial fractals: the outlandish, self-similar forms of the Roman cauliflower (left); an highly amplified detail of the Mandelbrot’s set, one of the most famous numerical fractals (right). Images taken from the internet (original sources lost).

Strict scaling in cities is geometric. Morphological elements repeat themselves at different scales, usually in two dimensions. A good example is the street system of naturally evolving towns, which grows in dendritic fashion, with the same structure appearing at ever greater scales but serving wider and wider areas (Batty 2007). Metropolitan regions also show clear fractal morphologies, especially in the anfractuous boundaries of built-up areas and in their apparently haphazard spatial distributions. Several authors have used fractal geometry to study such patterns, with two distinct objectives: for describing growth and global form at the metropolitan scale (Batty and Longley 1994; Batty 2007), and for quantifying fractal parameters of urbanization at the metropolitan fringe, as an attempt to establish quantitative measures for sprawl (Frankhauser 2004; Frenkel and Ashkenazi 2008). The first line of research has shown that, indeed, fractals and fractal-based simulations are good first approximations to the global spatial structure of metropolitan urbanization. The second has made advances towards the definition of large-scale indicators for urban sprawl, based solely on geometrical properties.

However, the morphological descriptions that these methods provide are restricted to rather large scales and to coarse resolutions, becoming meaningless at the micro-scale. The geometric properties they address are *global by definition*: they measure the way urban form changes with scale (a measure of its complexity), but at the expense of *losing its detail*. Figure 11 provides an example of fractal geometry applied in urban morphology. Namely, for measuring the global geometry of continuous built-up areas in Istanbul metropolitan region (McAdams 2007). Note the similar values of the fractal dimension (quantifying the change of form as scale changes) at different territorial scopes: a clear sign of self-similarity. But note also the degree of morphological simplification that the analysis entails; moreover, the only things being measured here are the fractal relations between built-masses and open space (lacunarity) and the self-similarity of the pattern formed by them (fractal dimension), which are quite interesting but not really operational morphological parameters.

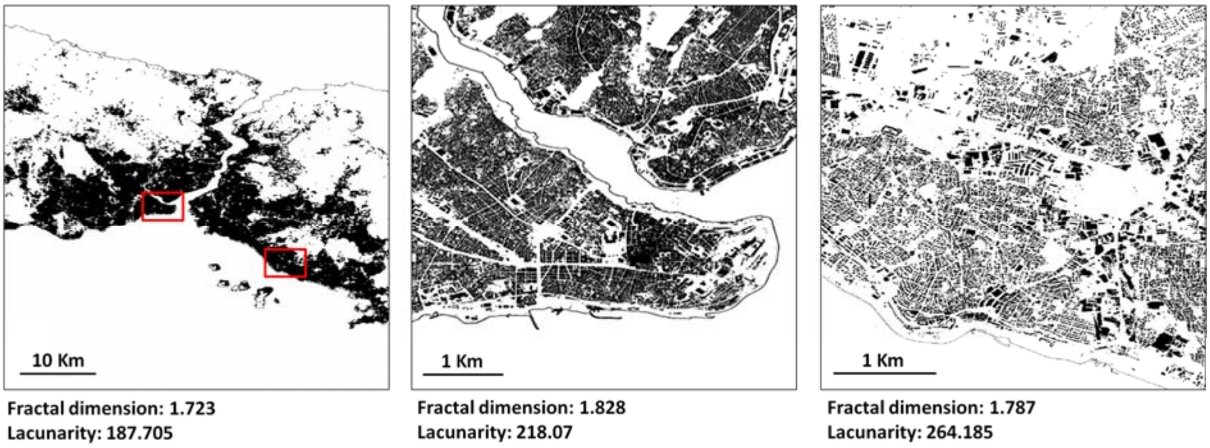


Fig. 11 – An exercise on fractal analysis, studying the global geometrical characteristics of continuous built-up areas in Istanbul metropolitan region. Adapted from: (McAdams 2007).

The object of these studies is urban geometry, even if a non-orthodox type of geometry in which dimensions may be fractional numbers. Therefore, their focus is *purely morphological*. However, the fractal nature of urban form is also the hallmark of *complex dynamics* underlying its generation (Batty 2007). And the *dynamics of urban morphogenesis* is the object of study of the two other analytical formalisms mentioned before, namely *cellular automata* and *agent based-models*. In this type of models, *morphology is a consequence of dynamics*: what is being modeled is the way cells or agents interact locally with each other, and nothing else; morphology is an *emergent property* of those interactions, and seen as something that can only be understood through the study of the dynamical phenomena that give rise to it.

Cellular automata (CA) are computable objects made of spatial units forming matrices of contiguous ‘cells’ whose characteristics, usually called ‘states’, change discretely and uniformly as a function of the states of neighboring cells, in their immediate vicinity. The state of each cell changes iteratively according to a given set of ‘transition rules’, defining the influence of the neighborhood on each cell. This representation is able to simulate processes where local action generates global order, i.e. where global or centralized order 'emerges' as a consequence of applying local or decentralized rules that in turn embody local processes (Batty 2007).

In CA models, whatever that is to be simulated does not move or migrate through space, there is no motion involved in the changes of cells' states. The model is dynamic in the sense that cells change their states through time, but absolutely static in what concerns actual movement through space. Agent-based models (ABM) are very akin to CA, but they allow for the integration of the more worldlier notion of *actual movement* between points in space. In ABM, 'agents' are objects or events that are located in respect to a background cellular space - the 'environment' into which are encoded 'environmental' characteristics - but objects that can *move between cells*. Therefore, agents are objects that do have fixed locations but act and interact with one another as well as with the environment in which they exist and evolve, according to some purpose. As with CA, the main objective is to observe which kind of global order may emerge from the interactions between agents and between them and their environment (Batty 2007).

One important characteristic of both CA and ABM is that, even though they may include probabilistic transition rules or some degree of randomness in the movement of agents or initial states of cells, these models are *deterministic*; i.e. the rules that govern local interactions do not involve any uncertainty whatsoever, and their individual results may be formally recorded and afterwards observed, step by step. However, these models are also extremely sensitive *initial conditions*: one single change in those conditions may amount to completely unpredictable results; in other words, the model's final state is *a priori unpredictable* from the model's initial conditions: the only way to know it, is to run the simulation. By no means a defect, this characteristic is actually one of the virtues of these type of models, and the reason why they are able to simulate chaotic and non-linear phenomena, otherwise out of reach (e.g. phase transitions in physical processes, turbulence in fluids, meteorological phenomena, forest fire propagation, epidemics and their dynamics, crystallization and other non-linear chemical reactions). Likewise, their application to the study of urban development and morphogenesis (Couclelis 1989, Silva and Clark 2005) are indeed capable of producing morphological patterns with significative resemblances to the spatial distributions of land-uses or of urbanization at large spatial scales (Figure 12, next page).

However, as Michael Batty (2007) admits, the large majority or urban CA and ABM models "still deal with hypothetical examples that emphasize some aspect of urban structure or dynamics such as the segregation of land-uses, the diffusion or migration of resident populations and so on. [...] It is worth noting that at urban scales where most of these models operate - the city and the city-region - agents can be only very loosely defined and are often the same as lumps of population and employment defined in traditional urban models. [...] What makes all these applications non-operational for urban planning is the scale at which they are represented. Many divide complicated regions into only 100 x 100 cells. Even 1000 x 1000 scale representations are rarely sufficient to capture the kind of detail being modeled." Op. cit. p. 142-144. Also Helen Couclelis, one of the first researches to have applied CA models in geography and urban studies, emphasizes that at best, they must be primarily seen as a metaphor for urban growth and change: "systems of the kind considered here have such volatile behaviour that models representing them may be (more) useful as 'metaphors' or conceptual organizing schemata, than as quantitative planning models." (Couclelis 1989), p.142.

Besides their low spatial resolution and loose representation of the phenomena being modeled, there also other limitations hampering the adoption of this type of models in real urban planning situations. One is the way dynamical interactions are conceptualized: the concept of neighbourhood, central in CA models, is defined only in terms of the *structure of the model itself* - it has nothing or little to do with the 'neighbourhood' as urban phenomenon; moreover, urban interactions are obviously more than just local, or restrained to a certain 'neighbourhood'. Another, is the actual nature of the objects being represented by cells or agents, which is often ambiguous: in CA, sometimes cells represent generic urban development (i.e. built-up areas), other times land-uses, or still a conflation of both; in ABM agents can be many things, from units of population or employment, to individual developers or planning agencies, but again the outcomes of their interactions are usually a mix of functional and physical aspects. In both types of models there seems to be a deliberate blurring of urban form and urban function which, from a morphological point of view, are interdependent but not miscible things.

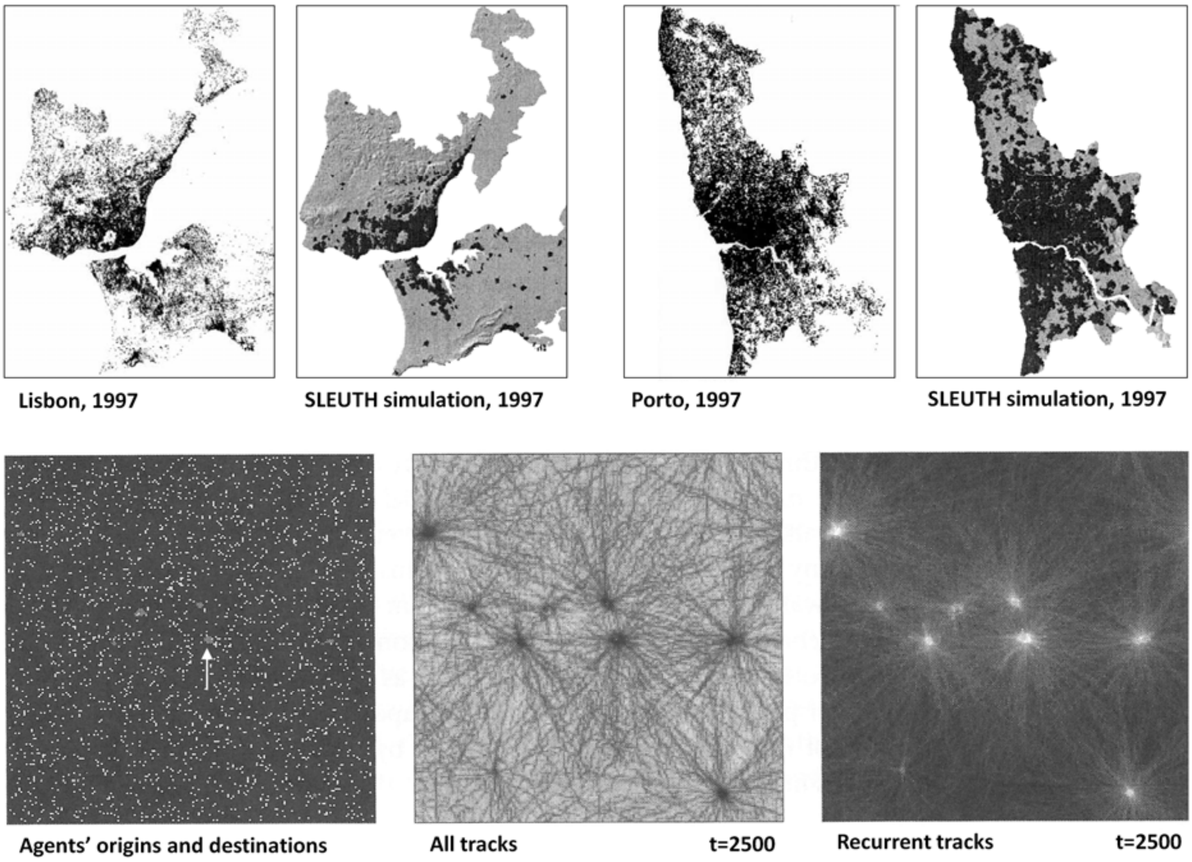


Fig. 12 – **Top**: A simulation of regional urban growth at Lisbon and Oporto metropolitan areas, using the SLEUTH cellular automata model; source: (Silva and Clarke 2005). **Bottom**: an exercise on agent-based modelling; left: the agents' origins (dots) and the locations or 'resources' (flagged with arrow); centre: all the tracks after 2500 iterations, taken by the random-walking agents in search for 'resources'; right: only the recurrent tracks, after 2500 iterations; source: (Batty 2007).

Finally, the most fundamental of all urban form's elements - streets and street systems - are frequently ignored and not integrated in the models. However, their importance to the way cities function is obvious and supported by strong evidence, coming from the urban morphology field but also from transportation research and urban studies in general. Space is treated as a flat, non-interacting entity, except in what regards the friction of distance. But is rather obvious that a city is not a checkerboard of changing cells, neither a continuous field of potential densities or event probabilities, crisscrossed by random walkers. Thus, in order to study the underlying dynamics of urban formation, these models almost loose urban from itself, reducing it to abstractions that only at very large scales may resemble real cities. Yet, at those scales, the more advanced models are able to reproduce with significative similitude the actual urbanization patterns observed in metropolitan regions (see upper images of Figure 12). Thus, it is not impossible that this type of urban models will achieve much more detailed results in the future, by progressively enhancing modelling formalisms and calibration procedures, while being supported by ever increasing computational power. However, right now they are not yet able to generate sufficiently realistic 'morphologies' or morphogenetic explanations, so as to constitute effective support tools for urban planning and design practices.

As mentioned earlier, these techniques will not be used in this work. However, the basic ideas behind their conception should also inform a potential 'integrated analytical framework for metropolitan form', because they constitute unavoidable aspects of the complex nature of cities as physical objects and of their dynamic development through time. The concepts to retain, regarding the objective of this work, are:

- The acknowledgement that cities are *complex systems* in a far-from-equilibrium state, growing and maintaining themselves through dynamic, *self-organizing processes*. Such self-organizing processes (whatever they are) are, at least in part, the generators of urban global structure and therefore cities must be seen as *emergent structures*.
- Likewise, metropolitan regions are *emergent structures*, not planned ones. As it always has been the case with cities, they grow through the *incremental actions* of a myriad of individual or collective agents, acting without *central coordination* and without *collective awareness* of the *aggregate results* of their actions. Traditionally, this would lead to self-organization; but nowadays different and powerful global drivers are in action, and local organizing principles may no longer hold, nor be the same. We may need to produce the same effect *deliberately*, in a way that is not yet clear.
- In fact, urban growth is now more *decentralized and uncoordinated* than ever, occurring in unprecedented territorial scales and within contexts of great political and administrative fragmentation, *making impossible* (or even undesirable) any attempt of *centralized morphological control*; thus, the only possible way to tackle such uncoordinated growth processes is *from the bottom-up*; i.e. with a type of control that is as decentralized as metropolitan development itself.
- In order to do this, we need to be able to analyze (at the same time) both the *micro and macro morphological aspects* of metropolitan regions, in order to make possible the investigation of the *causal links* between metropolitan *macro morphology* and the *micro morphology* of the individual incremental operations, constructing the metropolitan region through time.

Many of these ideas are, of course, exactly what the techniques described above are trying to do. However, as we have also seen, they have a significative number of drawbacks. But some lessons may be also learned from those limitations, bearing in mind the objective of this work. The following aspects are worth of note:

- The modelling techniques reviewed in this section (CA and ABM) were devised within the fields of mathematics and physics in the '40s of the 20th century[19], and thus are based in highly abstract formalisms. They may be applied with great success to systems resembling the formalism itself (e.g. true cells in organic tissues) but demand huge geometric and spatial simplifications when applied to urban phenomena. Their results make sense only at *large scales*, being meaningless below a certain spatial threshold. Moreover, such results are hardly comparable to those of the other analytical approaches to urban form. The lesson to be taken from this, is that an 'integrated analytical framework for metropolitan morphology' must include both *micro and macro analytical procedures*, and those procedures must be able to produce *comparable and mutually reinforcing results*.
- The reviewed techniques also do not include *street systems* as a basic component of their models, mainly because of the degree of simplification they entail. However, as we have seen before, *urban form and structure* is, to a large extent, also the *product of street systems*. Not

[19] CAs where invented by John von Neumann (1903-1957) and Stanislaw Ulam (1909-1984), when both worked at Los Alamos laboratory during World War II, on the less rewarding research project of creating the first atomic bomb. The concept of ABM may also be traced down to these two scientists, albeit it was only effectively developed in 1971 by Thomas Schelling (b. 1921), a Nobel-awarded American economist who used ABM for showing how racial segregation and ghettoization could be the global outcomes of individual racial preferences.

only because of their obvious functional purpose (i.e. spaces for public movement) but also because of their *structuring effect*. Thus, an 'integrated analytical framework' should also take that into account and have *streets and streets systems* as (at least one of) its *fundamental objects of analysis*.

- *Dynamics* is undoubtedly a very important aspect of urban *morphogenesis*, but it seems that numerical modelling may not be the only way to address the issue. In fact, classical morphological approaches have always taken the dynamic nature of the city into account. Not only by recognizing that urbanization is a *process that operates through time*, but also in its analytical procedures (albeit indirectly), through the technique of map regression. In fact, dynamics may be studied *directly* from the bottom-up (as we have seen in the current section), but also *indirectly* from the top-down (as we have seen in the previous section). Such approach is akin to *reverse engineering*, i.e. discovering why a given system has a certain structure and a certain working, by tearing it apart piece by piece and deducing how it was made and how it works.
- From this, it follows that if urban morphogenesis is critical to the understanding of urban form, any 'integrated analytical framework' *must include time* as one of its *fundamental dimensions of analysis*. However, *morphogenesis through time* may be observed *forwardly* (as in CA and ABM) or *backwardly* (as in the classical approaches). Even if the first option may be scientifically more elegant, the second is clearly more operative; besides, it does not entails any kind of simplification or drift, regarding the actual object of analysis.

1.4.3. THE 'CONFIGURATIONAL' APPROACH AND METROPOLITAN FORM

The third and last analytical approach to urban form (again quite different from the previous two), is based on the concept of *networks*: a paradigm that has invaded many scientific fields since the '60s, with wide repercussions in all of them. Today, the term 'network' has even become part of popular culture: a catchword, constantly popping-out on television advertisements or political speeches. However, in formal terms, a network is no more than an extension of a mathematical formalism called *graph*, invented in the 18th century. A network is a graph, only the term 'graph' is more used in mathematics and the term 'network' in all other scientific fields; also, 'networks' tend to be large graphs but, for all intents and purposes, both things are the same and the distinction is only semantic.

A *graph* is the simplest of things: no more than an handful of dots (called vertices, or nodes), linked by lines (called edges, or links). The dots can come in any number, just like the lines linking them; but not all dots need to be linked by lines, nor all connections between dots must exist: in fact, to be precise, we may even have a graph without any dots or lines, but that is a special case (called a null graph, or K_0). However, such a simple thing has an incredible descriptive power and has revealed many previously inaccessible aspects of the world around us: from the way social relations are structured, to unsuspected interaction mechanisms between proteins inside our cells, ending in the way infectious diseases spread among the world's population. Graphs can describe almost any type of phenomenon where there are interactions, or relations, between things. And what is more interesting, is that it was a city that inspired the invention of graphs and also the first object of their use.

In 1736, the brilliant Swiss mathematician Edward Euler (1707-1783) solved a riddle which, at the time, amused the inhabitants of Königsberg, then the thriving capital of East Prussia[20] (Figure 13). Königsberg had seven bridges over the two branches of the Pregel, the river that runs through the city forming an island and dividing it in four separated landmasses. The riddle was whether it was possible to visit all churches in the city by walking along a route that crosses each bridge exactly once, and

[20] Today the Russian city of Kaliningrad.

returning to the start point. Euler formulated the problem in a totally abstract way, eliminating all its physical features except the landmasses and the bridges that connected them, which he replaced with dots and with lines, joining those dots. This enabled him to prove that the answer to the riddle was "no" (without even taking a step), while at the same time creating an entirely new branch of mathematics, which as became known as graph theory.

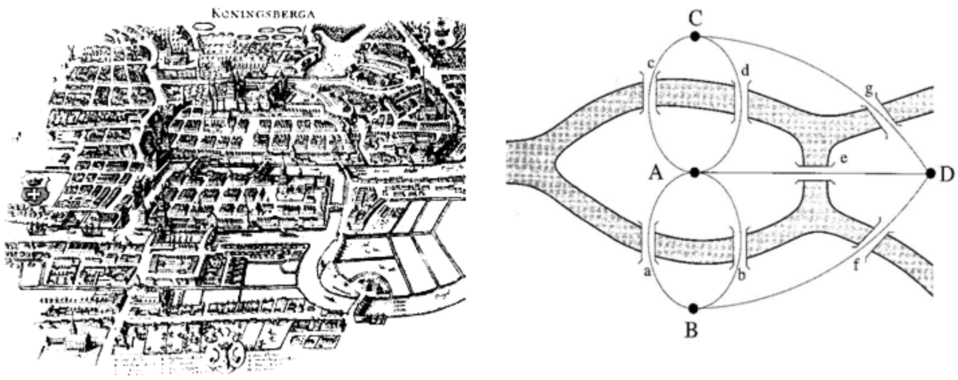


Fig. 13 – Königsberg in 1651 (left). A graph representing its four landmasses and the seven bridges connecting them (right). Adapted from (Barabási 2003).

Euler's proof was based on a simple observation: such a tour is possible if and only if there are no nodes with an odd number of links. Because each node (landmass) must be accessed by a bridge (link) and every bridge can only be traversed exactly once, it follows that for each land mass the number of bridges touching it must be *even* (half of them, in the particular traversal, will be traversed "toward" the landmass; the other half, "away" from it). That was not the case in Königsberg - and such a path is now called an Eulerian cycle in graph theory.

But there was a deeper message behind Euler's answer to the riddle: that graphs, or networks, have structural properties hidden in their construction, which limit or enhance our ability to do things with them. And this can have profound implications to the understanding of the complex world around us. Small changes in the topology, affecting only a few of the nodes or links, can open hidden doors, allowing new possibilities to emerge (Barabási 2003).

Graphs may can very useful to study urban form. They have found several applications in urban morphology but, as mentioned before, one of them as gained particular prominence and became an independent research field on its own, generically known as *space syntax* (Hillier and Hanson 1984; Hillier 1996). In this section space syntax's morphological approach will be quickly described, which will have a central role in this work. But a more recent application of graphs in urban morphology will also be addressed, namely the work of Stephen Marshal (2005) on the study and classification of street patterns, another important reference in further chapters.

As mentioned before, the epistemological 'great leap forward' of the space syntax's approach, was to realize that urban space is not just an immaterial and inert volume of air defined by the streets' pavement and the walls of buildings, but a 'construction' on its own right (albeit made by the absence and not by the presence of built mass); indeed the most important 'construction' in the whole city and the one that encloses the key to its functioning. In other words, what Bill Hillier and his colleagues founders of space syntax realized, was that the long-sought causal relations *between urban form and urban functioning* were not to be found in built-forms, but rather in the *form of urban space*: the whole set of streets, squares and other places, making up the city's public space system (Figure 14). Furthermore, they realized that this 'spatial object', with very particular characteristics, was in fact a *network* (of the spatial type, in this case) and that its form could be modelled, analyzed and studied as such.

However, space is not an easy object of analysis: the entirety of a city's spatial system is a very complicated, irregular and large geometric shape. Urban space can be compared to the many channels of a river's delta and urban blocks to the islands[21] formed by the intertwining channels. Urban space completely surrounds every 'island' of private land and provides access from one to the other. Like the river's water, space is a *global* and all-embracing *continuous entity*, which never exists *totally separated from itself* - urban blocks may be seen as 'islands', but there is no such thing as 'lakes' of public space; a public street is always connected to at least another street.

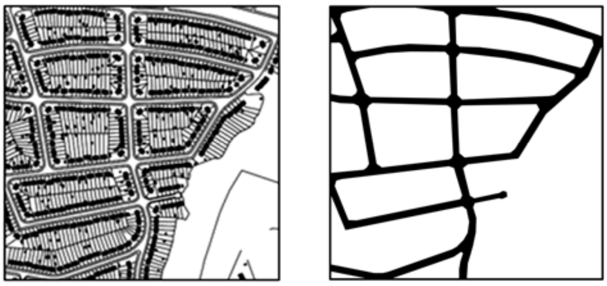


Fig. 14 – Left: urban form, including all its elements. Right: urban spatial form, space syntax's study object.

Therefore, urban space is a *continuous* and also a *global* object. This raises a problem which is prior to the analysis of space itself: how to represent a continuous and global object as to make its analysis as a network possible. Such representation must obviously involve some kind of partioning; but how to decide which spatial units should define such partioning? Space syntax proposes several methods for representing spatial systems as networks, based on the visual perception and use of space. Here, we will just review the most common of these methods, namely *axial representation*, to exemplify how the problem might be solved. More details about this and other methods will be provided in Chapter 3, and all space syntax's analytical procedures will be further developed in Chapters 4 and 5.

The axial representation of spatial systems (or axial mapping) is a way of converting the geometric complexity of urban space into a much simpler *network* of straight lines, which manages to capture its basic morphological structure (Figure 15). Axial maps (Hillier and Hanson 1984) are composed by the minimum set of line segments that are possible to draw over the open space system, such that every space[22] is at least crossed by one line and every line is at least connected to another one. Because it is the *smallest* of all possible sets of lines constructed in this way, it is also composed by the *longest* lines that meet these conditions. In other words, an axial map can be said to represent a spatial system as the set of the *longest lines of sight*, or of *straight movement*, that the systems offers to a peripatetic observer.

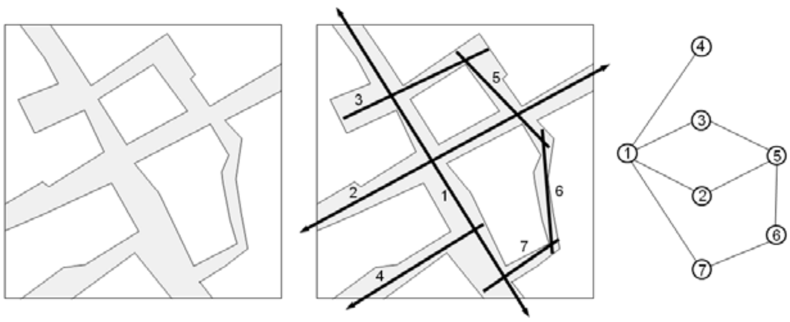


Fig. 15 – A fragment of a hypothetical street system (left), its axial representation (middle) and the resulting axial graph (right). Numbers indicate the ID of axial lines and nodes.

[21] The ancient Romans called their urban blocks *insulae*, which means 'islands' in Latin

[22] More precisely, every convex space. A convex space is such, that any line connecting two points of its perimeter, never intersects that perimeter. In other words, it is a space where any pair of its points are always visible from each other. It is considered in space syntax as the basic two-dimensional spatial unit.

Once urban space is represented as an axial map, its topological structure (i.e. the simultaneous relations between all of its spatial elements) may be examined by means of graph, in which every line is represented as a vertex (or node) and every connection between lines as an edge linking those vertices. The method of axial mapping and the creation of axial graphs will be thoroughly discussed in Chapter 3.

One can then analyze the graph using several metrics from graph theory and network analysis, or others that have been proposed by space syntax, in order to investigate the *relative importance* of each space (or of each axial line), as revealed by its *centrality* or *accessibility* regarding all the other spaces in the system (or all the other lines in the network). Because this is a quantitative method, its results are easy to compare to simple quantifications of the ways we use urban space as, for instance, observed distributions of moving people and vehicles. Strong statistical correlations between syntactic measures and urban movement rates have been found consistently in many studies (Hillier 1996; Penn et al. 1998) showing that the form of urban space (or more properly, its configuration as a network) is one of the most determinant factors of the way urban movement distribute itself within an urban grid. This has allowed to establish solid *causal relations* between *urban spatial form and human behaviour*, and has made of space syntax the only type of urban morphological analysis with intensive application in real urban planning and design situations.

The use of graphs in urban contexts is not exclusive of space syntax studies. Indeed, graphs have been used since a long time in the analysis of transport networks, including road networks. However, there is a crucial difference between the elements that are represented by graphs on those types of analysis and those represented in syntactic analysis. In the case of transportation networks, the vertices are nodal points of the network (airports, train stations, road junctions), and the lines of movement between them are represented by edges. This form of representation suits the analysis of networks where nodes are significant points of terminus and interchange. However, even if widely used in transports research, this convention is less effective for networks in which the morphology of the movement channels is the main focus of attention (as for the study of urban street systems). This can be illustrated by an example[23] (Figure 16).

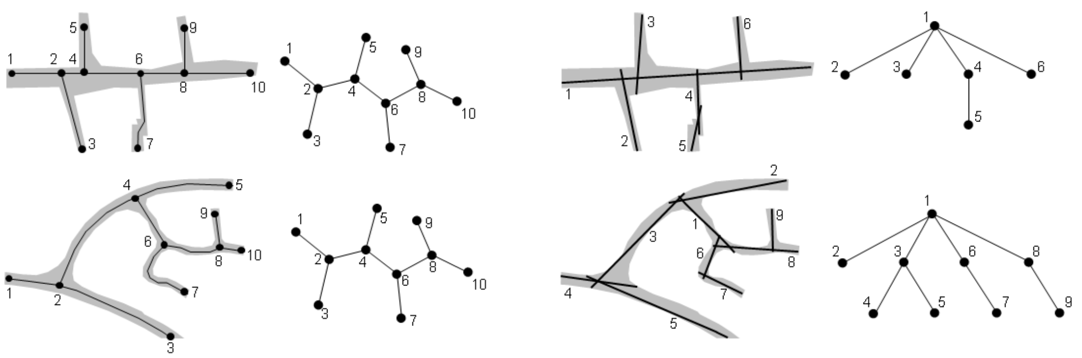


Fig. 16 – Two different street layouts, modelled with conventional graph representation of road networks (left) and with space syntax's axial representation (right). Adapted from (Marshall 2005).

Although the layouts in Figure 16 would appear to represent quite different morphologies, their conventional graph representations (junctions as nodes, streets as edges) can have exactly the same topology (being represented by the same graph with the same number of links and nodes). Therefore, graph-theoretical indicators cannot express the particular form of the two layouts, which is exactly what would matter to the study of their morphology. However, if both layouts are first represented as axial maps and then converted into graphs, we can see as the syntactic representation successfully distinguishes these as different structures (Marshall 2005).

[23] The example is taken from (Marshall, 2005).

By using axial lines as vertices, we are in fact encoding a morphological pattern into the graph, because axial lines are one-dimensional morphological representations of space (that are consistent insofar unobstructed sight and straight movement are possible along that line). Ultimately, what is being represented in the graph is the minimum number of changes of visual axis, or the minimum number of deviations from straight movement, that one must take to go from any point in the system to any other. Clearly, these are properties that are determined by the system's specific morphology. Yet, what is relevant to these properties is not the system's local form, but rather how its form is globally structured, i.e. how all its spaces relate to all the others, simultaneously. Defining how a vertex is located in relation to all the others is a common procedure in network analysis, and many metrics and distance definitions are possible. These will all be discussed in more detail on chapters 4 and 5.

However, one important analytical aspect is worth noting from the outset. It is the fact that syntactic analysis is *scale-independent*: it is able to scan the centrality pattern of the network from each node's topological neighbourhood (i.e. regarding only the nodes directly connected to it, or local analysis), to the entire network as a whole (or global analysis). Moreover, it can do this *progressively*, i.e. each node's centrality may be evaluated regarding all the nodes within progressively larger neighbourhoods (or *radii*), up to the entire network. This *scale-independence* of syntactic analysis, coupled with the fact that what it measures are *centrality patterns*, make it particularly relevant for studying metropolitan morphology. In fact, as we have seen in section 1.1, the fundamental characteristics of metropolitan regions are their *poly-centric nature* and the fact that such poly-centrality is *diffuse*, i.e. from the main regional centre (or centres), to second-order centres, down to local micro-centres. This complicated centrality structure is something quite within the reach of syntactic analysis.

However, in this section our aim is just to introduce space syntax's basic analytical methods, the morphological theory of the city that has emerged from them and how it has also been recently applied to the study of metropolitan regions. That theory was in large part articulated by Bill Hillier in several papers and in one important book (Hillier 1996), so his own words will often be cited.

Hillier (1996) argues that well-functioning cities can be seen as "movement economies": the configuration of the urban spatial network determines the way movement distributes itself within it, and then movement shapes the distribution of urban functions. Spaces travelled many times in each origin-destination trip (because their particular location on the global structure makes them more accessible) 'profit' with the by-product of that movement (i.e. being traversed many times), by attracting movement seeking functions, like tertiary and commercial functions. These functions then, acting as destinations, attract even more movement, creating a multiplier effect which is responsible for the emergence of dense and highly multi-functional urban areas. Other uses that do not gain directly from movement, like the residential use, tend to locate themselves in the less accessible interstices between the most integrated spaces (Figure 17, next page).

For Bill Hillier, cities, in spite of their obvious differences, are shaped by the same dual process, in which "each side of the duality explores the relation between space and movement in a different way. On the one hand, there is a micro-economic driven process that structures space in order to make it globally accessible, i.e. to optimize its reach from all other spaces and so maximize movement and co-presence; this tends to be invariant across cultures, as trade and exchange [are]. On the other hand, there is a residential space process, which uses space to restrain and structure movement in the image of a residential culture of some kind. […] This dual process leads to the emergence of the also dual structure of urban grids: a *foreground network* of highly accessible spaces linking centres at all scales, and a more segregated *background network* of primarily residential space in which the foreground network is embedded" (Hillier and Vaughan 2007), p. 218, our emphasis. These background and foreground networks are shown on Figure 17.

Fig. 17 – The dual structure of urban street networks as revealed by configurational analysis. Dark lines are more central, light grey lines more segregated. The images show the pattern of global choice (a type of centrality) for London (left) and for Tokyo (right). Source: (Hillier 2009).

This is the basis of what we could call the 'Hillierian' theory of the city, which is "a theory of the deep structure of the material form of the city, both as an autonomous reality in itself and as an essential constituent of the dynamic processes that make up the city" (Hillier 1989), p.5. Based on the interrelationships between spatial centrality and movement predictability through configuration, Hillier proposes that the tendency of traditional self-organized settlements to evolve into a more or less universal pattern, characterized by the dual structure described above, is explainable by what he calls *generic function*. This concept refers not to the different activities that people carry out in buildings or cities (or to functional programmes, be them architectural or urban), "but to aspects of human occupancy of space that are prior to any of these: that to occupy space means to be aware of the relationships of space to others, that to occupy [space] means to move about in it, and to move about [in space] depends on being able to retain an intelligible picture of it." (Hillier 1996), p.284-285. Therefore, generic function is prior to specific functions, in the sense that it is a kind of meta-function, moulded into the very basic morphology of well-functioning spatial layouts, allowing them to be useful and intelligible to human beings before anything else. It is also the property that restricts human spatial systems to a *limited array of combinatorial possibilities* and that makes them capable of supporting several specific functions. In fact, as it is the case in urban settings, almost any kind of specific function.

But Bill Hillier's urban theories do not exhaust the potential of space syntax as an analytical tool. In fact, much more than a theory, space syntax is a 'tool box' of techniques to model and analyse human spatial systems, be them buildings, cities or even entire regions. To our knowledge, the first applications of space syntax techniques to metropolitan studies were disclosed in 2005, at the 5th International Space Syntax Symposium, in Delft. Since then there has been considerable research on metropolitan form and structure using space syntax techniques (Jiang and Peponis 2005; Azimzadeh and Bjur 2007; Nes 2007; Rigatti and Ugalde 2007; Ugalde, Rigatti et al. 2009; Nes 2007, 2010; Serra and Pinho 2011; Serra and Pinho 2012). In particular, Stephen Read's (2005) 'Flat City' model has attained a high level of elaboration. We will now review some of these studies, which we consider more relevant for this study's objective.

Ruth and Nick Dalton (2005), in "A Spatial Signature of Sprawl: or the proportion and distribution of linear network circuits", study the spatial network of Peach Tree City, a suburb of Atlanta. Through the comparison of their case study with other urban and suburban spatial networks, they propose a way of measuring the "urbanity" of a given urban system by looking at the nature and number of its axial graph cycles[24]. The authors show how axial graph cycles have clearly different length distributions in

[24] In graph theory, a cycle is a path that starts and ends on the same node. On axial graphs, cycles usually correspond to `rings' of public space around nonpublic spatial `islands'.

urban and suburban environments, showing a marked peak for cycles of length 4 in urban environments (corresponding to blocks in grid-like street layouts) and being much more evenly distributed in suburban settings (Figure 18). These results, even though concerning only North American cities have, nonetheless, been also corroborated by our own previous research on Oporto's Metropolitan Region (Serra 2008; Serra and Pinho 2011; Serra and Pinho 2012).

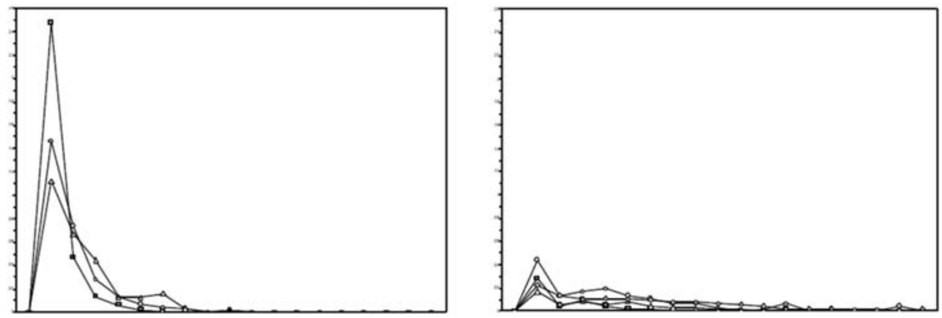


Fig. 18 – Histograms of axial cycle lengths for urban (left) and suburban (right) systems.
Source: (Dalton and Dalton 2005).

Peng Jiang and John Peponis (2005) investigated the differences between historical and emerging centres in metropolitan Atlanta. They found that the new centres are globally and locally less accessible than the old centres. Block sizes are considerably larger in the new centres. However, average axial line length is 27% shorter, implying a much more fragmented layout. The new centres' large blocks, mostly occupied by shopping malls, developed along time a secondary street network built in privately owned land (to account for the evolving needs of access and parking), which intersects and complements the system of public streets. The new streets thus created reduced the size of the previous blocks five-fold, while the average line length is reduced two-fold. Exploring the configurational properties of those networks, the authors found that connectivity, local and global centralities were enhanced by that progressive elaboration of internal block layouts, but the resulting network had become even more fragmented and confusing. They conclude that "from the point of view of description, […] the old centres have a spatial structure which mediates between local and global scales of spatial organization. The new centres express a fundamental original polarization and discontinuity between local and global scales. […] The evolution of the old centres is characterized by a relative permanence of the street system. […] In the new centres, by contrast, […] buildings take advantage of the pre-existing spatial morphology of movement, under the constraints of property lines. […] The spatial morphology of movement comes to link a system of buildings, under the constraints of a pre-existing framework of streets." (op. cit., p. 292).

With a far more sound theoretical approach, Stephen Read (2005) proposed at the same Delft symposium his 'Flat City' model of contemporary metropolitan movement networks, further developed on a series of subsequent papers (Bruyns and Read 2006; Read and Bruyns 2007; Read, Bruyns et al. 2007; Read and Gil 2012). Again, I will simply cite this author's words, for they are best then any possible rewriting.

Read (2005) starts by acknowledging two weak features of the space syntax programme: "one is its tendency to treat the urban object as a thing bounded by the limits of the densely built fabric of the centre; the other, to treat all movement spaces equally when it is quite clear that different classes of spaces in the fabric of the city perform quite differently at the levels of urban speed and function and at the level of human experience of space and time. […] In fact, today is becoming ever clear that the space of the centre is penetrated by mobilities and by their infrastructures which transmits urban speeds, functions and characters that belong to a much wider scope of the urban – and that the periphery, the locus of much of this wider urban we are becoming aware of, itself is becoming increasingly integrally part of an urban social and economic existence that far overflows the limits of the more traditional city. […] The net result of all this is, I believe, that space syntax is not fulfilling its potential as a manner of thinking the dynamical forms of the contemporary city." (op. cit., p.341-342).

Drawing on previous research results on the analysis of several Dutch cities (Read 1999), this author highlights "the central role of the so-called 'supergrid' in the functioning of many (if not most) traditional city centres. […] The supergrid has long been understood in space syntax as a part of the overall grid of the city which acts as a facilitator of long range movement in the central fabric, [distributing] itself fairly evenly through the entire fabric. […] This structure is of a two level layering in the movement grid of the historical fabric – one level […] tending to facilitate rather long distance movement, the other for very local movement […]. On the basis of these simple observations a hypothesis was set up; that the critical structure as far as the movement machine of the urban centre was concerned was a layered biplex structure of flat grids, its layers differentiated by speed and intensity of movement […]." (op. cit. p. 343, 345).

And on a latter paper, he insists: "It often appears to be this middle-scaled grid, or supergrid, that is critical for the production of the urban 'place-quality' that we understand from our experience of traditional, historically evolved, urban centres. [In metropolitan contexts] it is this scale of infrastructure *that seems most often to be omitted*, or that fails to work with the effectiveness required, and it is this scale of infrastructure *that we don't build anymore* as a matter of course into our environments." (Read and Bruyns 2007), p.6, our emphasis.

Read's idea of a biplex movement structure in urban space has several similarities with the above mentioned 'dual urban structure', proposed by Hillier. However, Read's concept is *infrastructural*, more based in the view of the movement flows themselves and their different speeds using the city as a 'layered movement technology' and not so much in the idea of the mechanistic shaping of movement by urban form. Moreover, the notion that the all-important 'middle-scaled grid' is no longer present, or at least is ill-structured, in contemporary metropolitan contexts is highly revealing. In fact, it is typical of the metropolitan movement experience to travel from one place to another along the regional network of metropolitan highways (which is, of course, useful), but then to land at our destination in a confusing local grid, where orientation becomes almost impossible; because, between the macro-infrastructure of long-range movement and micro-infrastructure of short-range movement, there is no longer an intermediate meso-structure interfacing the previous two. Stephen Read uses this model to explain the spatial structure of contemporary cities beyond their central core (Figure 19). The core, he explains, "is an integral condition of supercentrality.[…] As ones moves away from the core, however, the opposite tendency occurs; the supergrid network becomes more and more distinct and defined, the interconnectivity between supergrid and local movement grids diminishes, and the supergrid and local grids begin to disengage from each other.

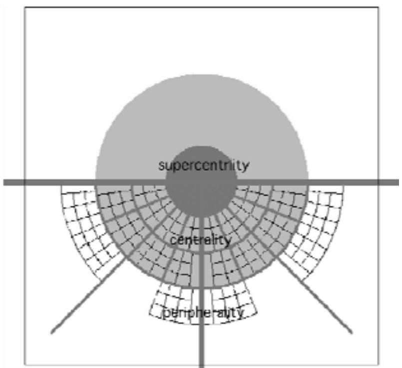


Fig. 19 – Supergrid variation across the contemporary urban surface. Source: (Read 2005)

The overlap between these networks begins to unravel and local-scaled grids become unequivocally local while supergrids become more and more specialized. […] One can see here the emergence of the condition of peripherality, where that peripherality is defined not as a quintessential condition in relation to [...] an historically produced centrality, but as a condition out of the ecologies produced by a simple set of movement and communication networks. Centrality and peripherality become not simple accidents of history over which we have no power, but products of definable movement and communication network infrastructures and their relationships, which we have the power, if the will be there, to establish or to change." (op. Cit, p.353).

As with every simple and good idea, Read's model seems obvious at first but, on reflection, has notorious implications. Its greatest virtue is that of overriding the deadlock created by the old centre/periphery dichotomy, introducing a much more acceptable and plausible paradigm of a *potential urbanization field*, which is not defined in relation to any geographical centre and which becomes actual when activated by the presence of movement infrastructures, not in a concentric but rather in an isotropic, or non-centric, way. Because each layer's grid conveys different movement scales (e.g., neighbourhood, city and regional movements) it just a step to imagine that urban functions should be drawn to each layer according to the scale of their 'customer base' (e.g., local functions in the local grid, metropolitan functions in the metropolitan grid, and so on). And, as a matter of fact, they do (Figure 20).

Fig. 20 – The coincidence between movement grid and urban functions. On the left: local-scaled grid and local functions; on the right: middle-scaled grid and city-scale functions. On both images the local-scaled grid is light and the middle-scaled grid is dark. Source: (Read and Bruyns 2007)

Stephen Read's model of contemporary metropolitan movement networks, as layered systems of differently scaled movement infrastructures, is essential to understand the apparently ungraspable structure of metropolitan regions. It has the great virtue of looking directly at what is important and of making transparent what is accessory. As stated at the beginning of the current section, such stance is essential when addressing the problem of metropolitan form. Several of his conclusions will be central to this work: the conceptualization of urban spatial nstructure as a layered system of movement infrastructures (or movement 'shells'), intersecting each other frequently, albeit differentiated by their characteristic 'speeds' and territorial 'reaches'; the fact that such system is an on-going 'construction' with historical correlations with the evolution of society's socio-technical paradigms (namely: the pre-industrial, industrial and post-industrial paradigms, corresponding to also different modes of urban organization); the acknowledgment that the contemporary city and its current top-tier infrastructure (i.e. the networks of metropolitan highways) are no more than the current 'post-industrial' manifestation of that correlation and that we must learn how to integrate it harmoniously with the infrastructural legacy of previous (pre-industrial and industrial) socio-technical paradigms; and, finally, the notion that this has been, up till now, neglected and that the continuity of the former top-tier 'industrial' infrastructure (i.e. the current middle-scaled grid) has been jeopardized at the regional (or metropolitan) territorial level, creating a fracture between movement layers.

Stephen Read's ideas are a fundamental theoretical reference for this work. However, at the analytical level, many advances were made in the space syntax's field since Read's 'Flat City' paper, presented in 2005. The most important was perhaps the introduction of *segment angular analysis* (Hillier and Iida 2005), or ASA: a technique in which axial lines are broken at their intersections (which are usually street junctions) and transformed into individual *segments.* Each of these segments is then encoded into a graph, in the same way axial lines are; only now, the basic units of analysis are no longer *straight street stretches* (or entire streets, when these have no bends), but *street-segments between junctions*[25]. Thus, spatial centrality in ASA is calculated at the *street-segment level*, which allows for a significatively *finer-grained analysis*. Furthermore, in axial analysis the distance between two intersecting lines is always unitary (i.e. equal to 1) whatever their actual geometric lengths (i.e. a discrete topological metric was used to account distances between adjacent nodes in the axial graph), and the *radius* of analysis (i.e. the distance defining the graph neighbourhood around each node, for which centrality calculations are made) was also defined in the same way[26]. But in ASA an important innovation was introduced: distance between non-collinear segments becomes a *function of their angle of incidence*; i.e. adjacent segments forming obtuse angles are *less 'distant'* then adjacent segments forming acute angles.

The rationale behind this conception of distance is rooted in space syntax's foundations. In fact, the reason for partioning space in axial lines, is that there is no *cognitive cost* in moving along a space whose *entire length we can see*; but when we *change from one visual axis to another* there is a cognitive cost, because a new part of space becomes visible. This can also be expressed as an *information* cost. If someone asks us for directions in a city, and the place is just at the end of the street (no matter how long the street), we just need to say: "go straight ahead"; but if the place is somewhere implying many right and left turns, the *length* of our explanation will be much longer (i.e. its informational content will be larger). The same is to say that the information contained in an axial line is unitary, and each turn of space (i.e. each new axial line) entails an additional unit of information; therefore, the entire number of axial lines in a spatial system may be seen as its *total informational content*, which is proportional to its degree of *complexity* (or of informational entropy).

What ASA does then, is to *weight* that unitary information cost by the angle between segments, with that cost being *zero* if the segments are collinear, *one* if the segments make a 90^o degree angle and *two* in the case of 180^o degree angle; furthermore, distance becomes *continuous* within the [0,2] interval, and no longer discrete (i.e. measured in integer numbers). Obviously, the hypothesis behind this is that the cognitive cost of making a change of visual axis very close to zero degrees is insignificant, while a 90^o visual change has an higher cost and a 180^o change a maximal cost. Several studies (Hillier and Iida 2005; Barros et al. 2007) have shown that ASA is a better postdictor of urban movement than standard axial analysis; something that will also be shown in this work on Chapter 4. Moreover, significative evidence from cognitive science points to fact that humans tend to mentally break routes into discrete visual chunks, and to correct bends to straight angles and turns to right angles (Allen 1981, Hochmair 2002, Duckham 2003).

Besides using an *angular conceptualization of distance*, ASA also allows defining the *radius of analysis in metric units*, measured through the network along the segments' lengths. Apart from the fact that it is easier to imagine a radius in metric units than in topological units, it has been shown that it is also a much more uniform and rigorous way of constraining the system (Turner 2007). Moreover, the distance defining the radius of analysis becomes also *continuous* and no longer discrete, which adds even more analysis resolution, to the gain in resolution already provided by the use of segments

[25] There are many exceptions to this statement, as it will become clear later. But at this stage of the argument, to consider it general makes explanation easier.

[26] All distance concepts and radii-definition metrics will be detailed in Chapter 4.

instead of axial lines. In fact, the range of possible radius of analysis becomes then very large (e.g. 250, 300, 350, … , 3500, 3550 meters, and so on); or even *infinite*, because the metric defining the radius of analysis is continuous and not discrete.

ASA has produced a significative number of new findings, revealing very detailed and previously unsuspected structures in urban street systems, which we will discuss in a moment. But two other factors worth of note have contributed to major analytical advances within space syntax in the last decade. One, was the creation of *DepthMap*, a piece of software for syntactic analysis written by Alasdair Turner (2001, 2004), whose use has become generalized. DepthMap was initially created for performing *visual graph analysis* (VGA, a technique not used in this work), but has progressively incorporated all the other techniques, including axial and segment analysis. DepthMap has been a factor of analytical advance because its code is highly optimized, extremely efficient and fast, allowing the processing of very large graphs. The second factor was, of course, the increase in processing power of computers in the last decade. Both these two factors make now possible the modelling and processing of graphs representing the street networks of entire metropolitan regions, even of entire sections of countries.

Therefore, in recent years, not only the *detail* of spatial analysis has greatly improved, as its *territorial scope* has become regional. We illustrate this with two last examples. In a recent paper, based on new findings resulting from ASA, Bill Hillier (2009) has proposed that the structure of naturally grown cities (like London), showed a very complex centrality pattern to which he called *pervasive centrality* (Figure 20a). Unlike the concept of metropolitan poly-centrality discussed before - meaning an urban-regional networked structure of several large centres of varying sizes but always above the 'town' level - the concept of pervasive centrality regards a much more complex structure: "linked centres at all scales, from a couple of shops and a café at the smallest scale to whole sub-cities at the largest. […] Emergent multi-scale centrality should be seen as a pervasive function in cities, with clear spatial correlates, and not simply as a hierarchy of locations. What appears to be a multi-scale pattern of linked centres arises in cities through a well-defined process of self-organisation, based on the relationship between the grid structure and movement at all scales." Op. cit., p.6.

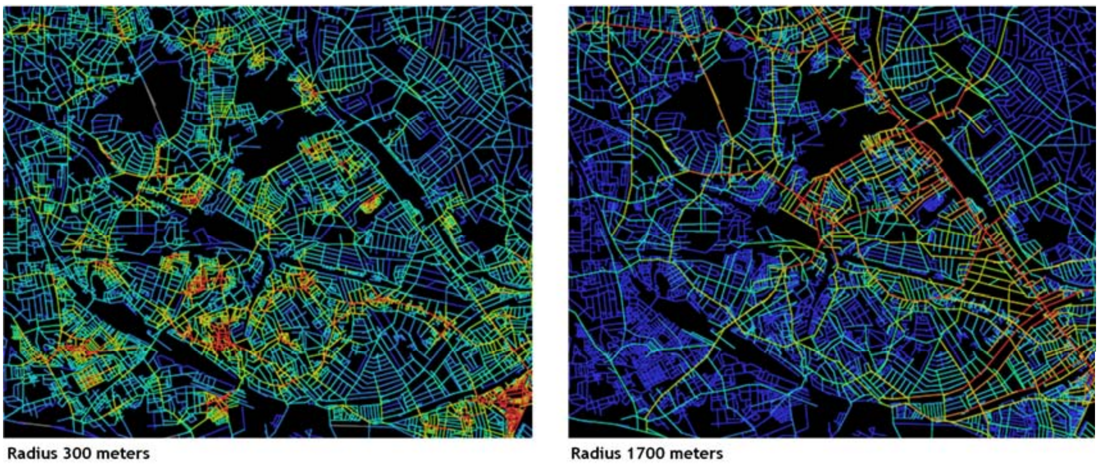


Fig. 20a – Pervasive centrality in London: local micro-centres (left) and linear meso-centre (right) within the same area (Ludstown, northwest London). Source: (Hillier 2009).

This capability to detect patterns along the entire centrality spectrum of very large urban regions, from the smallest street segment up to the entire metropolis, has an obvious utility to this study's objective. Not only to investigate the largest scales of that spectrum, where the poly-centric structure of macro and meso metropolitan centres becomes apparent, but also to study its smaller and more delicate centrality structures, at the neighbourhood's micro-scale and even below. In the same paper, Hillier also shows how the importance of these micro-centres may vary across spatial scales. In fact, it seems that centres can have many roles, beyond the coarse classification of macro, meso or micro. Spatial centrality is a *continuous property*, producing areas that are locally or globally central, but also areas showing all types of possible *centrality behaviours* along the entire metropolitan spatial spectrum. Figure 21 illustrates this, through the variable centrality of the high-street of one of London's 'urban villages' (Streatham), as revealed by segment angular analysis. A small part of the high-street starts as a very small, local centre at the range of walking distances (400 meters), but its length becomes progressively more central as the radius of analysis increases (800, 1200 meters), attaining its peek at radius 1400 meters, where the entire high-street shows high centrality levels; finally, at the scale of the region (radius infinity), the Streatham's high-street is no longer the most central place in the area.

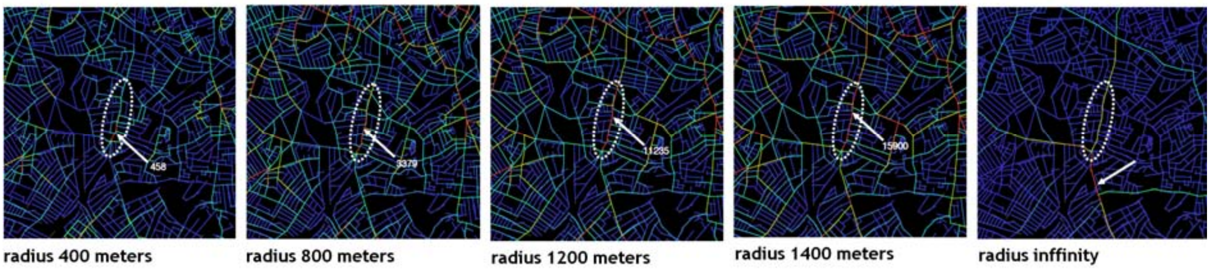


Fig. 21 – The evolution of Streatham's high-street centrality across spatial scales. The dotted ellipse marks the high-street and the arrow flags the most central segment at each radius. Source: (Hillier 2009)

This illustrates the degree of analytical detail that is now available within the space syntax framework. The territorial scope may be demonstrated by other study by Akkelies van Nes (2009), this time regarding the *entire Randstadt urban-region*, in the Netherlands (Figure 22). The model represented in Figure 22 has no less than 20 cities and towns, covering an area of 7200 Km^2, within which every street is represented.

In summary, syntactic methods are now capable of analysing street networks with hundreds of thousands of nodes, encompassing entire urban-regions, while having for smallest spatial unit (i.e. for lower limit of spatial resolution) the street-segment. Moreover, analysis is completely scale-independent, covering the entire spectrum of metropolitan spatial scales, from the neighbourhood to the regional level. The analytical methods are quite objective, being based on well-defined centrality measures and automatic computation, whose output is quantitative; therefore meeting one important requirement in terms of its concomitant use with any other numerical method. All these qualities make it a very interesting tool for the aim of this work.

However, all these advantages entail with them a difficulty. It is true that today we may construct regional spatial models and study them across many spatial scales, using several centrality measures that reveal different aspects of the structure of metropolitan street networks. But a few simple multiplications are enough to disclose an unexpected side effect of such analytical prodigality. For instance, a graph with 100.000 nodes, analysed for 20 different radii (say, from 250 to 25.000 meters, divided into 1.250 meters intervals), and for two types of centrality (e.g. closeness and betweenness[27]), will produce the scary number of 4.000.000 centrality values, or 40 centrality values for each of its 100.000 nodes. As it seems, we have a fantastic analytical machine; indeed so fantastic that we cannot cope with the amounts of data it produces. A truly paradoxical situation: either to drown in oceans of data or to use the machine well below its capabilities, choosing arbitrarily one or two radii of analysis and make do with that. Still, a solution for this analytical hindrance will be proposed in the next Chapter and its implementation will be demonstrated in Chapter 5; at this point, I would like just to highlight that problem.

[27] Closeness and betweenness are two centrality metrics used in space syntax and in general network analysis. Both will be explained in detail in Chapter 4.

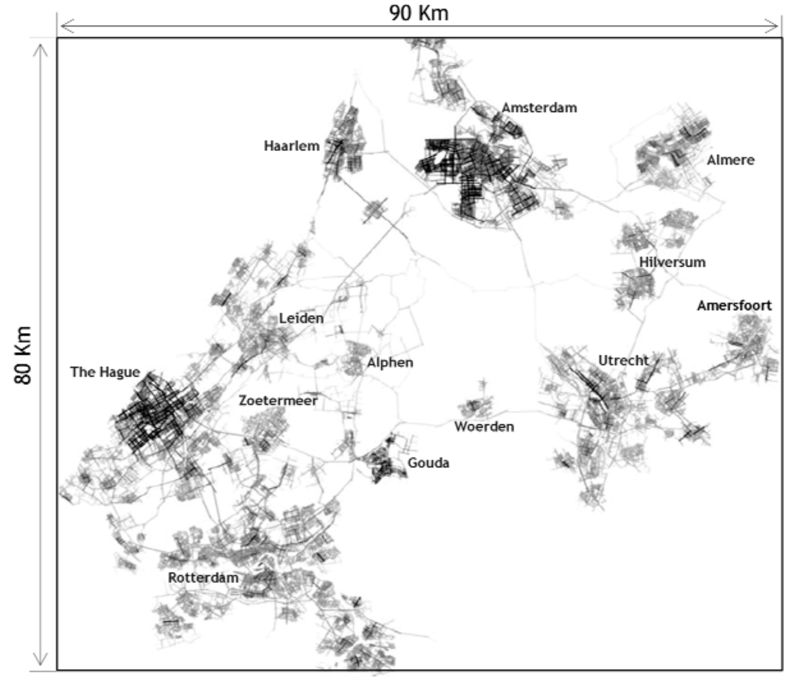


Fig. 22 – A syntactic model of the Randstadt urban-region in the Netherlands. Source: (van Nes 2009)

A last reference is due in this section, regarding yet another recent use of graphs in urban morphology, namely the work of Stephen Marshall (2005) on the description, classification and analysis of street layouts, to which we will call 'street pattern analysis'[28]. An important aspect of space syntax is that it analyses *only entire street networks*, whose graphs *must be connected* (i.e. without free nodes, disconnected from the overall graph). In other words, space syntax deals only with street networks as *collective entities*, studying the relations between each node and all the others. It makes no sense, within that framework, to isolate and analyse *individual components* (or sub-graphs) of the network; because, by definition, the configuration[29] of a local area depends on its embedment within the entire network. If we isolate a sub-graph from the rest of the network, we will in fact create *two new networks* (i.e. the sub-graph and the previous network without that sub-graph). All analytical results will henceforth be different: because we removed an object from its configurational context and, simultaneously, we changed the context's configuration transforming it into something different.

However, as stated at the end of the previous section (1.4.2), an 'integrated analytical framework for metropolitan morphology' ought to be able to study the individual incremental additions constructing the metropolis through time, and to relate such study to the analysis of the evolving global morphological structure. What the analytical techniques developed by Marshall (2005) allow, is the quantitative analysis of *individual* street patterns (or street layouts), in order to achieve consistent *typomorphological classifications*. Moreover, these techniques have some affinity with syntactic analysis, because they are also based on topological characteristics and their outputs are numerical.

The subject of typological classification of street patterns is particularly illusive, as we have seen in section 1.4.1. Usually, street typomorphologies are either too general to be useful or so detailed as to be idiosyncratic. Marshall's (2005) book, "Streets & Patterns", addresses this specific problem. This author starts by recognizing the recurrent inconsistencies in the existent terminologies of street typomorphologies, with different terms referring to the same thing and vice-versa. Some terms refer to the topology of streets, others to the shape of their interstices, yet others to the alignment of routes.

[28] I should point out, however, that this is just a personal choice and that nowhere in the book "Streets & Patterns" does Stephen Marshall refers to his methods using that expression.

[29] In fact, the expression 'spatial configuration' refers to the *simultaneous relations* between *all the spaces* in a street network.

Moreover, those terms are not necessarily mutually exclusive, creating continuous ambiguities and double meanings. And, above all, it is quite evident that morphological types are ‘canonical’ moments in a real morphological continuum of possible urban forms. Therefore, according to Marshall (2005) “what is needed first, […] is a more useful set of elemental types, and a better description of the continuum, with explicitly calculable positions on it.” Op. cit., p.81.

“As a first and fundamental step, we can make a distinction between two types of formation: those relating to absolute physical geometry, as opposed to those referring to abstract topology. These may be referred to as *composition* and *configuration*. […] Composition refers to absolute geometrical layout, as represented in a scale plan, featuring absolute position, lengths, areas and orientation. Configuration refers to topology, as represented on an abstract diagram [or graph], featuring links and nodes, their ordering (relative position), adjacency and connectivity.” Op. cit., p.86-87.

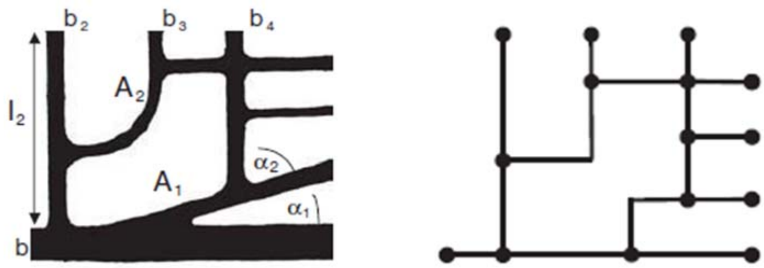


Fig. 23 – Composition and Configuration. Source: (Marshall 2005).

Using this basic distinction (Figure 23), Marshall is able to create a first set of elemental types that, rather than being a list of more-or-less arbitrary terms, is structured by a *taxonomic logic*; i.e. in which each level of the classification has the properties of the upper levels plus their own, from the most general upper level to the lowest and specific ones, guaranteeing that the whole taxonomic schema retains its systematic integrity (Figure 24). This taxonomy is then extended, to show that it can accommodate any desired degree of precision or elaboration (Figure 25, next page). Many of the possible types within it are clearly not forms of urban street patterns, for they are elemental types. But, as such, they can be combined to form hybrid types, or applied at different scales and at any degree of resolution. Also, it is possible to make combinations of different (albeit non-exclusive) elemental types, with the two basic types of junction (‘X’ and ‘T’ junctions), leading to one more level of typological definition while increasing the similarity with actual street patterns (Figure 26, next page).

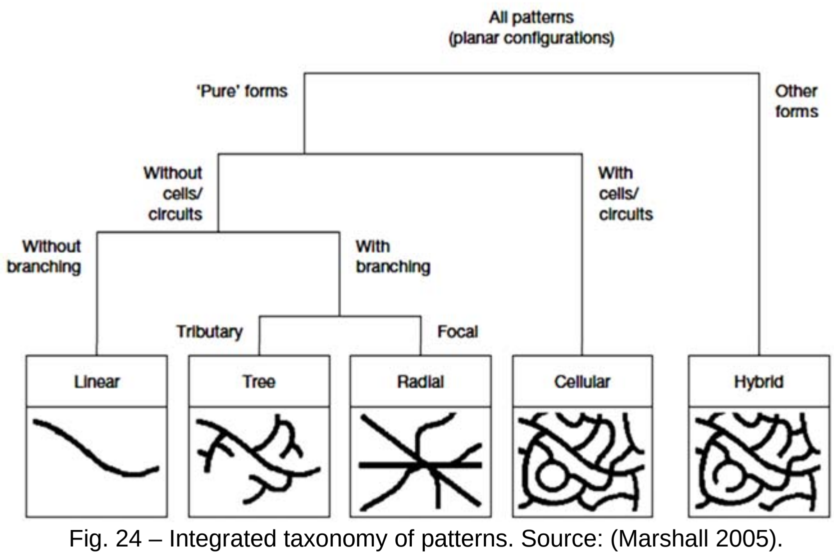


Fig. 24 – Integrated taxonomy of patterns. Source: (Marshall 2005).

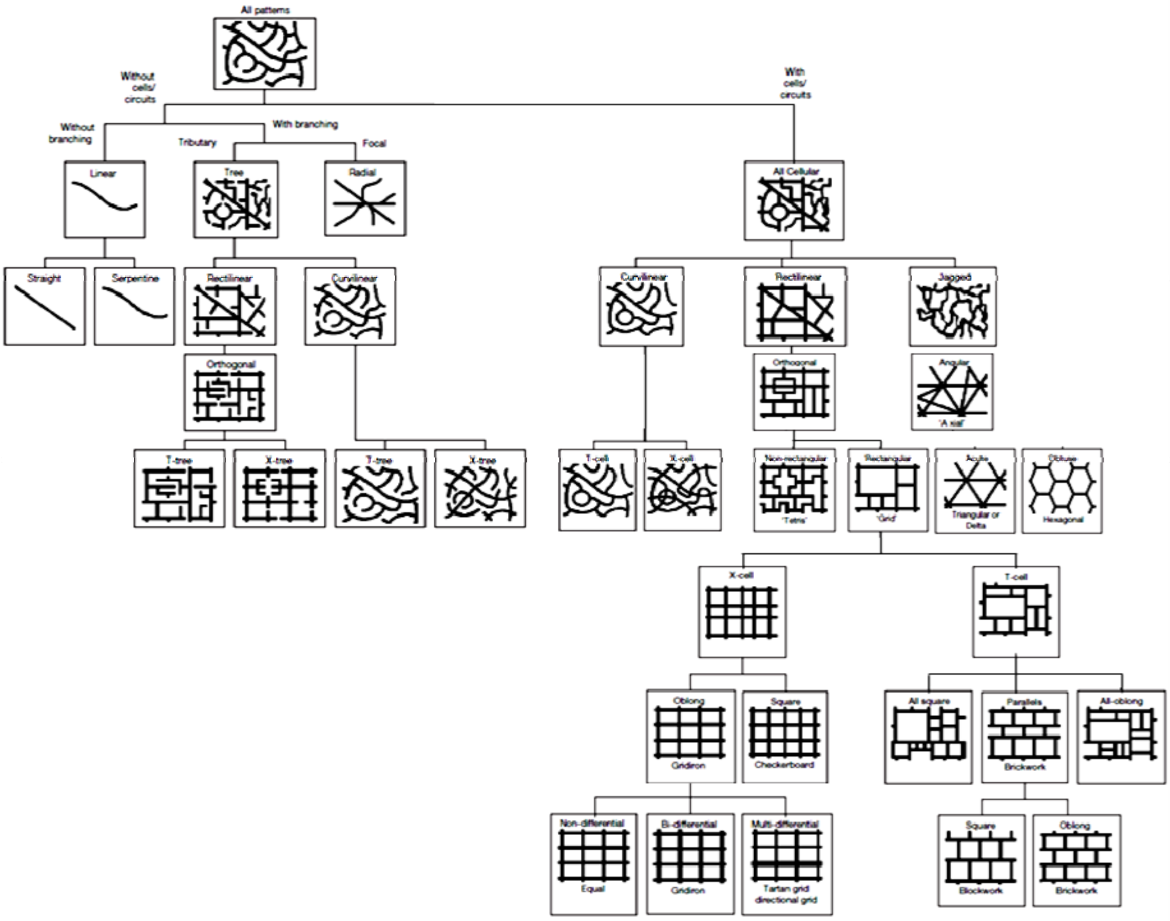


Fig. 25 – Elaborated taxonomy of patterns. Source: (Marshall 2005).

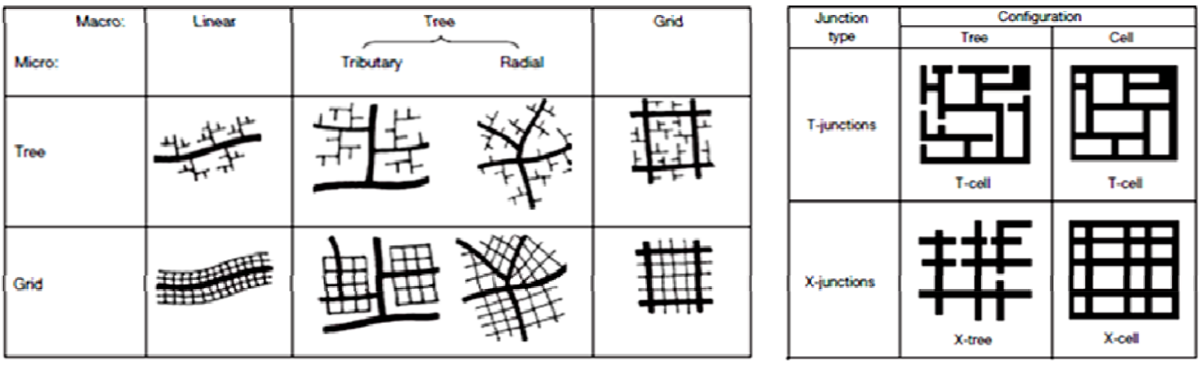
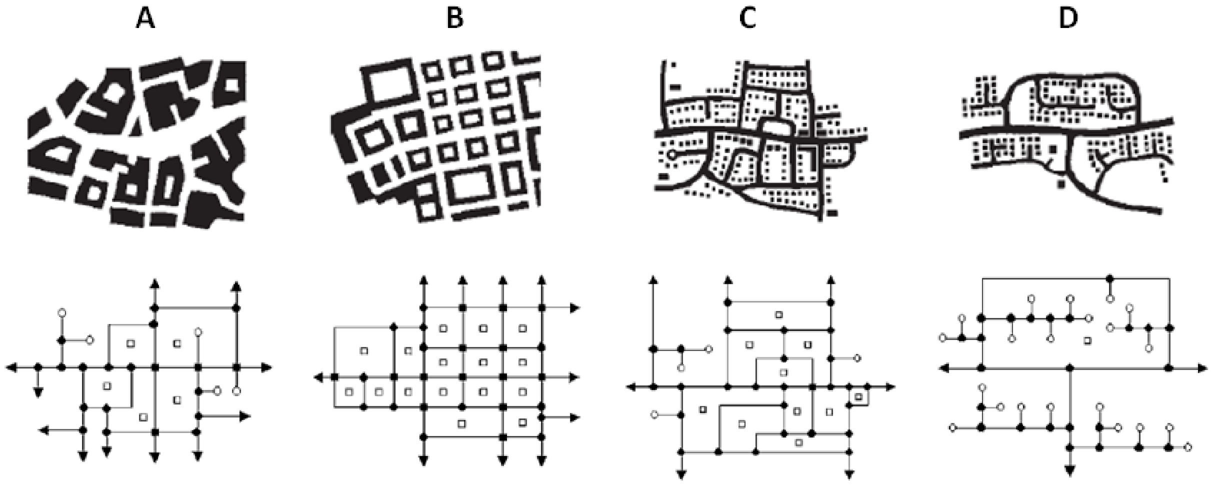


Fig. 26 – Creation of hybrid patterns as permutations of macro and micro scale structures (left). Permutation between basic configurations and street junctions (right) . Source: (Marshall 2005).

Overall, the advantage in the recognition of these basic patterns is that they possess quantifiable characteristics in the form of simple topological attributes as, for instance, the number of cells (spaces surrounded by streets, or cycles in graph terms), of dead-ends (culs-de-sac), or the number and type of junctions. Thus, it is possible to define some simple parameters which are able to quantify the position on the morphological continuum of permutations between those basic types. Marshall introduces four of such parameters: the 'T and X ratios' and the 'cell and cul ratios' (Figure 27, next page). The 'T' and 'X' ratios simply express the number of 'T or X-junctions' in a given street pattern as a proportion of the total number of junctions. In street patterns comprising only T-junctions, $T_{ratio} = 1$ and $X_{ratio} = 0$, while in networks with only X-junctions, $T_{ratio} = 0$ and $X_{ratio} = 1$. In almost any real street layout, both ratios will lie somewhere between 0 and 1.

The cell and cul ratios work in the same way, only now expressing the number of cells (i.e. graph cycles) and the number of culs-de-sac (i.e. nodes with no ‘successors’, or ‘end-nodes’) as proportions of the total number of cells plus the total number of culs-de-sac. In a pure tributary grid with no cycles, $Cell_{ratio} = 1$ and $Cul_{ratio} = 0$; conversely, in a pure cellular layout (such as a pure grid), $Cell_{ratio} = 1$ and $Cul_{ratio} = 0$. As before, usually both cell and cul ratios will lie somewhere between 0 and 1. These simple measures, describing the elemental morphology of street patterns, may be plotted on a two-dimensional diagram in order to facilitate the visualization of their location on the space of all possible forms (Figure 28).



Example configuration	A	B	C	D
No. of three-way junctions (●)	16	13	27	24
No. of four-way junctions (■)	4	14	1	0
Total no. of junction nodes	20	27	28	24
T-ratio	0.8	0.48	0.96	1.0
X-ratio	0.2	0.62	0.04	0.0

Example configuration	A	B	C	D
No. of cells (□)	5	16	10	1
No. of culs-de-sac (○)	5	0	4	21
Total	10	16	14	22
Cell ratio	0.5	1.0	0.71	0.05
Cul ratio	0.5	0.0	0.29	0.95

Fig. 27 – T / X ratios and Cell / Cul ratios, quantified for four examples of street patterns. Source: (Marshall 2005).

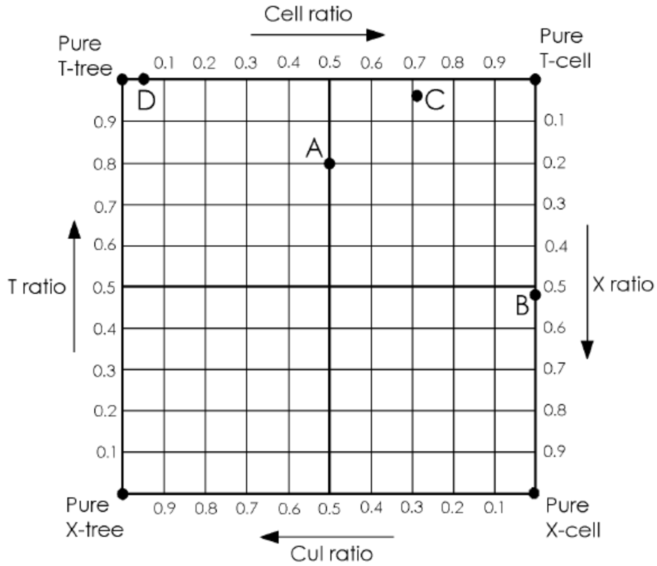


Fig. 28 – Two-dimensional plot relating the X / T ratio and Cell / Cul ratio. The letters A, B, C and D refer to the four examples of street patterns of Figure 27. Source: (Marshall 2005).

From here, Stephen Marshall carries on with the structural exploration of street patterns, arriving at a new technique to describe and quantify the structure of routes, which we will not use in this study. But what is important in Marshall's work, is that it shows that urban typomorphology may also adopt *quantitative analytical methods*, as suggested at the end of section 1.4.1. The first consequence of this, is that urban types may be then described by *numbers and not by words* (or by exemplificative drawings, which are as vague as words). The canonical nature of each type becomes a set of numbers (or values of morphological parameters): objective, exchangeable and common to all - in contrast with an ill-defined morphological idea, which may have different materializations within each of our highly variable minds. The second consequence, is that urban typomorphology may then attain a *truly scientific status*, because its findings will become *objectively defined*, *reproducible*, *testable* and *falsifiable* by others.

We may now summarize the potential advantages and shortcomings of the 'configurational approach' to urban form, regarding this work's objective. In this particular case, the following qualitative assessment refers to two different types of analysis (space syntax and street pattern analysis) whose qualities are also quite different, and therefore will be distinguished when necessary. Regarding their potentialities to metropolitan morphological analysis, the following aspects are worth noting:

- Both space syntax and street pattern analysis are *quantitative methods* of morphological analysis, whose results are *numerical*. This is a very important aspect; firstly, because it makes both techniques compatible *a priori*; secondly, because their results may be statistically compared to quantifications of any other kind of urban phenomena.
- Both techniques have *streets and street systems* as their sole *objects of analysis*. Generally speaking, this may be seen as a constrain, for urban form is not limited to those elements. But those are also the most structuring of all elements, and the ones for which causal relationships were found with urban functioning. Thus, in the specific case of metropolitan morphological research, which needs to be selective in order to cope with the size and variability of its study object, that is a clear advantage.
- Both techniques have a *high level of spatial resolution*, having for minimal spatial unit the street segment. However, street pattern analysis is *restricted* to the study of street layouts at the *micro-scale*, being that its natural scope of application. But space syntax is a *scale-independent* analysis technique, the only limitation being the size of the available spatial model. Analysis can be run over the same model at *any spatial scale*, from the individual street segment up to an entire metropolitan region. This is, perhaps, the most relevant space syntax's quality, regarding the study of metropolitan form.
- Space syntax has for main analytical theme, the *centrality patterns of street networks*. Again, this may be considered a reductionist approach. However, as we have seen before, one of the specific characteristics of metropolitan regions is the fact that they have complex, *poly-centric structures*. Thus, space syntax's capability of *revealing those structures* - not only at the regional level but *across all scales*, from local micro-centres up to macro, regional centres - has great potential advantages for the study of metropolitan morphology.
- Street pattern analysis is a perfect example of the possibility of quantifying urban form's microscopic properties, allowing for the inception of a *numerically defined urban typomorphology* (in this specific case, of street patterns typomorphologies). As mentioned before, this is a fundamental step forward, which will be further developed in this work.

There are, however, also a few limitations of these two 'configurational approaches' to the analysis of urban form, which are worth of note. Namely:

- Space syntax and street pattern analysis are *static analytical methods*. Both methods simply *describe* the topology and/or the centrality patterns of street networks, not their *temporal evolution* of *formation dynamics*. However, as mentioned before, these are very important aspects for the study of urban form, which are at the core of the two previously reviewed approaches. Therefore, if the techniques included in the 'configurational approach' seem promising for this work's objective, the *temporal evolution* of metropolitan street networks must also be addressed, even if indirectly.
- Scale-independency and centrality assessment are the two aspects that make space syntax an ideal tool for studying metropolitan morphologies. But space syntax only addresses street networks as *collective entities*; i.e. analysis only makes sense when the entire network is taken into account. However, as mentioned previously, an 'integrated analytical framework for metropolitan morphology' must include the possibility of investigating potential *causal links* between the metropolitan macro morphology (accessible to space syntax) and the morphology of the *individual incremental operations* constructing it through time. This latter aspect cannot be addressed by syntactic analysis and therefore another method must be used. Street pattern analysis seems a good candidate, as well as any other type of *quantified typomorphology*.
- The *analytical prodigality* of space syntax's most recent techniques is another factor that makes it interesting for this work. However, such prodigality entails with it the production of *huge amounts of data*, which are not manageable by traditional methods (e.g. visual analysis of centrality patterns, simple descriptive statistics). Moreover, within these very large data amounts, interesting patterns and structures may be hidden, even if the same traditional methods are unable to capture them. Thus, in order to exploit space syntax's full potential and to investigate such possible hidden structures, the results of syntactic analysis must be investigated by *new methods*, capable of *handling and of scanning very large datasets*.

1.5. SYNTHESIS

The previous literature review had two purposes: to provide a quick glance of the contributions that each urban form's analytical approach has given to the study of metropolitan morphology; and to show the extent to which these several analytical approaches are dissimilar and potentially incompatible. It is important to stress that this incompatibility pertains to the way the results of each method are conveyed, and not to the results themselves. If that was the case the situation would be indeed worse, because it would mean that at least some of those approaches were simply wrong, or inadequate. That is not the case. None of those approaches denies or opposes the findings of the other, even if sometimes they seem to ignore them (e.g. the rare internalization of urban movement networks in CA and ABM models).

The problem has to do with the way each of these techniques should integrate each other's findings, on one hand; and to the output format of each technique's results, on the other. The former issue is in large part an effect of the latter. This creates a great fragmentation within the discipline, clearly hindering its advance. Each analytical technique explores different aspects of urban form and none of those aspects is secondary; but they are approached by so different means, entailing so different research 'languages', that the analytical outputs are very difficult to translate. As Karl Kropf (2009) points out: "If urban form remains monolithic we must be satisfied with a fascinating but ultimately mysterious phenomenon. If we separate aspects but leave them isolated and free-floating, we must be content with listening simultaneously to a number of unrelated conversations". Op. cit., p. 119.

This disciplinary fragmentation has been particularly deleterious in the case of contemporary metropolitan form, which is a recent research subject. As stated before, that is probably the reason for the paucity of knowledge on that matter, because some ‘factions’ study it since their beginnings (e.g. the ‘spatio-analytical approach’) while others are only know starting to look at it (e.g. the ‘classical approaches’), but one cannot inform the other because they speak different ‘languages’.

The objective of this work is to devise an ‘integrated analytical framework for metropolitan morphology’. The word ‘framework’ was not chosen at random, because the aim is not to invent yet more ‘approaches’, but rather to select what each one has to offer to the problem (namely, the study of metropolitan form) and to try to integrate that into a coherent and efficient ‘research package’, allowing for the systematic study of a difficult research issue and for the production of substantive operational outputs. That will be the theme which we will delve along this work. But now it is time to synthesize what has been said previously, in order to define a set of initial necessary conditions to attain the objective.

Three things seem acquired, in what concerns metropolitan physical structure. The first, is its huge territorial extent. Metropolitan regions are vast by definition, and no less than its entire territory should be object of study. This seems almost too obvious to be mentioned, but the regional territorial scope of such object entails an immediate research constrain: that in face its vastness and diversity, the final product of this work will necessarily need to adopt a *selective*, albeit *strategic*, stance towards the aspects of urban form it will address.

The second ‘acquis’ is that metropolitan form is *intrinsically different* from traditional urban form and that it will never resemble its elder counterpart. Actually, traditional urban form is no more than just one type among many others, within the metropolitan morphological ‘zoo’. Independently of the facts that we may like traditional urban form and of our possible academic dislike of contemporary metropolitan form, we must abandon once and for all traditional urban form as a ‘morphological ideal’. Traditional urban form may be aesthetically satisfying, but as operational ‘morphological ideal’ it is absolutely useless out of historical urban cores; any tentative of trying to reproduce it outside its context (even if by no means unheard of) is, to say the least, shallow. On the contrary, what is needed is objective, non-dazzled knowledge on the potentially qualities and flaws of contemporary urban form. All this implies that analysis should be as immune as possible to any kind of aesthetical consideration, and as far as possible based only on *objective* and *structural* aspects of urban form.

The third and last acquired fact, is that within contemporary metropolitan regions the old notion of a city with *one centre* and a surrounding *periphery* has lost any sense. Metropolitan regions have not one centre but many, of different sizes and with different roles. The metropolitan region is *polycentric*, a *networked territory* where urbanization exists at many levels of centrality, density and functional interdependence, usually within highly fragmented administrative contexts. Metropolitan growth processes are decentralized and distributed, ruled by infrastructure and accessibility and not by the gravitational pull of a dominant urban core. Therefore, an analytical framework for metropolitan morphology should have the capability of *naturally analyzing* this type of *polycentric spatial structure*, without being restrained by surpassed models of urban spatial organization.

The literature review also made clear the importance of understanding urban form as the result of a dynamic process occurring through time. Cities are in permanent transformation and growth, and each temporal urban morphological state must be seen as the consequence of a chain of past events that have led to that state and that will also condition subsequent states. In other words, the process of urban formation is *path-dependent* (i.e. has an inner ‘memory’), and is exactly because of this property that inferences about its formation processes can be made. Therefore, the integration of the temporal dimension in the analysis and the possibility of observing the development of urban form across that dimension, seems fundamental in any potential analytical framework for metropolitan morphology.

Finally, if that potential framework is to deserve the qualification of 'integrated', the analytical methods involved must meet several suitability and operational conditions. First, they must be able to cope with metropolitan structural specificities, namely: territorial extent, complex centrality structure and incremental development. Secondly, they must be able to address the specific urban form elements chosen as descriptors of local and global metropolitan morphology. Thirdly, they should be objective and quantitative methods, with comparable numerical outputs, not only between themselves but also with other quantifications of non-morphological urban phenomena, so that their results may be tested against them.

These premises may be systematized as a series of necessary conditions for the establishment of an integrated analytical framework for metropolitan morphology. They result from what has been discussed during the literature review but also from the conjoint analysis of the characteristics and potentialities of the several analytical approaches, summarized on Table 1 (next page). These have been organized according to seven assessment criteria, namely: their object, method and scale of analysis; and their analytical advantages, drawbacks and relevant inputs, regarding this study's objective. The specific contributions of each approach to that objective are highlighted with different colors, corresponding to the following set of necessary conditions:

Territorial scope and scale of analysis - metropolitan regions (as the name indicates) are regional structures. Therefore, the regional territorial scale must be accessible to analysis, as well as the entire spatial spectrum below that level (i.e. from the region to the neighbourhood). In fact, the lower scales are as important as the regional scale, but in any case that upper limit must be within the scope of the chosen analytical techniques.

Morphological elements subject to analysis - The territorial scope of metropolitan regions is vast and their morphological diversity considerable. It is impossible to access all urban form's elements (street, plot and building systems) at the same time over so large territorial scopes (for simple reasons of analytical feasibility, but also because the available historical information on each type of morphological element differs significatively). Therefore a choice must be made on which type of element should be object of analysis, using their different structural relevancies as main criterion.

Time and morphogenetic dynamics - metropolitan regions are emergent structures, built incrementally through time, from the bottom-up. The temporal dimension must be included in any framework for urban form analysis, because urbanization is a gradual process operating over time, in which previous events affect those that follow. Regressive temporal analysis (or diachronic analysis) allows for the observation of morphogenetic dynamics; i.e. the progressive construction of global metropolitan form through the local accumulation of incremental additions and transformations. Furthermore, the simultaneous observation of formation processes at the micro-level and of the evolving global morphology in its regional context, seems the only way to investigate empirically (i.e. through observation and not through modelling) potential micro-macro causal effects.

Suitability and operability of analytical methods - The choice on which methods to integrate in an analytical framework for metropolitan form should address the specificities of metropolitan spatial and physical structures, namely: their regional extent, the large range of spatial scales involved and their complex polycentric structures. The outputs of different analytical methods integrated in the same framework must be objective, comparable, reproducible and their results must be able to mutually reinforce and explain each other. Furthermore, they conjoint use must also be able to provide findings liable of being translated into operational knowledge.

	A - Classical morphological approaches	B - Spatio-analytical approach	C - Configurational approach Ca - space syntax Cb - street pattern an.
1 - Objects of analysis	**A1.1)** All urban form's elements (streets, plots, buildings). **A1.2)** Urban morphogenetic processes. **A1.3)** Urban typomorphologies.	**B1.1)** Geometrical and cellular formalisms (not the elements of urban form themselves). **B1.2)** Urban micro-macro dynamics.	**C1)** Urban spatial networks (streets and other public spaces). **Ca.1)** Entire public space systems. **Cb.1)** Street layout patterns.
2 - Methods of analysis	**A2.1)** Diachronic analysis (map regression). **A2.2)** Visual analysis. **A2.3)** Deduction.	**B2.1)** Numerical modelling (fractals, CA, ABM). **B2.2)** Induction.	**Ca2.1)** Induction and empirical testing. **Ca2.2)** Network analysis (centrality assessment). **Cb2.1)** Quantification of topological and geometric parameters.
3 - Scale of analysis	**A3.1)** Micro-scale (plot/building to neighbourhood).	**B3.1)** Macro-scale (regional)	**Ca3.1)** Scale-independent (street-segment to regional). **Cb3.1)** Micro-scale (neighbourhood).
4 - Output format	**A4.1)** Graphical and diagrammatic descriptions. **A4.2)** Discursive and semantic descriptions.	**B4.1)** Numerical outputs. **B4.2)** Graphical outputs of numerical models.	**C4.1)** Numerical outputs. **Ca4.1)** Graphical outputs of network analysis. **Cb4.2)** Chart visualization of numerical outputs.
5 - Analytical advantages	**A5.1)** Simple but effective methods, if carefully defined. **A5.2)** Temporal dimension is central to analysis. **A5.3)** Typomorphology has evident potential in operational applications. However, methods are currently limited.	**B5.1)** Quantitative modelling. **B5.2)** Temporal dimension is central to analysis. **B5.3)** Results may be compared with actual urbanization patterns and quantifiable urban phenomena, but only at large scales.	**C5.1)** Quantitative analysis of real spatial units (street systems and layouts). **Ca5.1)** Results may be compared with almost any type of quantifiable urban phenomena at any scale, including human behaviour patterns and spatial cognition processes. **Cb5.1)** Eloquent example of how to quantify urban typomorphologies.
6 - Analytical drawbacks	**A6.1)** Current techniques, laborious and non computer-aided, restrict analysis to small samples. **A6.2)** Quantifications are very rare, even if possible. **A6.3)** Lack of quantification leads to non-reproducible and to non-falsifiable results, which are particularly severe in the case of typomorphological studies.	**B6.1)** Current techniques entail a strong reduction of the actual elements of urban form, almost to the point of obliteration. **B6.2)** Street systems are seldom included in the models, in spite of their obvious importance. **B6.3)** Urban form is commonly conflated with land-uses, even if they are admittedly different things.	**C6.1)** Static techniques. However, time may be integrated indirectly. **Ca6.1)** Space syntax addresses only global street networks, local areas cannot be decontextualized. **Ca6.2)** Current syntactic techniques are very powerful, but they also entail a 'data boom'. For exploiting their full potential, results need to be explored by non-conventional methods, which are still to be defined.
7 - Relevant inputs for the research objective	**A7.1)** Streets and public space systems are the most perennial, and therefore with greatest structural importance, of all urban form's elements. **A7.2)** Urbanization is a time-driven process, in which a finite set of modular forms, or types, progressively build the urban object. Types are not immutable and change over time; but they are resilient socio-cultural products, which must be known, assessed and taken into account by urban planning. **A7.3)** Many of the current analytical drawbacks of the classical approaches could be mitigated by the systematic use of GIS technologies. Indeed, GIS and a more quantitative stance could lead these approaches to entirely new levels of objectivity and social relevance.	**B7.1)** Metropolitan regions are complex emergent structures, produced by the actions of a myriad of agents, acting without central coordination or any type of collective awareness of the aggregated results of their actions. **B7.2)** The only way to tackle such decentralized and uncoordinated growth processes is by new types of urban control, as decentralized as metropolitan development itself. **B7.3)** A new type of 'bottom-up physical planning' is conceivable: informed by, and making use of potential causal relationships between metropolitan macro-morphology (not liable of being controlled), and the micro-morphology of individual incremental operations that give rise to it (which can be and are controlled, but which could be also directed towards the progressive production of desired global results).	**C7.1)** Both techniques are quantitative and produce numeric results, pertaining to actual urban form's elements, namely street systems, moreover the most relevant of such elements. Their outputs are mutually compatible and statistically comparable with non-morphological, quantifiable urban phenomena. **Ca7.1)** The scale-independency and the centrality assessment typical of syntactic analysis make it ideal for studying metropolitan morphology, because its main characteristics are the huge territorial scope and polycentric structure. **Ca7.2)** Existing syntactic morphological theories are based on well established empirical findings, therefore allowing for the quick interpretation of analytical results. **Cb7.1)** Street pattern analysis is the best example of how and why urban typomorphologies should be quantified. Independently of its literal application, it may serve as a source of relevant morphological parameters for similar exercises.

Legend: Territorial scope and scale of analysis · Object of analysis (morpho. elements) · Time and morphogenetic dynamics · Methods: suitability and operability

Tab. 1 – Summary of the reviewed morphological analytical approaches. The highlighted topics match the criteria indicated on the legend.

2
METHODOLOGY

2.1. ASSESSING THE INITIAL CONDITIONS

The previous chapter ended with the enunciation of a set of necessary conditions for attaining this study's objective, namely the construction of a *integrated analytical framework for metropolitan morphology*. Several inputs and contributions to that objective were identified, stemming from the existing analytical approaches to urban morphology also reviewed on that Chapter. In the current chapter we will articulate that information more clearly, translating it into the definitive components of a series of analysis modules, which together will constitute that integrated analytical framework. We will start by discussing the results of the previous Chapter's last section (1.5), namely by analyzing in the detail the indentified inputs of the current analytical approaches to each of the conditions enunciated before. On that process, we will continuously refer to Table 1 (page 51). For easier reference to the several identified inputs and to their positions on that Table, they will be noted also by their respective identification codes (the initial letters and numbers, pertaining to the analytical approach from where they stem and to the assessment criteria to which they were allocated).

2.1.1. TERRITORIAL SCOPE AND SCALE OF ANALYSIS

An integrated analytical framework for metropolitan form, must necessarily have to deal with the regional territorial scope of its object of analysis. However, that is a necessary but not sufficient condition. As it was stated previously, the regional scale must be accessible to analysis, but also the entire spectrum of spatial scales below that. In fact, metropolitan regions have complex centrality structures because they are not only composed by regional centres, but by centres at all scales, from local areas up to entire cities.

Regarding this first condition, three relevant inputs were identified: the micro-analytical techniques of the classical approaches (A) and of street pattern analysis (Cb), quite efficient at the neighbourhood scale (A3.1 and Cb3.1); and the analytical scale-independency of space syntax (Ca3.1), a most important characteristic that makes it ideal for studying large-scaled morphologies (analysis may be run at all possible scales, form the region down to the individual street-segment). The techniques included in spatio-analytical approach are equally capable of addressing the regional territorial scale - indeed that is the only scale at which they are successfully applied (B3.1). However, they lose meaning below that scale and have several restrictions considered disadvantageous regarding our objective (namely, B1.1, B6.1, B6.2 and B6.3); thus they will not be integrated in the framework. However, the spatio-analytical approach has very important conceptual inputs to offer to this work, which will be mentioned further ahead.

I. The techniques included in the *classical analytical approaches* and *street pattern analysis* are selected for studying individual metropolitan *micro-morphologies*; and *space syntax* for studying *global metropolitan form*.

Nevertheless, these techniques have also some disadvantages that must be tackled. Regarding the classical approach those are points A1.2, A4.1, A4.2, A6.1, A6.2, A6.3, from which we would highlight the discursive format of results (A4.2) and the lack of quantification and numeric methods, leading to the non-reproducibility and week definition of results (A6.2, A6.3). The static character of both configurational techniques (C6.1) is also worth of note; and regarding space syntax specifically, the ‘data-boom’ problem created by its current analytical techniques (Ca6.2) should also be taken into account.

2.1.2. Morphological elements subject to analysis

The second condition is a direct consequence of the first. Because of the huge territorial extent and immense morphological variability characteristic of metropolitan regions, an integrated framework for studying their morphology must entail a reductive choice among the three elements of urban form (street, plot and building systems), because it impossible to address them all simultaneously. Thus, in order to minimize the effects of such choice, it should be aimed at selecting those elements with the greatest structural importance and functional relevance.

Regarding the second condition, the following inputs were identified: the fact that streets and street systems are undoubtedly the most perennial and structuring of urban form’s elements (A7.1), and the fact that the configurational techniques of analysis being entirely dedicated to their study (C1, Ca.1 and Cb.1).

II. *Streets and public space systems* are selected as unique object of metropolitan morphological analysis, for the following reasons: i) because of their structural morphological importance and proved relevance regarding urban functional distributions; ii) because of the availability and capabilities of the above mentioned techniques to analyze such systems; iii) and because streets are always represented exhaustibly and with significative accuracy in old cartographic sources (which is important for the third condition), unlike the other elements of urban form (particularly plot systems, seldom represented in old or current cartographies).

Regarding these choices, the following caveats should be noted. The fact that space syntax only addresses street networks as collective (or relational) entities (Ca6.1), not allowing for their decomposition or analysis of isolated parts. This restrain its use to the analysis of global metropolitan form; the morphological analysis of individual developments constructing the network through time (which is part of the third condition) will be addressed by classical and street pattern analyses, whose consistency of results with space syntax must be assured.

2.1.3. Time and morphogenetic processes

The review of both the classical and spatio-analytical approaches has made quite clear that cities and metropolitan regions are emergent structures: built over time through incremental micro-processes, leading to their permanent change and growth. The classical approach has also revealed the strong path-dependency of such processes, in which some structures (particularly streets) are highly conditioning of the urban system’s future states. Therefore, time is a unavoidable dimension in urban morphological studies. Moreover, adding the temporal dimension to morphological analysis makes possible the observation of those micro-processes and of the global consequences of their action. Therefore, both morphological evolution across time and morphogenetic micro-processes, must be within the reach of an integrated analytical framework for metropolitan form.

Regarding the third condition, both the classical and spatio-analytical approaches provide important theoretical concepts, namely: the notions of urban morphogenesis and urban micro-macro dynamics (A1.2 and B2.1); the notions of urban type and typological process, pertaining to the fact the set of morphologies that incrementally construct the city through time is finite (and not randomly variable), which has important consequences to urban management and planning (A1.3 and A7.2); the notion of cities as complex emergent structures, produced by decentralized and uncoordinated actions (B7.1), and that the only way to deal with such decentralized processes is through also decentralized, local morphological control (B7.2).

III. Therefore, regarding the third condition, it becomes clear that the analytical framework that we aim at building must internalize *time as a fundamental dimension of analysis*, as well as being capable of *modelling the temporal evolution of street systems*. Moreover, it should also be capable of: i) observing the *individual units* (described by their street layouts) that incrementally build-up metropolitan street systems through time; ii) of analyzing their *individual morphologies*; and, iii) of indentifying morphological regularities in order to define *metropolitan typomorphologies*, liable of informing current planning and design practices.

The classical analytical approaches study urban morphogenesis and typologies since their beginnings and therefore have analytical techniques to deal with those issues (A2.1, A5.1), even if those techniques also raise some doubts with which we will need to cope (A4.1, A4.2, A6.1, A6.2, A6.3). But the main hindrance is the fact that both space syntax and street pattern analysis are static analytical techniques (C6.1), a question to be discussed within the context of the next condition.

2.1.4. Suitability and operability of analytical methods

The fourth and last condition as to do with possible hindrances and disadvantages of the chosen analytical approaches, regarding their suitability to this work's research object (metropolitan form) and objective (constructing an integrated analytical framework for that object). The basic conditions are the following: that the chosen techniques are coherent and consistent, regarding the previously enunciated conditions; that they are able to deal with metropolitan spatio-structural specificities, namely regional spatial extent, wide range of spatial scales and complex polycentric structure; that their analytical outputs are mutually comparable and synergetic (preferentially expressed in numeric terms); and that those outputs may also be tested against other data describing urban non-morphological phenomena, while being reproducible and operational.

Regarding the suitability of the chosen methods to the research object and objectives, the following strong points should be noted: classic approaches use simple but effective methods to explore urban micro-morphology, namely diachronic analysis through the technique of 'map regression' (A2.1, A5.1); urban typomorphology is paramount for studying and classifying individual morphologies at the micro-scale (A5.3); space syntax's analytical procedures are scale-independent (Ca3.1), focused on spatial centrality structures (Ca2.2) and their outputs are numerical and comparable with other quantifications (Ca2.1, Ca5.1) - thus they, seem particularly appropriated to our objective (Ca7.1); street pattern analysis studies the morphology of street networks at the micro-scale (Cb3.1) and is also a quantitative method, with numeric outputs (Cb2.1, Cb4.2).

Regarding the operability of the chosen analytical methods: typomorphology has evident operational outputs, because it defines the range of individual morphologies constructing the city through time, which may be used to inform urban policies with morphological aims (A5.3); it has some technical limitations, but if supported by GIS those limitations may be highly reduced and the analytical scope expanded (A7.3); space syntax has also evident operational outputs, because its methods and theoretic inferences are empirically supported (Ca2.1, Ca5.1, Ca7.2); street pattern analysis is an eloquent example of how urban typomorphologies may be quantified and systematically classified (Cb5.1), shedding light on how to improve classical typomorphological methods (Cb7.1), thus having at least indirect operational outputs.

IV. Therefore, regarding their *suitability* to the study object, the chosen techniques seem to *complement each other*: classical typomorphology and street patterns analysis are suited for studying micro-scaled and individual street layout morphologies and space syntax is perfect for studying global street networks of any size and at any scale, while being specifically focused on the study spatial centrality patterns. The objective of their conjoint use and integration in the same analytical framework seems quite achievable, provided that *typomorphological analysis is quantified*. Then, they may become complementary methods, seemingly capable of providing operational results.

But there are also difficulties to overcome, namely: the effective numeric quantification (A6.1, A6.2, A6.3) and integration of typomorphology with space syntax, even if this can be greatly facilitated by GIS (A7.3) and by the example and use of street pattern analysis (Cb7.1); dealing with space syntax's static nature (C6.1), by providing data for syntactic analysis already encapsulating that dimension; and resolving the 'data-boom' entailed by current syntactic analysis, in order to take full advantage of its potentialities (Ca6.2).

2.2. Defining the analytical modules

The analytical framework that this works aims at constructing must necessarily have a composite structure, made up of several modules corresponding to different analytical purposes. Each of these modules will be responsible by a series of functions and processes, producing different types of outputs. These inner functions correspond in general to methods and techniques already reviewed. However, there are two other technological resources which will also be central in this work. They were not reviewed before because they are not urban morphology techniques; however, they can have very useful applications in urban morphology, as we will see in the following chapters.

The first of these resources is *Geographic Information Systems* (GIS). GIS provide today an increasingly data-rich and computation-rich environment. They are capable of handling huge digital geographic datasets and of dealing with quite sophisticated computational procedures. The several analytical modules and their respective outputs will be integrated within GIS, in order to store, visualize and analyze the data produced by each one, and to provide a single transversal platform for the entire analytical framework. We will use standard GIS analytical operations (e.g. spatial querying, layering, buffering or joining), but also other less common applications, as spatial statistics and interpolation techniques.

The second technological resource is *data mining*, a termed coined to define a set of statistical methods which are used for data exploration purposes (Fayyad et al. 1996). The term refers more to a certain analytical stance than to the methods themselves (which were devised well before computers): data mining is based on the idea that among the oceans of data produced today on a daily basis around the world[30], there may be hidden patterns and structures; and that those patterns may be discovered, interpreted and distilled into relevant knowledge. Part of these data masses comes from sensor networks, cameras, microphones, mobile devices, e-commerce and other sources. But another part is scientific data, produced in increasing amounts on several fields, especially in particle physics[31], astronomy and genomics. The only way to analyze such 'big data[32]' is by computer-aided, data mining techniques; otherwise, these disciplines hardly could advance further today. Similarly, such techniques may be quite useful for exploring the huge amounts of data produced by recent space syntax techniques, or for analyzing large morphological samples described by numerical parameters.

[30] A rough estimative points to the fantastic number of 2.5 quintillion (2.5 x 10^{18}) bytes created every day around the globe.

[31] For instance, the four detectors of the recently built Large Hadron Collider (LHC), produce approximately 200 petabytes (200 x 10^{15}) per year.

[32] 'Big data' is a colloquial term in computer science to refer the massive datasets produced today in many fields of society and science.

Both GIS and data mining applications will be further detailed in the following chapters. But they should be mentioned now, because they will integrate the analytical modules of our integrated framework for metropolitan form. These modules will correspond to the following analytical purposes.

2.2.1. Incorporating time in network data

The encoding of the temporal dimension into the data that will be subjected to analysis by the several chosen techniques, is a fundamental first step. Because space syntax and street pattern analysis are static techniques, the networks that they will analyze must be previously modeled at different historical periods. These will be done through a process similar to the 'map regression' used in the classical approaches, but now focusing only in street networks representations (as axial maps). This technique has been previously used in space syntax studies, but with several limitations.

Usually, a first axial model corresponding to the current state of the spatial network is produced; then, axial lines are erased by overlaying the model over old cartographies and identifying the spaces that were not present in each of those cartographies. However, this is usually done in CAD platforms and not in GIS; lines are definitively erased in each version of the network, and no record is kept regarding the changes made to each line or the reasons why such changes were made. Thus, instead of accumulating diachronic information this method entails the loss of information, as networks are modeled into increasingly distant time-periods.

However, by taking advantage of GIS capability of storing information both in spatial and tabular formats, it is possible to record all additions and transformations made to the spatial network over time, without entailing any information loss. Instead of deleting axial lines, an attribute recording their period of occurrence may be used, as well as other attributes recording the type of transformation concerned (e.g. construction, total or partial demolition, alteration). In this way, instead of producing several network models, a single diachronic database may be created, storing all temporal network states simultaneously and all the desired information regarding each individual line or segment.

Such diachronic network database will have two of outputs: producing several temporal versions (at predefined historical periods) of the entire metropolitan spatial network for subsequent analysis by space syntax; the identification of the individual elements created between each historical period, to be individually studied by classical and street pattern analysis.

2.2.2. Analyzing the evolving global morphology of metropolitan spatial networks

The spatial centrality patterns of the several temporal versions of the spatial network, extracted from the diachronic database described above, may then be analyzed using space syntax's techniques. This will reveal the progressive transformation of the spatial network from an initial pre-metropolitan state towards its final, contemporary state.

However, as mentioned before, current space syntax's methods entail the production of huge amounts of data, making their traditional management, further analysis and interpretation very difficult. Other methods must also be employed, not only to post-process and organize those data, but also to further explore them in search for relevant hidden structures. This will be done through statistical exploratory and data mining methods. Therefore, besides traditional space syntax's centrality assessments, the morphological analysis of the global metropolitan spatial network will also produce different and innovative results, providing as final output concise but exhaustively distilled descriptions of the evolving global metropolitan centrality structures.

The processing of the graphs corresponding to each temporal version of the metropolitan street system will be done with standard space syntax software. But the subsequent post-processing, exploration and visualization of results will need the support of other methods and computer applications, whose use will be described later. Also here GIS will have a central role, for gathering, storing and visualizing information.

2.2.3. Analyzing the individual morphology of metropolitan incremental developments

Besides creating several temporal versions of the metropolitan street network, the diachronic network database will also incorporate all differences between each of those temporal versions. Obviously, these differences correspond to the spaces (streets, roads or other open spaces) created between each historical moment. The sub-networks corresponding to these structures will be further divided and identified with the individual development operations they belong, through methods included in the first analytical module. This will be the raw data to be analyzed through quantitative typomorphological techniques.

Two types of analytical procedures will need to be developed. Firstly, the devising of a set of parameters capable of allowing an effective quantitative description of the individual morphologies of each development operation, that should be akin to the characteristics explored by space syntax methods, namely topo-geometric aspects of spatial systems. Secondly, the choosing of objective, reproducible and automatic classification methods, capable of exploring very large samples of individual observations. Also here, we will employ techniques borrowed from data mining and exploratory statistics will be used. Those methods are capable of finding non-evident regularities in very large datasets, otherwise inaccessible. Therefore, they are called *unsupervised* classification methods, because the final classification does not use any previous criteria but is derived only from the data themselves. Thus, providing that the individual morphologies of metropolitan developments are quantified, such methods seem the ideal tool for discovering previously unknown typomorphologies which, moreover, have the advantage of being defined not through visual analysis and intuitive criteria, but through well defined classification algorithms.

2.2.4. Analytical modules and their internal functions

We can therefore devise *three analytical modules*, each with different purposes and outputs (Figure 29, next page). Their analytical functions complement each other, together forming the basis of an integrated framework for metropolitan morphology (Figure 30, next page). All dimensions of metropolitan form become accessible, including the possibility of understanding potential relationships between the emerging global metropolitan object and the individual developments producing it through time. The analytical modules composing the framework are:

1 - A *diachronic modelling* module, whose purpose is that of integrating the temporal dimension in the analysis of street networks, by reconstructing their past states at different historical moments within a single, GIS database. This module has the following internal functions: i) gathering, storing and georeferencing in GIS the original datasets describing the metropolitan street system at different moments in time; ii) modelling the current state metropolitan street network, using the available sources (preferentially orthophotographies or satellite imagery) and any of the available techniques for that purpose (in this case axial modelling, but any other spatial network representation is allowed); iii) reconstructing the street network past states at previously chosen temporal periods (i.e. diachronic network modelling), using the method developed and described in Chapter 3; iv) identifying and individualizing each individual development operation made to the metropolitan street network between each of the previously chosen temporal periods, using a method also described on Chapter 3.

2 - A *macro analysis* module, where the several temporal versions of the metropolitan street network, extracted from the database produced before, are analyzed using space syntax methods and further explored with statistical and data mining techniques. This module has the following internal functions: i) encoding into graphs the graphic representations of the several temporal versions of the metropolitan

street networks; ii) processing those graphs for centrality analysis on a software platform for that effect (these two functions are automatic); iii) mining the resulting data, which will typically have a large dimensionality (time, plus a wide range of centrality dimensions for several metrics and many spatial scales); iv) visualizing and interpreting the results of that data mining exercise, studying the temporal evolution of the centrality structures thus revealed; v) summarizing and distilling the discovered metropolitan centrality structures into meaningful and easily understandable knowledge.

3 - And a *micro analysis* module, where the morphology of the individual development operations (extracted from the database and represented by their street layouts) will be quantified and classified by unsupervised methods, in order to obtain rigorous and well-defined urban typomorphologies. This module has the following internal functions: i) defining a set of quantitative morphological parameters, which will be used to describe the individual development operations; ii) using GIS techniques for semi-automatically quantifying the values of those parameters for each object in the datasets of metropolitan development operations; iii) pre-processing the resulting quantitative morphological descriptions with simple statistical techniques (e.g. checking distributions and outliers); iv) mining the resulting datasets with automatic, unsupervised classification techniques, in order to discover and define, objective urban typomorphologies, describable in numeric terms; v) summarizing those urban typomorphologies into meaningful and easily understandable knowledge.

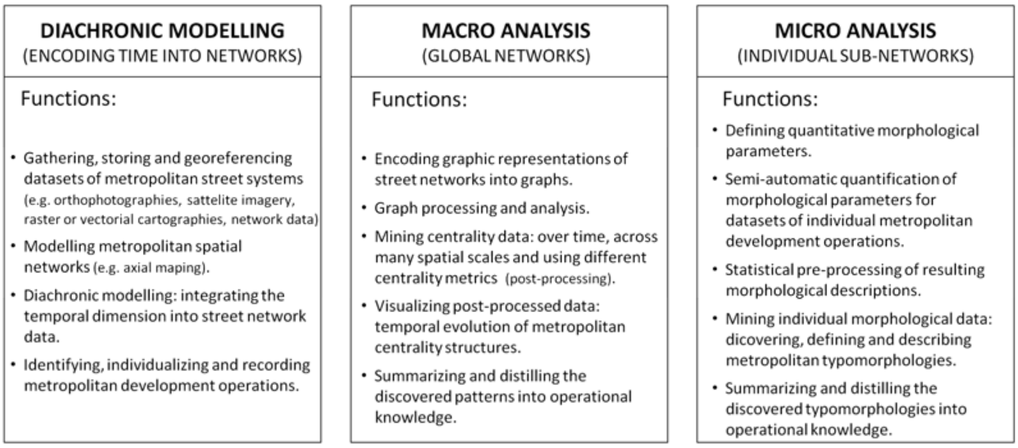


Fig.29 – Analytical modules and their internal functions.

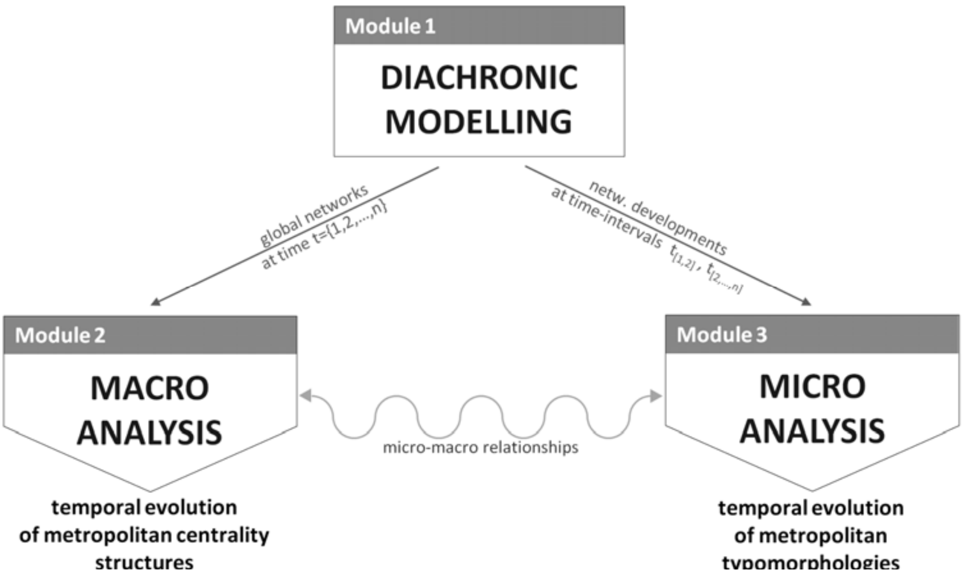


Fig.30 – Functional diagram of the integrated framework for metropolitan morphology.

2.3. RESEARCH WORK-FLOW

The remaining of this work will focus on developing and testing the above mentioned analytical modules. Each of the next chapters will be dedicated to one module; except Chapter 4, which will constitute a pause in the framework's development (necessary for methodological reasons described below) and Chapter 7, containing the research's conclusions (Figure 31).

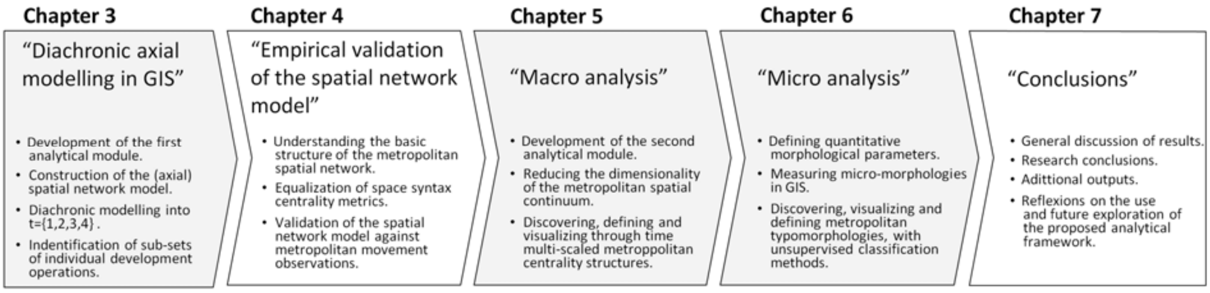


Fig.31 – Research work-flow.

Chapter 3 will be dedicated to the development of the first module of the proposed framework. The construction of the spatial network model (in this case produced by axial mapping) will be described, and new GIS method for creating diachronic street network databases will be proposed. Such method is based on the 'map regression' technique of classical urban morphology; but because it uses GIS data tables and not only graphic functions, it accumulates information instead of discarding it as it recedes in time, storing that information into a single spatial database. This method includes also another feature, namely a process for indentifying and tagging (i.e. assigning and ID attribute) every individual development operation made to street networks between each time period, through the visual inspection of current orthophotographies; that information is also integrated in the same spatial database and made available for querying and extraction.

Chapter 4 describes a fundamental step in this research, albeit not part of the proposed analytical framework. It is dedicated to the empirical validation of the current state of the spatial network model, produced in Chapter 2. Because that will be the basis of the entire research, from which all other past states of the street network will be modelled, we cannot progress without being sure that such model is capable of emulating current metropolitan functioning. Therefore, the version of the model representing the present state of the metropolitan spatial network will be tested by correlating its processed results (using space syntax centrality analysis) with observations of metropolitan vehicular movement flows (obtained from independent and official sources). Furthermore, because several types of graphs may be generated from the axial map, which in turn may be analysed according to several centrality and radius definition metrics, the third Chapter will also study all these analytical possibilities and test them against the empirical data. This will entail the development of methods to equalize such metrics, in order to make them comparable and thus conjointly testable.

Chapter 5 will then develop the second analytical module of the proposed framework. It will start by acknowledging and describing the large-dimensionality problem created by the analysis of very large networks, with space syntax's current (and powerful) methods. In doing so, it will also define a new representational concept of metropolitan spatial structure (to which we have called 'metropolitan centrality palimpsest'), in which the centrality variability of each space in the network, along the entire spectrum of spatial scales, is taken into account. Global metropolitan spatial structure is identified as a data cube of large-dimensionality, which space syntax may reproduce entirely but whose internal structure needs to be explored by other methods, capable of dealing with large amounts of data. The remaining of Chapter 5 is dedicated to the identification and adoption of such methods (constituting the bulk of the analytical functions of the third module of the proposed framework), and to the exploration of the 'metropolitan centrality palimpsest' and its evolution across time. This will lead to the production of concise, but thoroughly distilled and novel pictures of metropolitan spatial structure.

Chapter 6 develops the third and last analytical module of the proposed framework. Using the datasets of individual development operations produced in Chapter 3, a new method for discovering and defining urban typomorphologies is advanced. As a first step, a number of numeric morphological parameters will be defined, in order to describe the morphologies of the individual development operations observed along this study's time-span (represented by their street layouts). Then, using semi-automatic GIS techniques, their morphologies will be quantified according to the previously defined parameters. The data objects thus produced will be explored by unsupervised classification techniques, leading to the discovery of objective and automatically defined urban typomorphologies of street layouts. The temporal frequencies and spatial distributions of such typomorphologies are then studied, disclosing clearly different temporal frequencies and spatial distributions among the several typomorphologies. The chapter concludes by suggesting how the proposed method is able to explore, classify and thus make accessible and understandable, the otherwise apparently indescribable metropolitan morphological diverseness.

Chapter 7 presents the research conclusions. A summary of all chapters' methods and findings is followed by their discussion and by the extraction of the work's final conclusions. Because some of the previous chapters will lead to the production of additional outputs not directly related with the research objective, they will be also summarized and discussed. This thesis ends with a final set of reflections on the utility and applicability of the proposed analytical framework for urban planning and design practices, as well as for future research projects.

2.4. STUDY AREA CHARACTERIZATION

The purpose and objective of this study is mainly analytical. It aims at proposing new solutions, methodologically and technically integrated, for the analysis of metropolitan morphology. However, analytical methods must be tested and applied on some kind of object; otherwise, they may well be just vague proposals. Our object is Oporto's metropolitan region, the second Portuguese metropolitan conurbation and the largest of the Peninsular Northwest.

In this section we will make a quick characterization of this urban-region and in particular of the study area that we have defined there in. This will not be an exhaustive characterization, because our aim is just to provide the reader with the indispensable knowledge of the study's geographical and urban general contexts. The methods proposed in this work are intended to be applicable to *any* metropolitan context, and not only to the one described here. In fact, our aim is to produce analytical methods that are *context-independent*, so that the same research methodology may be applied to any geographical location and thus large comparative metropolitan morphological studies may be carried out. However, the territory that will serve as laboratory and test area for the proposed methods must obviously be introduced, in order to provide context for the results discussed in the following Chapters.

Oporto's Greater Metropolitan Area (GAMP) is the current official designation of Oporto's metropolitan region. It encompasses 16 municipalities, over an area of 2.089 Km2 and has a population of approximately 2.295.000 inhabitants. GAMP's territory represents only 9% of Portugal's northern region (the country's most populous NUT II area, 35% of the nation's total). However, GAMP concentrates almost half of that region's population (45%) and more than half (51%) of the wealth generated therein (AMP 2008). Even if GAMP was officially instituted as an administrative region, its true institutional power is insignificant and depends totally on the partial interests of its constituents (the individual municipalities represented by their Mayors). Therefore, in administrative terms, the metropolitan territory in effectively governed at the municipality level.

Furthermore, its administrative delimitation is barely representative of the actual territorial occupation. GAMP is only a part of a much more vast urbanized territory, which starts to the South in *Aveiro*, encompasses Oporto city on the way and reaches *Viana do Castelo* to the North, on a total span of about 170 Km of the Portuguese northern coast (Domingues 2008).

But for the purposes of this work, which is initial and has a limited timeline, we have defined as study area the region contained within a circle of 30 Km radius, centred on the centroid of the polygonal shape formed by Oporto's municipality limits (Figure 32). This is, much like any other, a slightly arbitrary definition of boundaries. However, excluding 'Arouca' (the least populous of GAMP's municipalities, with a population density corresponding to just 8% of the metropolitan's mean density[33]), which is left out of the defined limit, the study area corresponds to 83% of the area within GAMP's administrative boundary; while including at the same time other areas, which are not part of GAMP for the only reason that they belong to some municipality that is not either, even though they present clear continuities of spatial development. The radius of 30 Km, encompassing the generality of the metropolitan region's urban centres (see Figure 35, page 64), was chosen as the territorial extent liable of being modelled and studied within this work's timeline. Furthermore, from the point of view of a spatial network study, such circular shape is rather more stable than the actual administrative limits of GAMP.

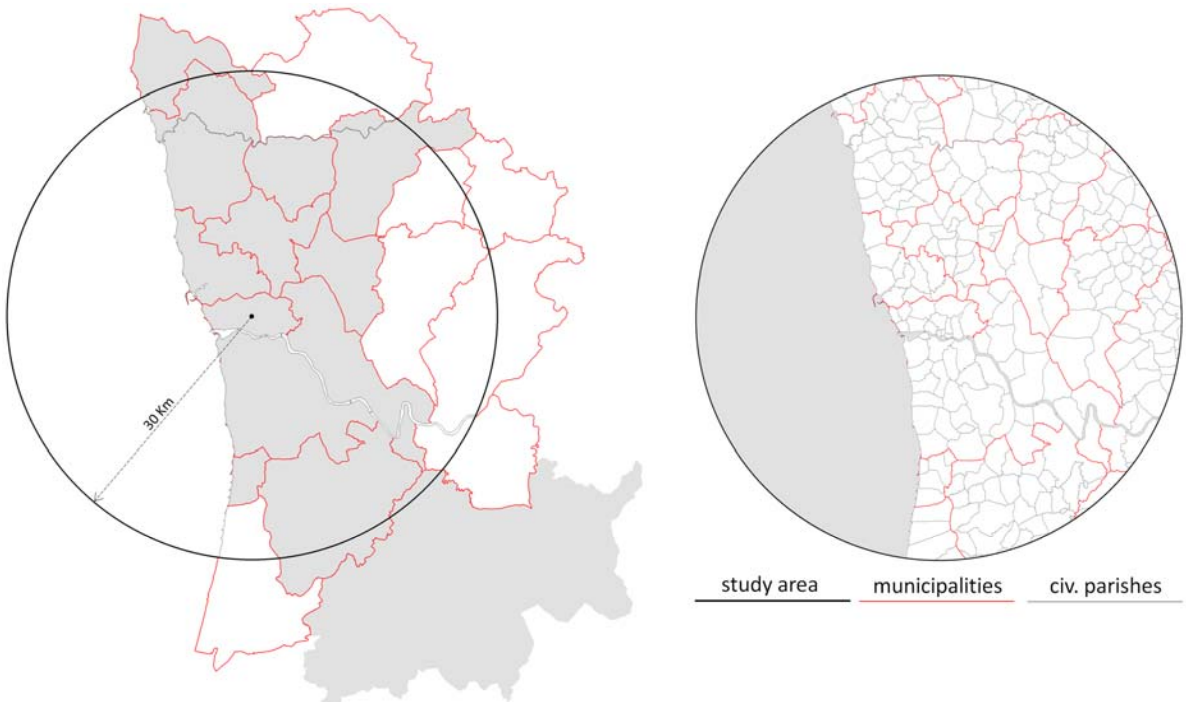


Fig.32 – Study area. On the left image, the grey area denotes the municipalities belonging to GAMP

The geophysical structure of the territory (Figure 33, next page) is characterized by mild topographical reliefs, which become more pronounced towards the east of the study area. A chain of not very high, but rather sharp hills, cuts the territory diagonally from North to Southeast, constituting a physical barrier quite untouched by urbanization. Two main rivers cross the study area, flowing from the east towards the sea: the Douro river, reaching the ocean at Oporto; and the Ave river, following an almost horizontal path, near the study area's northern limit. These rivers constitute also natural boundaries to urbanization, especially the Douro, whose north and south banks show rather different settlement patterns (more concentrated at north and more disperse at south; Figure 34, next page).

[33] Arouca is the large municipality to the southeast of the study area. This municipality is mainly rural and with a very large share of natural and mountainous territory. The average population density of GAMP is 887.5 (Pop. per km^2) while that of Arouca is 68.17 (Pop. per km^2).

There are also some significative extents of natural and forested areas, following the chain of hills mentioned above. Agriculture is also quite present, even if with a very fragmented pattern of small parcels, highly mixed with other land-uses. These correspond in general to household subsistence farming and not to intensive production fields. Likewise, forestry is explored at the household level, within the same pattern of small parcels mixed with other land-uses (see Figure 36, page 65). The only exception to this fragmented rural structure is an extensive and highly fertile area, north of the Douro river along the coast and around the final course of the Ave river, near the northern limit of the study area. This is a zone of quite continuous and intensive agricultural use, being also relatively untouched by urban development.

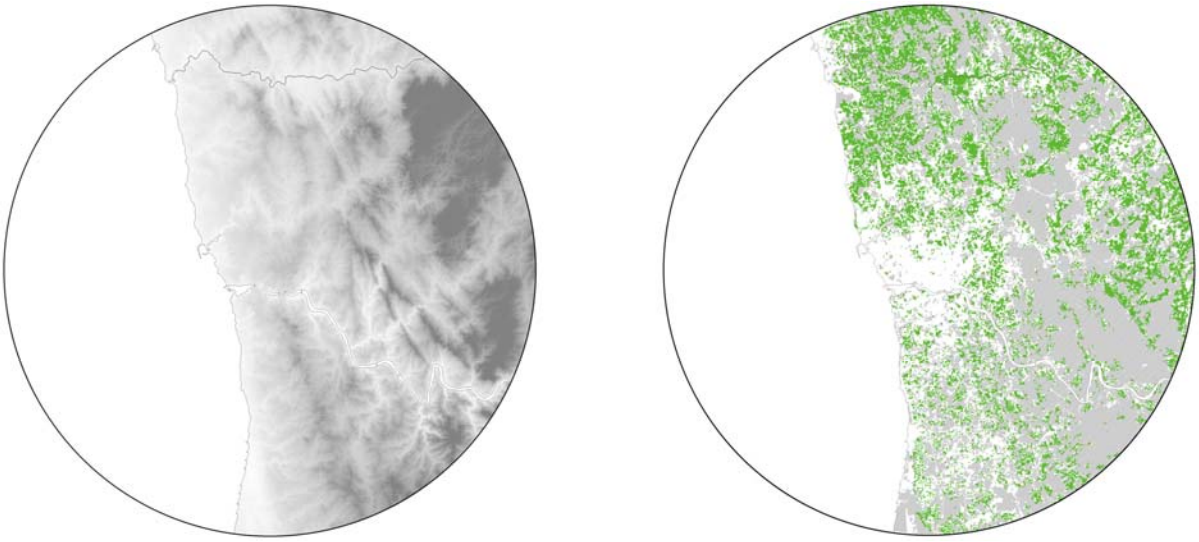


Fig.33 – Study area. Left: topographic relief. Right: non-urban land uses (green: agriculture; dashed: natural and forested areas).

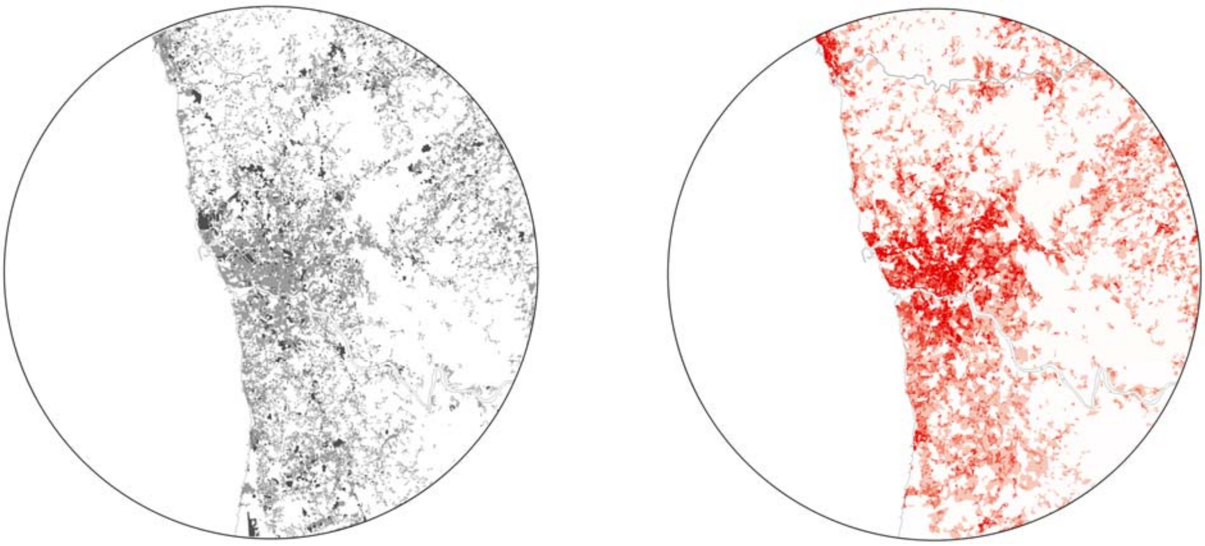


Fig.34 – Study area. Left: built-up areas (industry in dark grey). Right: population density (n. inhabitants / area of statistical sub-section; dark red means higher density).

Unlike Lisbon's metropolitan area, which is clearly gravitational, with a strongly centralizing capital city forcing a binary logic between a dominant core and a diluted surrounding region (Salgueiro 2001), the context of a strong hegemonic centre never existed in Oporto's region, at least not from a functional point of view. This happened mainly because industry, spreading diffusely over the territory and constituting the main source of employment, has never generated the concentration of wealth and services at the main urban core, typical of early industrialized cities (Cardoso 2010).

Adding to this industrial diffusion (which started late, well within the first half of the XX century), a much older, but equally dispersed type of territorial occupation was already in place. The previously mentioned land-tenure structure, characterized by small and irregular land parcels whose division dates back from the Middle Ages. This cadastral division has generated a pre-metropolitan diffuse occupation, made up of many small villages, hamlets and towns, and especially huge amounts of old infrastructures (paths, roads, informal crossings), irrigating a former agricultural territory now eager for urbanization.

The Portuguese geographer Alvaro Domingues (2008) provides some insights into the basic structure of the type of urbanization that has colonized this old infrastructural network. He notes that we should "understand the articulation between two territorial logics. The first one, inherited from the past, is the finest capillary network of […] thousands of kilometres of roads and paths, supporting constructions and mobility patterns, that became very dense in the recent past […] through great changes, but there was no new infrastructures or plans to support them. People would build their houses where there was road access and the micro-property pattern has facilitated this self-building process. The second is the motorway network, and its nodes, moving away from the old urban centres (cities and towns) and producing a different spatial pattern that resulted from velocity and accessibility logics – time becoming more important than space" (op. cit., p. 135).

The type of territorial occupation that these processes generated is illustrated on Figure 34 (previous page; showing the built-up areas and population density, at the level of the smallest statistical territorial unit[34]) and also on Figure 36 (next page). The dispersion of the built-up area was, and still is, supported by a vast and labyrinthine capillary road network of ancient 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 has gained importance over the last two decades, deeply changing regional and local accessibility patterns. Rodrigo Cardoso (2010) has put forward an inspired visual comparison between this type of urbanization - advancing much more by colonization and densification of the ancient infrastructural network than by sheer expansion - and an image of the filigree jewellery, typical of the region (Figure 35).

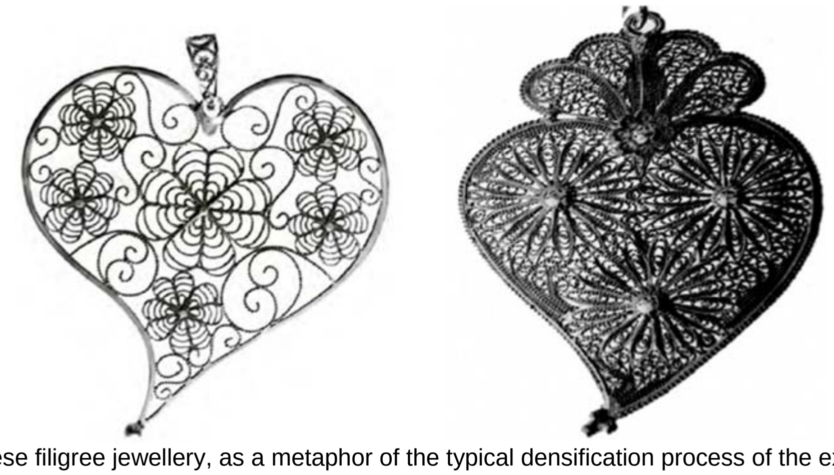


Fig.35 – Portuguese filigree jewellery, as a metaphor of the typical densification process of the existing rural road infrastructure at Oporto's metropolitan region. Source: (Cardoso 2010).

A close-up on a small region to the south of the study area, illustrates even better this amorphous and highly fragmented urbanization pattern (Figure 36, next page). A mix of four land-uses - residential, industrial, agricultural and natural/forested - characterizes the metropolitan landscape. These land-uses jostle with each other, cohabiting in close proximity, free from any kind of functional segregation.

[34] In Portugal, this is called 'statistical sub-section', the smallest homogeneous land-use area within a 'statistical section' (corresponding to civil parishes, see Fig. 32). In urban areas it corresponds to blocks, becoming progressively larger in rural areas.

In face of this image, it is important to note that systematic urban planning is rather recent in Portugal and that the pattern visible on Figure 35 was already installed, when the first generation of Municipal Master Plans was produced (starting at 1990). Obviously, the physical structure of urban centres is rather different. However, those are the exceptions and not the rule. The rule is *zwischenstadt* (Sieverts 2003) represented in Figure 35. How can we deal with this type of urbanization pattern? Surely not by paying much attention to its aesthetical looks. But perhaps by trying to understand its structural origin and current characteristics. Throughout this work, we will try to collect and to integrate analytical methods for that purpose.

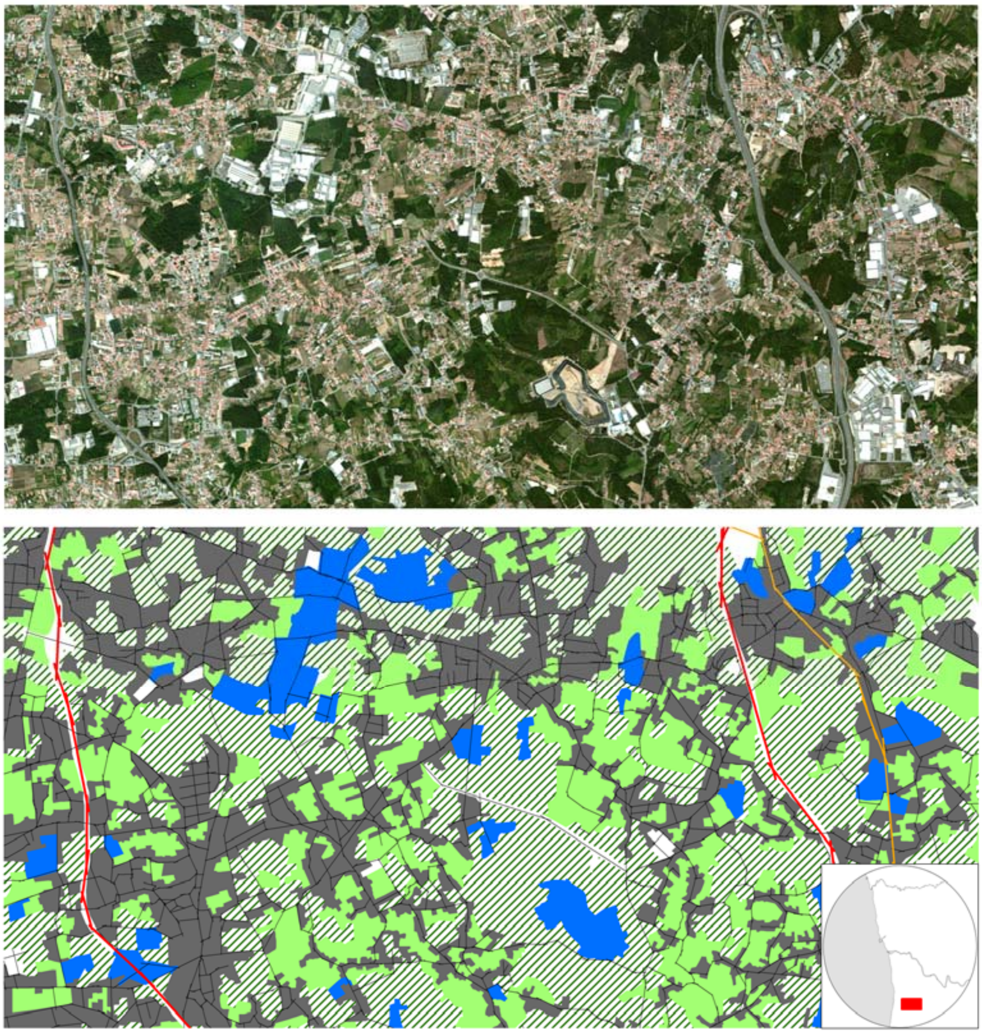


Fig.36 – Metropolitan urbanization pattern at Oporto's region. On the lower image, residential areas are in dark grey, industry in blue, agriculture in green, and natural / forested areas in dashed green.

3
DIACHRONIC AXIAL MODELLING IN GIS

ABSTRACT

In this chapter we describe the construction of the spatial network model, its subsequent deconstruction into increasingly distant time periods and the encoding of the resulting diachronic information into an integrated axial database. We start by introducing the technique of axial mapping and by discussing the general representation criteria adopted to produce the contemporary version of the axial model. We then present the technique developed to observe, record and encode in GIS, the evolution of the street network through time. We show how such technique avoids some of the limitations of traditional diachronic axial modelling and how it allows for the creation of queryable diachronic axial databases, incorporating potentially relevant information about the morphological evolution of street networks. Furthermore, we also show how it is possible to identify, isolate and integrate in such database, all the individual interventions made to the street network along time, through the simultaneous visualization of orthophotographies over the sub-sets of all the lines created or altered in each period. We end by summarizing the outputs of the current exercise, which will constitute the main sources for the subsequent research.

3.1. CONSTRUCTION OF THE AXIAL MODEL

Axial maps are the workhorses of space syntax's urban analysis. Even if several times criticized by their lack of a strong formal definition (Ratti 2004, Batty2004), they have shown to be an extraordinarily successful heuristic for representing urban spatial systems. The accumulated results of the space syntax research programme, developed through the last three decades by an ever growing research community, have demonstrated that axial maps are (by themselves or through their subsequent transformation into segment maps) a consistent, systematic and most fruitful structural representation of urban space (Hillier 2009).

The basic form of the open space system of any urban settlement can be defined two-dimensionally as a polygonal surface with many holes (where the built forms fit), forming a lattice-like and continuous structure (Figure 37, next page). Such a shape can be described in several ways, either geometrical or topological. In geometrical terms, real cases are often very varied and complex, with seemingly little resemblance between them. Topologically, however, strong structural regularities have been found among many geographically and culturally different settings, showing that urban space has a deep and general structural order, albeit not always apparent to the "naked eye" (Hillier 2002, 2009; Hillier and Vaughan 2007). The technique known as axial mapping has contributed significantly to this understanding.

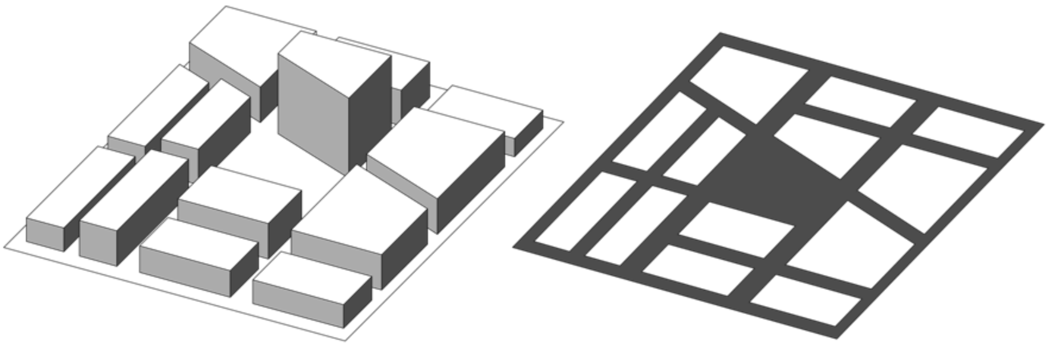


Fig.37 – A fragment of a hypothetical urban settlement (left). The planar representation of its open space system as a polygonal surface with holes (right).

An axial map is a skeletal representation of urban space, in which the convex geometry of its planar representation is approximately described as 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 any possible intersection with any other line is made. Hillier and Hanson (1984) provide the following definition of the axial map:

“An axial map of the open space structure of a settlement will be the least set of axial lines, which pass through each convex space and make all axial links.” (Hillier and Hanson 1984, pages 91-92).

Although many times equated with lines of movement or visibility (to which, nonetheless, they obviously relate) it is important to stress that axial lines are purely geometrical entities, defined only through their adequate placement within a planar geometrical representation of space. Thus, the axial map constitutes a one-dimensional reduction of the bi-dimensional convex geometry of a spatial system or, in other words, a concise description of how much the system is jagged in convex terms. The relevance of such description is that it turns the almost intractable absolute geometrical variation of urban space into a much simpler representation which, nonetheless, encapsulates is basic geometry and whose topology can easily be studied through its encoding into a graph.

Axial lines can be collapsed into the nodes $V = \{1, \ldots, N\}$ of an undirected graph $G(V, E)$, 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 (i.e. when it is possible to move freely from one line to the other). The adjacency relations between all lines are encoded by edges $(i, j) \in E$, if and only if $i \sim j$. Figure 38 illustrates the process of axial representation and its subsequent graph encoding. In the following chapters, we will develop further the formal definitions of the graph properties and metrics used in space syntax.

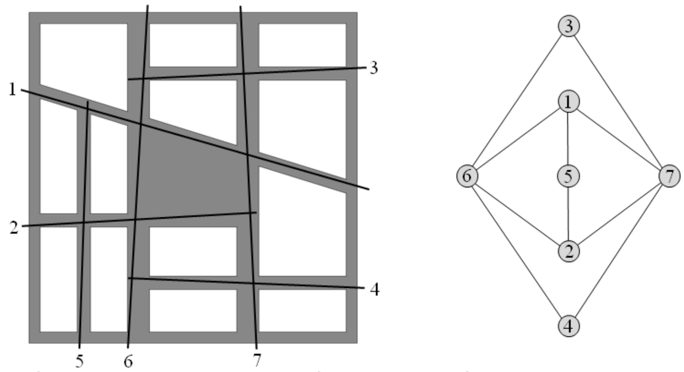


Fig.38 – Axial description of the open space system of Figure 37 (left). The resulting axial graph (right). Numbers on axial lines indentify the corresponding graph nodes.

The technique of axial mapping has undoubtedly proved to be efficient in unveiling and describing the topological properties of urban space, and is easily and intuitively controllable by anyone willing to apply it. However, it also has several practical drawbacks and even some theoretical complications. Axial maps are ultimately hand-drawn[35], entailing a laborious and time-consuming process. Even if apparently well-defined and easy to grasp by people, the criteria and process for axial line placement has proven to be very difficult to implement computationally. Batty and Rana (2004) have shown that a set of axial lines fulfilling Hillier and Hanson's (1984) criteria cannot be precisely defined. Indeed, it has been proved that there is no formal procedure for generating a unique partition of a polygon with holes into a sub-set of convex polygons (O'Rourke 1987) and that the problem of axial line placement is, in fact, NP-Complete[36] (Sanders 2000). Nonetheless, approximation algorithms have been proposed by (Peponis et al. 1998) and more effectively by (Turner et al. 2005), but these remain restricted to small problems (in the order of a few thousand lines) and serve more as proofs of concept than as real operational solutions.

More recently, it has been proposed by some authors (Dalton et al 2003, Turner 2007) that standard road-centre lines[37] could be used with angular segment analysis (ASA), which we will discuss later, thus taking advantage of the readily-available and very large geographical datasets of such kind. This has opened the way to the study of huge spatial systems, ultimately only bounded by data availability and by computation power (both currently massive). This method, however, entails with it the total abandonment of precious structural information contained in the axial map (such as axial connectivity), together with several analytical parameters (such as syntactic intelligibility) which have a profound research interest. Moreover, such type of data is only relevant when ASA is concerned, being pointless for other types of syntactic analysis. Thereby, even if our study area is rather vast, we have chosen to create a traditional, hand-drawn axial model of Oporto metropolitan region's complete street network, as the main tool to probe its morphological development.

Just as any cartographic representation is ultimately dictated by the cartographer's decisions on what to represent or not, also the creation of an axial map implies decisions on which level of axial description to consider. In other words, the construction of the model implies a choice on what it aims at describing (i.e. the detailed spatial structure of a local area, or the broad spatial structure of a city-region) and on what it aims at predicting (e.g. local pedestrian movement or regional-scale general movement patterns). It also implies decisions on how to represent several aspects of urban space not describable through mere convexity or linearity, as urban parks or large and complex plazas. More specifically, it raises several questions on how to model particular features of contemporary road and highway design. In any axial modelling exercise there is therefore the need to establish representation criteria, which should be consistently respected through the process of axial mapping. The clear stating of such criteria (however trivial they may be) and commitment to their consistent application are fundamental for such a process to be minimally reproducible[38].

The large regional scale of the area to be modelled implied a parsimonious axial description. Creating strong heterogeneities in the degree of axial description (e.g. highly detailed in central urban areas and less in peripheral ones) produces artificial node and edge densities in some zones of the resulting graph, which will overshadow others for the simple reason of these being sparser. A similar level of

[35] Obviously, not on paper but in any CAD or GIS platform.

[36] In computational theory, NP-Complete problems are those that cannot be solved by any algorithm in polynomial time (i.e. the algorithm's running time is not upper bounded by a polynomial expression and grows asymptotically with the size of the problem). Although any solution to a NP-Complete problem can be verified quickly, there is no known efficient way to locate a solution *a priori*.

[37] Road-centre lines are vector line data, usually produced and disseminated by local governments, representing the centre of road rights-of-way on transportation networks and used to encode a large number of attributes (e.g. name, width, official classification, speed limit).

[38] Even though, in this as in any cartographic exercise, complete reproducibility is never achievable.

axial description should therefore be maintained across the entire axial map, ensuring that, when in fact there are differences in the density of nodes and edges, these correspond to real different densities in the grain of the urban fabric. Such differences exist in reality, of course, but they should not be artificially augmented or diminished by random variations in the degree of axial description.

As an initial premise, we chose to only represent spaces of mixed pedestrian and vehicular circulation or exclusively vehicular. When clearly bounded by built forms (or by non-accessible areas, as defined below), public space was modelled as simply and economically as possible, without any distinction between pathways dedicated to different transportation modes (as sidewalks or separated street lanes). Whenever public space was not so clearly defined by built forms (e.g. when a regional road becomes the only subject of modelling), the same economical criteria was applied and the limits of movement channels provided the boundaries for axial line placement. Any space accessible only to pedestrians was not represented, leaving out all exclusively pedestrian pathways in large public gardens or squares, which were treated as non-accessible areas. This might seem odd at first but, on reflection, it would also be difficult to believe in the importance of such pathways to the overall spatial structure of the metropolitan region. Besides, apart from a few large urban gardens and squares in central Oporto, and even fewer in the surrounding towns, such cases are scarce in the study area. Exclusively pedestrian pathways can, of course, be important to the microscopic functioning of certain urban areas, but that is not the only (nor the principal) scale at which this study is carried out. Clearly, at the regional scale, pedestrian movement is irrelevant and vehicular movement prevalent. The pedestrian use of space becomes important at the local scale, but then again it happens mainly in spaces shared with vehicles[39]. On the face of the dilemma of detailing thoroughly some areas and not others (simply because public space is more formalized on some places than on others), we have opted to maintain a low level of axial description across the entire study area. As such, the principal criterion for axial modelling was the concern with a constant, consistent, optimized and economical representation, bearing in mind the model's regional scale.

The axial model was constructed in a GIS platform[40] over orthophotographies with rather good resolution[41]. The coverage date for the study area is 2011[42]. Axial drawing over orthophotography is much more straightforward than over traditional cartography, even when in digital (vector) format. The interpretation of what exactly are the boundaries of modellable space becomes intuitive and evident, almost as if one was on the spot. Moreover, the very recent coverage provided up-to-date data, which is not the case with Portuguese municipal digital cartographies, usually already a few years old and significantly outdated.

As stated before, there are also several features of contemporary road design which constitute non-trivial issues from the point of view of axial modelling. Simple non-linear features, as curves, are merely handled through the principle of axial optimization, i.e. finding the minimal number of axial lines that match the geometry of the curve. But more complex features, as dual carriageways, highway interchanges, roundabouts, flyovers, underpasses, tunnels or bridges, deserve some discussion.

[39] Across the study area we have found some cases of recent 'pedestrianization' of once mixed vehicle and pedestrian streets. This kind of intervention occurs mainly in central urban areas and in historical main streets, usually where retail functions are very prevalent. Even if blocked for passing-through traffic, these streets remain open to local-access traffic and as such were also represented.

[40] ESRI's ArcGIS 10.

[41] 'Bing Maps Aerial', a free web mapping service from Microsoft, built-in in ESRI's ArcGIS 10 and offering worldwide orthographic aerial and satellite imagery. In all the study area, the side of a pixel is equal to 30 cm in reality.

[42] The resolution and the coverage dates of Bing Maps are not ready available, but can be obtained with the 'Bing Image Analyzer Tool' (provided by OpenStreetMap.org), which reads Bing's tiles metadata giving the resolution and capture date of each tile. The tool can be accessed at http://ant.dev.openstreetmap.org/bingimageanalyzer.

The process of constructing the axial model was inevitably slow and gradual, interspersed with several processing moments of the ongoing axial map. This allowed inspecting the results of multiple drawing options and making corrections if necessary, which was several times the case. The problem of axial lines which are intersected in the map but that, as nodes, are not adjacent in graph (i.e. any situation of vertical separation between pathways, as some of the mentioned above) is easily solved by the piece of software for configurational analysis that we used, UCL Depthmap V10[43], originally developed by Alasdair Turner (2001, 2004). Any pair of intersecting axial lines that should not be adjacent in the graph can be 'unlinked' with a tool for this effect. Thus, bridges, tunnels and the like, don't present any kind of representational problem, being modelled as axial lines as they are and then unlinked in this manner. Less obvious is the axial representation of the other mentioned road features. They pose again the problem of excessive and unequal axial representation, i.e. to which extent shall one model spatial features that are the sole product of road engineering standards and designed only for motorized vehicles, like large highway interchanges with their paraphernalia of curved access ramps and flyovers? The possibility to unlink axial lines allows representing thoroughly the whole structure, but does it make any sense to model such spaces, which are experienced quickly and by car, in the same way of some narrow winding street in the historical core of the city?

We started by doing so, nonetheless. In initial versions of the axial model we represented axially both carriageways on all roads with central reservation, the full layout of interchanges and all the roundabouts we encountered. The first processing tentatives, however, revealed that such options clearly induced artificial depth in the model and produced several uncanny effects. The systematic representation of roundabouts had a strong negative impact on the accessibility of the incident lines, in particular when occurring in a sequential way; long, straight roads, whose junctions with other streets were made by roundabouts, systematically showed implausible low accessibility levels. The representation of dual carriageways showed at times marked differences between both channels of the same road, one much more accessible than the other. In general, all roads of this kind showed relatively low accessibility, despite of their intensive use. Interchanges produced even more odd effects, with different access lanes and ramps of the same structure appearing with clearly different accessibility levels.

The systematic reduction in the detail of axial description of this kind of structures produced significant improvements in the plausibility of the model's processing results. In fact, the same argument invoked for not representing pedestrian-only pathways can be used here, perhaps even more appropriately: which importance in the overall spatial structure of the city-region could have the morphology of a highway interchange? As for roundabouts, they are normally created for safety purposes, but structurally they serve exactly the same purposes of street junctions. And as for the representation of dual carriageways, because the axial graph is undirected and insensible to traffic directions[44], it simply does not make sense to treat them differently from any other kind of road. Cognitively speaking, we do not think in terms of dual carriageway, but simply in the existence of a certain road, linking certain locations along a certain route. And, likewise, while navigating urban spatial networks, we do not care about the structure of interchanges but simply about changing from a highway to the other; as a matter of fact, pretty much in the same way as with any other crossroads.

[43] UCL Depthmap is open source software, today developed at UCL and worldwide by the space syntax research community. The software can be downloaded at http://www.spacesyntax.net/software/ucl-depthmap/

[44] This argument also applies for roundabouts.

In the definitive version of the axial map all these road artefacts were reduced to a minimal axial representation. Roundabouts were ignored[45], with the axial lines simply intersecting as they would in a normal road junction. Dual carriageways were also ignored and modelled as any other road, i.e. by a unique thread of axial lines, constrained only by the limits of the movement channel. Highway interchanges were deeply simplified, normally to the point of total suppression, with the connection between highways being made by their simple and direct intersection (i.e. not unliked). Only in the most complex interchanges, where more than two highways meet and where there are also multiple links to the local grid, some level of detail was introduced, but aimed at reproducing the structural relations between roads and not the overall geometry of the interchange. Figure 39 depicts some examples of the modelling options stated above, while Figure 40 shows the final version of the axial map (previous to diachronic modelling).

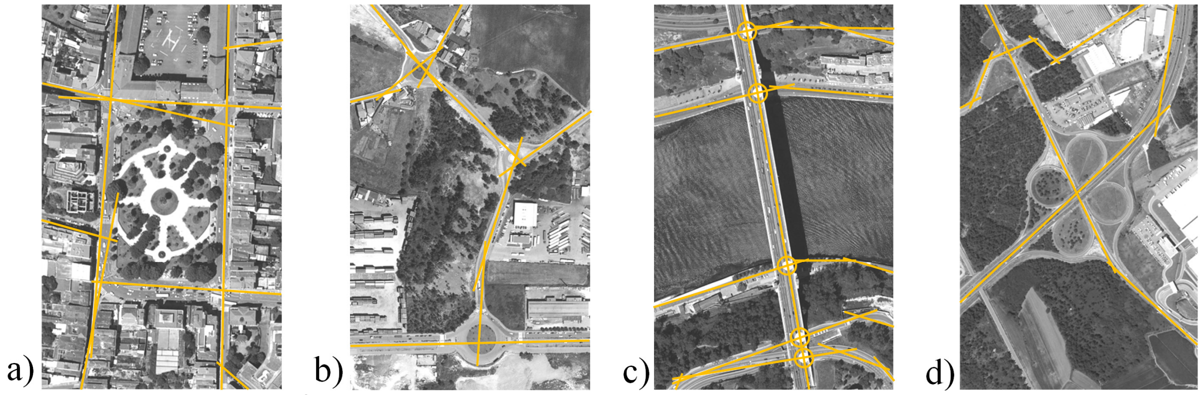


Fig.39 – a) An example of a non-modeled, exclusively pedestrian area. b) Roundabouts modeled as simple intersections. c) A bridge over the Douro River, with unlinked axial lines (yellow circles). d) Highway interchange modeled as a common road intersection (i.e. not unlinked).

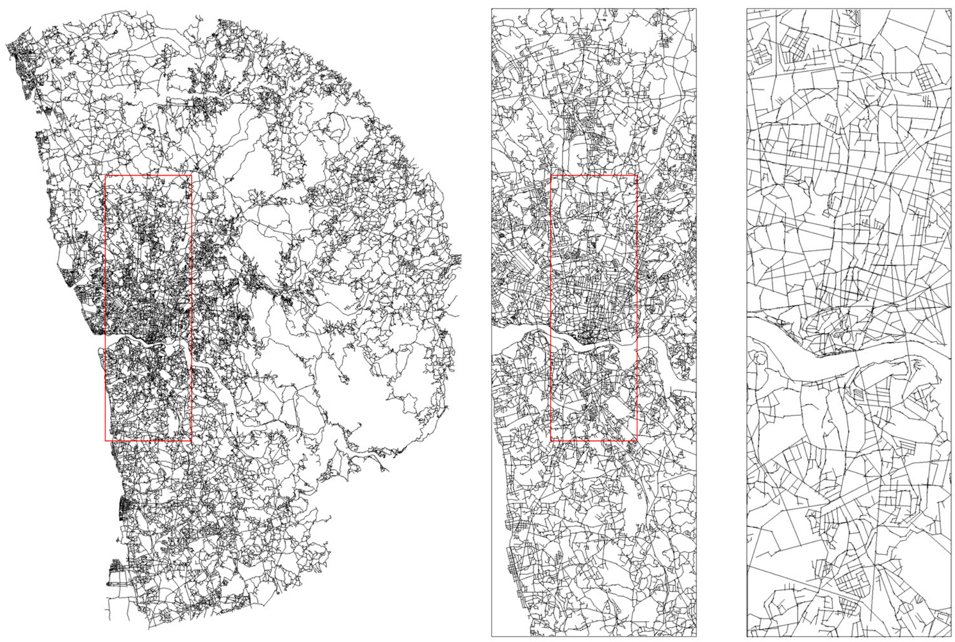


Fig.40 –The axial map in its definitive, current state (left). The red rectangles correspond to the areas shown in the central and right images, each one magnified 100% in relation to the previous.

[45] Actually, not all. When a roundabout was sufficiently large to include a public garden in the middle (as it is the case of the Boavista roundabout, an early twentieth-century important garden plaza in central Oporto), they were treated in the same way as other large public squares, exclusively pedestrian (i.e. as a non-accessible areas, surrounded by axial lines modelling the spaces of movement shared by pedestrians and vehicles). In the entire model, there are only three such cases.

3.2. DIACHRONIC AXIAL MODELLING IN GIS

Diachronic descriptions of urban form are widely used in urban morphological research. Indeed, they provide the main instrument through which processes of morphological change and evolution are conceptualized. Likewise, in space syntax studies, diachronic analyses of the evolving spatial structures of cities are common (Azimzadeh 2001, 2007). This is usually done through the production of several axial maps, drawn within any computer-aided design (CAD) software, over increasingly older digitalized cartographies of a certain urban setting, typically by erasing the lines that did not exist previously and by introducing those that ceased to exist after. These maps are subsequently processed in one of the several pieces of software for configurational analysis available, and the results of the analysis of each map are compared. Such a method, however, has several limitations. Firstly, each axial map thus produced is independent of one another, i.e. diachronic axial information is not integrated into a single spatial database; secondly, information about changes made to each axial line between each analysis period is not recorded, or at least not in a systematic way; and thirdly, diachronic axial information is produced only at the overall system level, and not at the level of the additions and transformations made to the street grid between each analysis period.

We have developed a technique to recreate the street network of the study area in three previous temporal moments, which avoids the abovementioned drawbacks, by taking advantage of the excellent visualization and data management capabilities offered by geographical information systems (GIS) [46]. There are obvious advantages of drawing axial maps in GIS, namely the easiness how spatial data (e.g. orthophotos, older cartographies, axial maps, etc) can be rigorously superimposed by georeferentiation and visualized together. But the concomitant encoding of non-geometrical attributes into axial lines can also be extremely helpful in the construction of diachronic axial models, as we will try to show next.

The idea of using old cartographies to recreate the past form of the city is recurrent in urban morphology and has been applied since its beginnings (Kropf 2001). Nowadays, the availability of digital vector cartographies and CAD has made this an increasingly easy and accurate procedure. For example, Pinho and Oliveira (2009) describe a simple method for systematically recreating past states of urban form, through the computer-aided 'redrawing' of current vector cartographies (which are, of course, fully editable), layered over older digitized cartographic elements. This makes possible the exhaustive geometric reproduction of an urban layout through time. As stated before, this is also what is normally done with axial maps, but then regarding only the axial description of urban space and not its entire geometric constitution. The technique we have developed is based on the same straightforward idea, but it makes use of GIS capability of storing data also in tabular format. Basically, instead of creating several independent versions of the axial map and gradually erasing axial lines if they did not exist at each of observation, we have produced a single database containing all the axial lines that were present, created or altered along the study's time span, distinguishing them through attributes encoding their period of occurrence and type of transformation. Besides integrating all temporal information in the same database, this simple method turns the exercise of diachronic axial modelling into a process in which information is gradually produced and accumulated, instead of gradually lost (as with the simple deletion or permanent alteration of axial lines). Such information, including each and every change observed in the street grid at each period of observation, can thus be recorded and made available for querying and analysis.

As stated in the previous section, the contemporary version of the axial map was created over orthophotographies dating from 2011. Using this map as starting point, three more periods of analysis

[46] The initial idea for the proposed technique resulted from several fruitful conversations with my colleague Miguel Torres, to whom I owe not only that but also much of my introduction to GIS.

were defined, accordingly to the historical cartographical elements available. There are many reliable cartographical sources for the central zone of the study area (corresponding to the city of Oporto), dating as far back as the beginning of the XIX century[47]. However, outside Oporto's administrative limits, historical cartographic sources are extremely scarce and not reliable, at least until the first aerophotogrametrical survey of the country, conducted in 1947[48]. This survey resulted in the first (and still the only) entire cartographic coverage of the national territory at the 1:25 000 scale, published by the Portuguese Army Geographic Institute (IGeoE) and updated afterwards several times. Despite the relatively small scale, this cartographic series is extremely information-rich and is normally used as the basis for many studies regarding landscape evolution over the last half century.

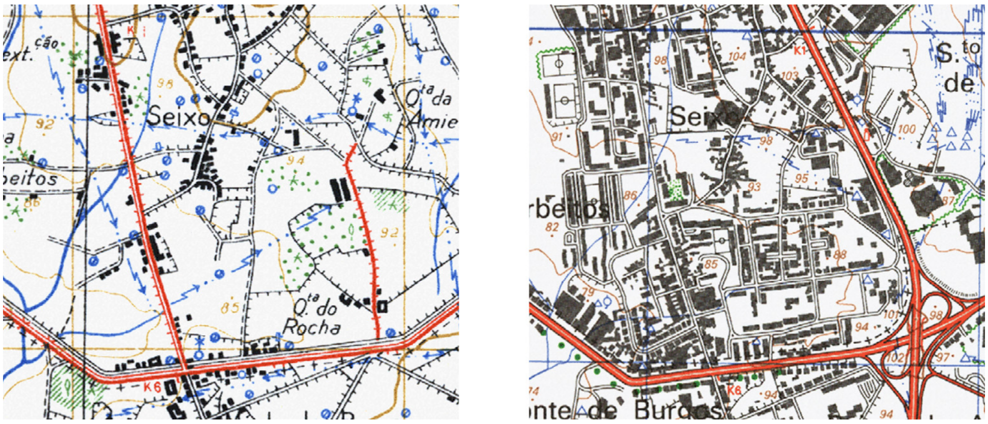
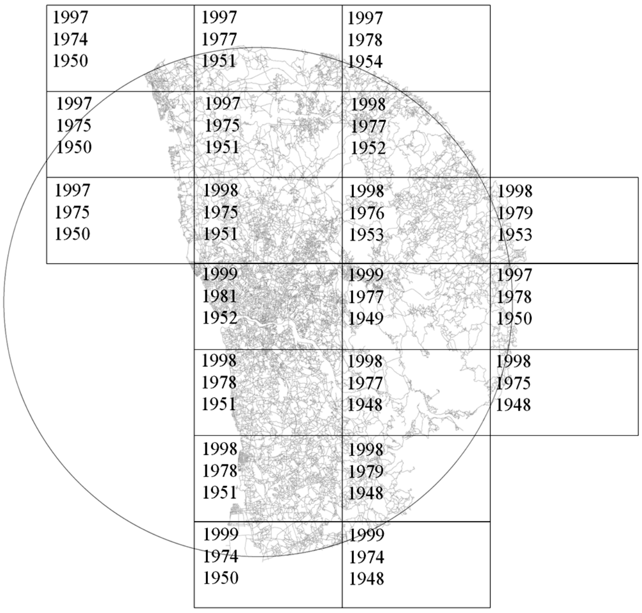
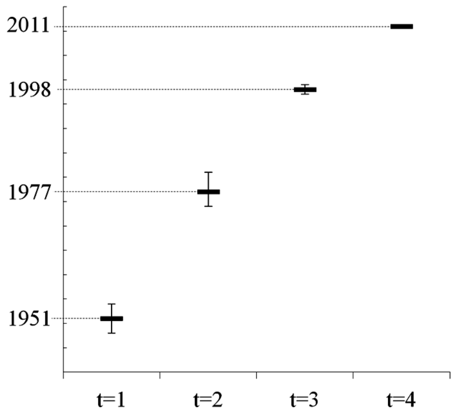


Fig.41 – Two extracts of the same zone from the IGeoE cartographic series at the 1:25 000 scale; time is *t*=1 (left) and *t*=3 (right).





	mean	std. dev.	min.	max.
t = 1	**1951**	1,8	1948	1954
t = 2	**1977**	2	1974	1981
t = 3	**1998**	0,7	1997	1999
t = 4	**2011**	0	2011	2011

Fig.42 –Publishing dates and geographic position of the twenty cartographic sheets covering the study area (left). Their respective mean dates for *t* = {1, 2, 3, 4} are summarized on the table and plot (right). The error bars on the plot indicate maximum and minimum dates for each *t*.

47 Pinho and Oliveira (2009) provide a detailed list of these sources.

48 This survey was conducted by the British Royal Air Force, without official demand and for reasons not completely understood. However, the photographs were offered one year later to the Portuguese Military Cartographic Service, subsequently resulting in the first national precise cartographic coverage.

The twenty cartographic sheets covering the study area and their respective publishing dates are summarized in Figure 42 (previous page). Each sheet has variable publishing dates (maximum differential of 7 years), but their means are representative (maximum standard deviation of 2 years). Together with the date of the current orthophotographies, these dates correspond to four moments in time $t = \{1,2,3,4\}$, respectively corresponding to the years: 1951, 1977, 1998 and 2011. The total time span of the study is 60 years, divided in the intervals, $t_{[1,2]}$, $t_{[2,3]}$ and $t_{[2,4]}$. We note each interval's time-length (in years) as $\Delta t_{[a,b]}$, with $a, b \in \{1,2,3,4\} : a < b$. Thus $\Delta t_{[1,2]} = 26$ years, $\Delta t_{[2,3]} = 21$ years and $\Delta t_{[3,4]} = 13$ years.

The proposed method for diachronic axial modelling in GIS starts with the current (*t*=4) version of the axial map. For each axial line, five attributes are created. Four are numerical (binary) attributes, which we name [T4], [T3], [T2] and [T1]. Each of these attributes encodes the presence or absence of each line at each observation time t. We use the value '1' for present and '0' for absent, but of course any other pair of values would serve, provided that they are used in a consistent way. A fifth alphanumeric attribute is also created, which we name [OBS], and is used to record the type of transformation (if any) that a line may suffer through time. At a certain moment in time, an existent axial line can be demolished (value 'dem'), extended (value 'ext') or trimmed (value 'tri').

As a first step, at *t* = 4, the fields [T4] and [T3] are entirely populated with 1 values. Then, the cartography corresponding to *t* = 3 is loaded, and the process of recording absences or alterations of axial lines begins. Every line that is absent at *t* = 3 (i.e. its correspondent space is not represented in the *t* = 3 cartography because it had not yet been built) sees its [T3] value changed to 0, but its [T4] value remains 1. Thus, the creation of such axial line sometime during the time interval $t_{[3,4]}$ has been recorded.

It may also happen that spaces represented in the *t* = 3 cartography are not visible in the *t* = 4 orthophotos[49], which means that they have been demolished in the meantime. In these cases, the lines describing the state of the grid at *t* = 3 are introduced in the model, encoded [T4] = 0, [T3] =1 and [OBS] = 'dem'. Thus, the demolishing of such axial line (or lines) sometime during the time interval $t_{[3,4]}$ has been recorded. This is, by far, the most common type of axial line alteration and is frequently associated with the appearance of large road infrastructures that disrupt the previous grid. Sometimes, also associated with axial line obliteration, is the creation of new lines (e.g. present at t = 4 and absent at t = 3) that 'sew up' the grid, usually not far from the observed disruption. Such lines are simply encoded [T4]=1, [T3]=0, as any other newly created line. Any other type of transformation of the street network involving the local demolition of existing structures and their replacement by others is also treated in this way.

But there are also two more types of possible axial line alteration through time, namely their extension or trimming. In these cases, the existing line (or lines[50]) at *t* = 4 is encoded [T4] = 1 and [T3] =0, as newly created. However, one or several new axial lines are also introduced in order to describe the past state of the grid, present at *t* = 3 but absent at *t* = 4. These lines are then encoded [T4] = 0 and [T3] =1, and the field [OBS] registers the type transformation they endured during the $t_{[3,4]}$ time interval (i.e. values 'ext' or 'tri').

This process is executed for the entire study area and iterated for each moment of observation. Once the process is completed for *t* = 4 and t = 3 (that is, when all the alterations occurring in the $t_{[3,4]}$

[49] It should be made clear that here we are talking about spaces that are represented in the old cartographies as roads or streets, namely as "allowing motorized vehicles access" (which is specifically a representation class of the chosen cartographic series). We do not refer to footpaths and other informal paths, which can be also represented in the old cartographies and of which there is no trace in the current aerial photographs.

[50] In the case of trimming, the result can be the transformation of a previous line in two or more lines.

interval were recorded), the contents of the [T3] field are copied to the [T2] field. Thus, the state of the grid at $t = 2$ is initially declared equal to $t = 3$, and thus made ready for a second iteration of the same process. The cartography corresponding to $t = 2$ is then loaded and the process restarts, with the recording of the differences between $t = 3$ and $t = 2$ in the [T2] field. The same is done until all observation periods are concluded.

The process implies that, once defined at the end of each cycle, each temporal field cannot be modified further. In other words, it implies that a line that was demolished at a certain moment in time cannot be built again, or at least not exactly as the same axial line. The migration of the information from a field to the next one, implies that sequences of temporal attributes [T4,T3,T2,T1] of the kind [1,0,0,1] are not possible, because that would mean that the same line was created twice. However, sequences of the kind [0,1,1,0] are quite possible, representing lines that were created, prvailed for some time and then were demolished. In any case, the situation where exactly the same space is deliberately destroyed and then reconstructed is so improbable, that it did not occur a single time in this study.

This simple method is capable of registering into a single GIS database all the transformations made to the street network over time. Even if equally laborious and time-consuming, the method has advantages over the usual process of simple deletion of axial lines. As it recedes in time in order to recreate the past form of the street network, it creates and accumulates information instead of destroying it. Moreover, it makes possible the record of the type of alteration (i.e. creation, demolishing, extension or trimming) that each axial line eventually endures through time. The extraction of temporal axial maps, or of other information regarding axial line transformation, becomes then a process of simple database querying[51].

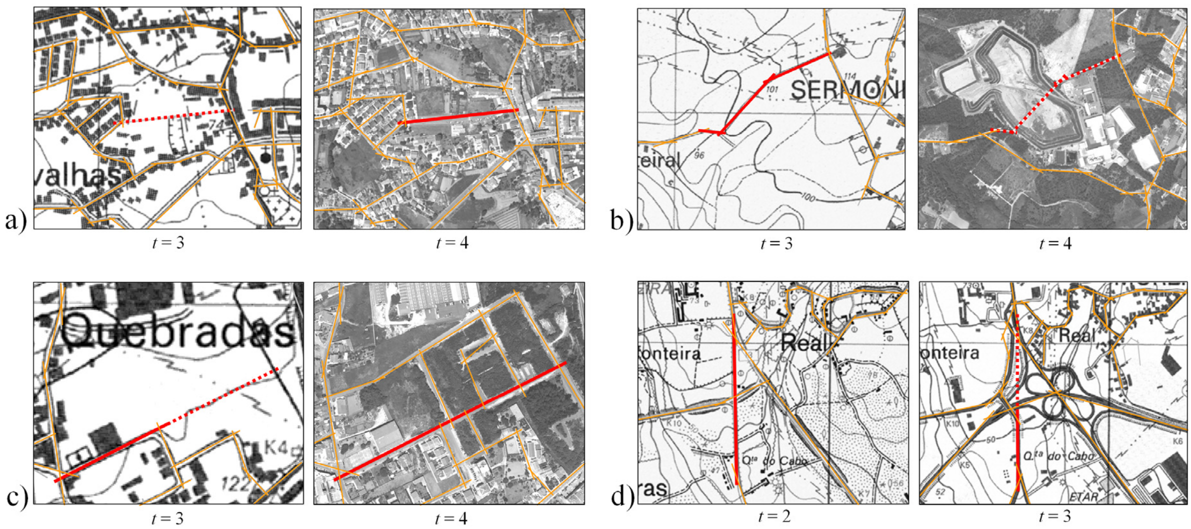


Fig.43 – Examples of the four possible events of axial line transformation: a) creation, b) demolition, c) extension, and d) trimming.

3.3. OUTPUTS OF THE PROPOSED METHOD

The first obvious output of this exercise is the production of individual axial maps for each t. In Figure 44 (next page) we show the axial maps for $t = \{1,2,3,4\}$. These maps will constitute one of the main sources of information for this study and will be extensively explored in following chapters. However,

[51] For example, in order to extract the axial lines added or transformed during $t_{[2,3]}$ one can use the following SQL query condition: [T2] = 0 AND [T3]= 1; or, to extract only the demolished lines during the same interval, the query: [T2] = 0 AND [T3] = 1 AND [OBS] = "dem".

their simple visualization and some elementary quantifications can, already at this stage, give us some clues on general processes and dynamics of metropolitan growth.

The study's time-span covers roughly the entire metropolization process of Greater Oporto, starting with the central city surrounded by an almost intact rural hinterland (dotted with a few small towns of ancient foundation), and ending in today's metropolitan region. Oporto's metropolization process was tardy, but fast. The urban Portugal of the early 1950s was characterized by a relatively slow pace of development, mirroring the country's economical and political isolation and the parochial *ethos* of the dictatorial regime then in force. Cities are contained and the rural population is still very significative, even if a relative growth of the urban population is noticeable since this time (Marques 2003). However, between the beginning of the 1960s and the early 1970s, the longest period of economical prosperity in Portugal's recent history, urban growth becomes definitively an ever-growing trend and some city systems (particularly around Lisbon and Oporto) start coalescing into metropolitan regions. In 1981, the Portuguese urban population eventually surpasses the total rural population. Around that time, also of relative economic abundance, Portuguese cities undergo an accelerated growth phase; accordingly, from 1981 to 2001 the population of Oporto's metropolitan area has an increase of 15% (AMP 2008). Such a growth trend is sustained until today, but shows signs of slowing down from the early 2000s on, accompanying the steady decline of the Portuguese economy's vitality ever since (Carmo 2006).

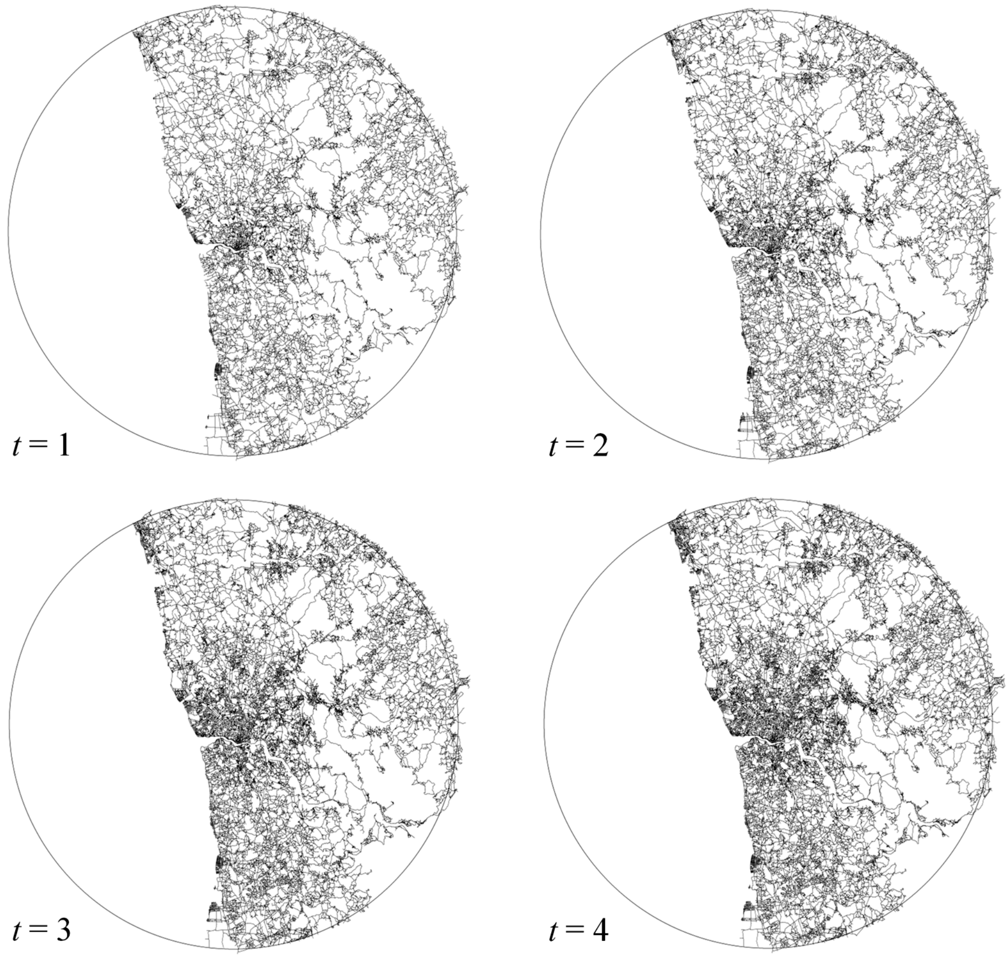


Fig.44 – Axial maps for t=1 (1951), t=2 (1977), t=3 (1998) and t=4 (2011).

These historical circumstances are reflected on the evolution of the spatial network of Oporto's metropolitan region, as represented by the $t = \{1,2,3,4\}$ axial maps (Figure 44, previous page). A simple visual inspection is enough to suggest this. At t = 1 (1951) network densifications are only visible in the central city's core and in other (much smaller) surrounding towns. These are still truly individualized settlements, separated by a much sparser and irregular network, of very ancient and rural origin, criss-crossed by some regional roads. At t = 2 (1977) urban growth becomes apparent, as the areas around the above mentioned condensations become denser and new ones appear. By this time, the central city and some of its immediate satellites coalesce into a continuous dense area. At t = 3 (1998) the transformation of the spatial network is most significative, as $t_{[2,3]}$ corresponds to the period of urban-boom mentioned before. The central denser area now largely surpasses Oporto's administrative limits and has engulfed many of its (previously independent) immediate satellites. Likewise, several of the more distant network condensations have clearly expanded. In the northern part of the study area (i.e. north of the Douro River) these denser zones show arborescent patterns, suggesting preferential directions of urban growth. However, the southern part of the study area seems to densify much more evenly and not following preferential directions. Altogether, urban growth seems to happen more-or-less everywhere: it does not emanate solely from some well-defined central core but from all previous condensations at the same time. Finally, at t = 4 (2011), the pace of transformation has apparently slowed down, even if further densification of the previous structures is still noticeable.

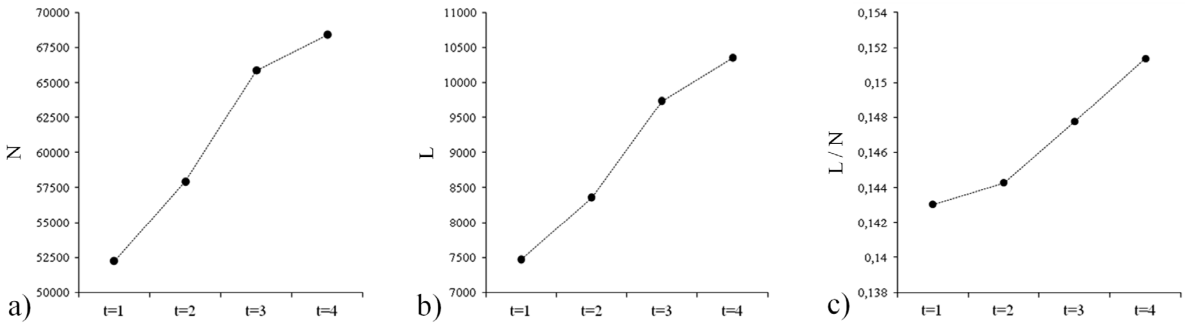


Fig.45 – Evolution of: a) the number of nodes N (equivalent to the number of axial lines); the total length (in Km) of the spatial network, L; and c) the ratio between total network length (L) and number of nodes (N), L/N.

For each temporal version of the street network, we quantify the number of nodes (N, which is equal to the number of axial lines), the total length of the network (L, expressed by the sum of axial line lengths in Km) and the ratio between these two quantities[52] (L/N). In Figure 45, we plot these three variables for each observation moment, t. The evolution of N and L through time is very similar, reflecting the obvious interdependence of the two variables. During the study's time span, N increases 31% (from 52240 to 68399 nodes) and L increases 39% (from 7472 Km to 10354 Km). The pace of increase of both variables is not constant along time, varying according to the above mentioned historical contingencies. Increase is fast during $t_{[1,2]}$, even faster during $t_{[2,3]}$ but slows down during $t_{[3,4]}$. The first two intervals correspond respectively to the prosperity period of 1960-1970 and to the urban-boom of the 1980s. The temporal distance between t = 3 and t = 4 is the smallest, however; as we shall see, the slower pace of network growth at t = 4 seems to be explainable only for that, and not as an effect of the economic slowdown, since 2000 to the present. The last variable, the ratio L/N, gives us an idea of the type of growth, independently of its intensity and of $\Delta t_{[a,b]}$ (i.e. the span of each time interval). Because axial lines correspond to nodes in the axial graph, the ratio expresses the

[52] Actually, this ratio is equivalent to the average of the length of axial lines, because N is equal to the number of lines.

relation between the length of the network and the number of nodes (or of lines) that make it up: lower values mean that the network is mainly made up of short lines; higher values mean that the network has a greater share of long lines. This relation is not constant over time. At t = 1 and t = 2 the ratio L/N is roughly the same: growth in the $t_{[1,2]}$ interval does not alter the previous relation between network length and number of nodes. But it changes afterwards, increasing steadily until t = 4, indicating that there has been a continuous increase in the length of axial lines produced during the $t_{[2,3]}$ and $t_{[3,4]}$ intervals.

The second immediate output of the diachronic modelling exercise, is the extraction from the database of the subsets of axial lines produced or altered during the three time intervals, $t_{[1,2]}$, $t_{[2,3]}$ and $t_{[3,4]}$. In Figure 46 we show these subsets (in red), over the lines of the network that remain unaltered during the entire study's time span (in light grey). These images register with accuracy every single addition or alteration made to the metropolitan street network along 60 years, while separating them into three different moments of observation. The first two time-intervals are roughly similar (26 and 22 years) but the last is significatively smaller (13 years). Therefore, these images should be studied bearing that in mind. Nevertheless, their simple visualisation reveals interesting differences and peculiarities in the growth patterns and spatial distributions that they convey.

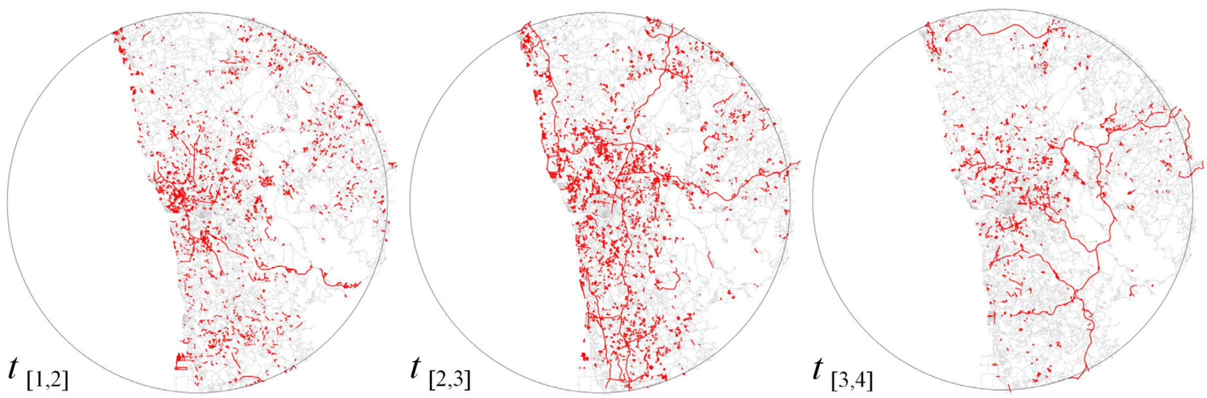


Fig.46 – The sub-sets (in red) of axial lines created or transformed during the $t_{[1,2]}$, $t_{[2,3]}$ and $t_{[3,4]}$ time-intervals.

Both the first two time-intervals show intense growth and transformation of the street network, but the $t_{[2,3]}$ interval, albeit not the longer, is clearly the most prolific. The third time-interval, $t_{[3,4]}$, shows less network additions, but is also the shorter. The growth patterns that the images convey are rather different. Network growth during $t_{[1,2]}$ seems to be mainly composed of small interventions, showing some concentration at the centre and around certain areas, but with an otherwise dispersed distribution. In contrast, during $t_{[2,3]}$, both the size and the concentration of grid interventions seem to increase. Furthermore, long road infrastructures make a sudden appearance[53]. These correspond to the establishment of the national and metropolitan highway systems, which started to be built only around 1990 and were inexistent during $t_{[1,2]}$. Finally, during the $t_{[3,4]}$ interval, network transformation is apparently much less intensive (even if this should be checked quantitatively, due to the interval's shorter time-span). Only a few interventions fall out of the orbits either of the central area or of some of the other smaller metropolitan urban centres. Dispersed development is rare. Further long roads appear, creating even more long-range connections in the network, as the highway system started in the previous period reaches its completion.

[53] Sudden, in urban-time terms of course. These are large, centrally planned interventions in the street network, built in short time by governmental decision and funding; very different from the myriad of small, unplanned and private-led interventions that slowly, but continuously, expand the grid along time.

One of the additional advantages of assembling a diachronic axial database in GIS is the possibility of analyzing it also with standard GIS tools, and not solely with network analysis techniques. Throughout this work we will often make use of that possibility. In order only to illustrate this, in Figure 47 we show three density surfaces generated from the subsets of axial lines discussed before, which corroborate and complement the previous visual analysis. Here we use kernel density estimation (KDE), a spatial interpolation technique in which a smooth, curved surface[54] is created over each spatial feature, with its highest value at the feature's location and decaying to zero at a certain limit[55]. A raster image is then created, in which each pixel acquires the value of the sum of all the kernel surfaces overlapping at that point. The technique is widely used to transform samples of discrete spatial phenomena[56] into continuous fields (or surfaces), in order to estimate and visualize their density of occurrence across space. Using the axial lines produced in the three time-intervals, we are actually creating surfaces that depict the density of network interventions occurring across the study area in each time interval. As the images in Figure 47 show, their density patterns are rather different. At $t_{[1,2]}$ the density field is little structured and quite sprawled, reflecting the dispersed spatial distribution of network interventions mentioned before. At $t_{[2,3]}$ it becomes much more heterogeneous and concentrated. Clear preferential growth areas are distinguishable: around the central city, along the coast, towards northeast and south. These two patterns strongly suggest different dynamics of network transformation, one more generalized and pervasive at $t_{[1,2]}$, and another more localized and directional at $t_{[2,3]}$. At $t_{[3,4]}$ the density field becomes even more heterogeneous and concentrated at roughly the same areas as before. However, the light grey areas of 'corridor development' linking these higher density zones disappeared almost completely, suggesting still a new network growth trend: more concentrated in the urban centres and less along the corridors linking them.

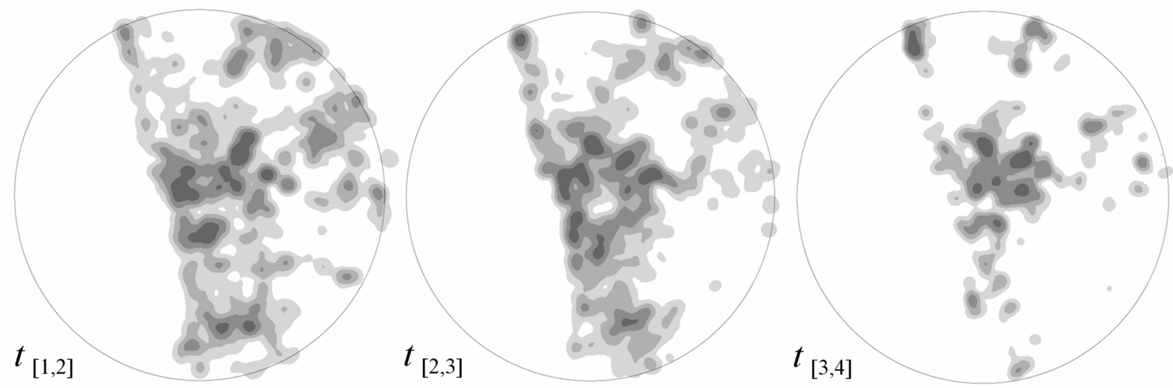


Fig.47 – KDE surfaces produced with the sub-sets of axial lines created or transformed during each time interval.

The same parameters that were quantified for the entire axial maps at each $t = \{1,2,3,4\}$, can also be quantified for the interventions made to the street network during each $t_{[a,b]}$. Only now, because the lengths of each time interval are different, we normalize[57] the number of new nodes N and the length (in Km) of created network L, by the total number of years in each time interval, $\Delta t_{[a,b]}$. This creates comparable values, namely the values of N and L produced on average per year during each $t_{[a,b]}$. In Figure 48 we show these values plotted for each time interval. The first plot (a) is informative because it shows that in spite of the apparently different growth intensities of $t_{[1,2]}$ and $t_{[3,4]}$, they actually have

54 The volume under this surface can be unitary (as it is the case here) or proportional to a certain attribute of the point.

55 This limit, or band-width, is a free parameter which needs to be defined *a priori*. Here, we use a band-with of 2000 meters around the centroid of each axial line.

56 As housing or population densities, crime occurrences, or any other discrete spatial data.

57 We do not normalize the ratio *L/N*, because that is an abstract quantity, immediately comparable between different time-intervals.

roughly the same average node-growth rates per year. This indicates that the decelerated pace of network growth observed for t=4 is mainly due to the relatively shorter span of $t_{[3,4]}$. On the other hand, the peak of new nodes in $t_{[2,3]}$ is revealing, regarding the intensity of network growth during that period. The second plot (b) shows the average growth in Km per year for each time interval. Here there is a significative difference between $t_{[1,2]}$ and $t_{[3,4]}$, with more network length produced per year in the latter than in the former interval. This is undoubtedly due to the considerable amount of long road infrastructures produced during $t_{[3,4]}$, and also a confirmation of the small-scale of the interventions of $t_{[1,2]}$. At $t_{[2,3]}$ the average network growth in length per year attains again the maximum. The last parameter, the ratio L/N of the interventions of each time interval, confirms what has been said before for the entire network at each *t*, but also shows that the relative length per node created is maximum during $t_{[3,4]}$, again due to the prevalence of long road infrastructures introduced during this period.

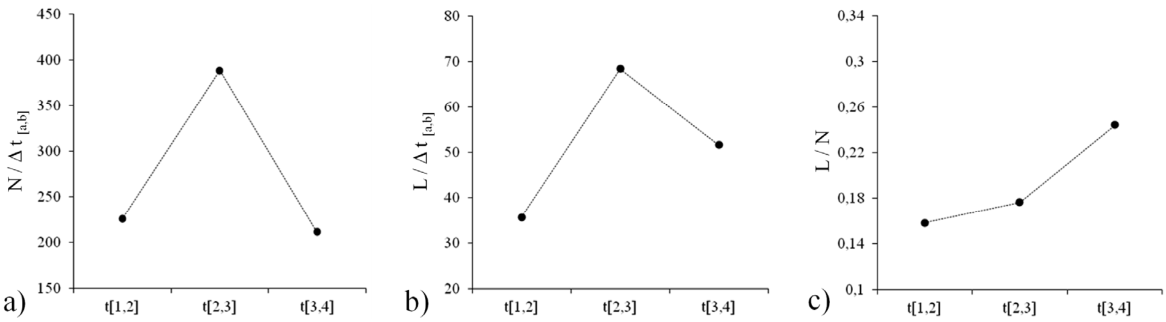


Fig.48 – Characterization of the sub-sets of created/transformed lines during each time interval: a) the number of new nodes *N*, and b) their total length (in Km) *L* (both parameters are normalized by the number of years in each time interval, $\Delta t_{[a,b]}$); c) the ratio between total new length (*L*) and number of new nodes (*N*), *L/N*.

We now look at a third output of the proposed method of diachronic axial modelling, namely the extraction of the sub-sets of lines that were altered (i.e. not newly created, but demolished, extended or trimmed) during the entire study's time span, $t_{[1,4]}$. In figure 49 (next page) we show these subsets, again highlighted in red. Their sizes and spatial distributions are very different, as are the reasons behind such transformations in the street network. Demolition interventions are by far the most numerous. Here, we must clarify what we mean by a demolished axial line. We mean that the stretch of road or street that it represents has been deliberately (and mechanically) demolished, and not that a certain road or street has been abandoned or disused in some way, and that therefore it should no longer be represented. Indeed, we could not have the means to observe such a thing: under no circumstances could we declare that a certain narrow rural path represented in an old cartography, but of which there is no discernible sign in the current orthophotos or in the subsequent cartographies, ought to be included in the network as a significant demolished structure. Furthermore, because we have chosen only to consider the spatial structures represented in the old cartographies as allowing motorized vehicle access (see footnote 15), such situations are in fact inexistent. All such roads either still exist entirely, or have been partially substituted by something else that is visible instead (as buildings, other streets or roads, landfills or whatever). It should also be recalled that road and street systems are the most persistent of all human spatial demarcations, having the capability to endure for millennia (Whitehand 1992). Therefore, their simple abandonment and disuse to the point of total obliteration is - at least in a 60 years' time-span - extremely unlikely if not entirely uncanny.

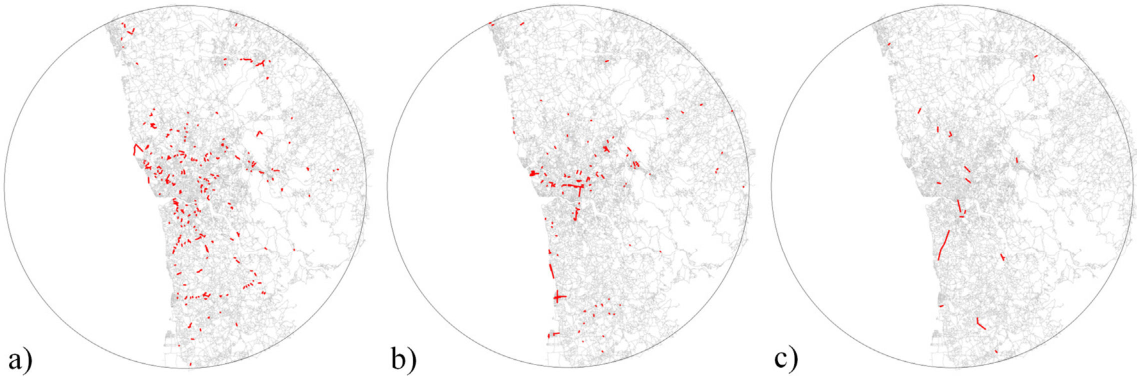


Fig.49 – The sub-sets of axial lines (in red) transformed along the entire study's time span: a) demolished lines, b) extended lines and c) trimmed lines.

Demolitions of axial lines tend to occur along certain alignments, in sequences of varying length. This is due to the simple fact that the creation of highways is the main cause of axial line obliteration. There are also other causes behind some of the observed demolitions; certain large scale housing or industrial/logistic developments, as well as other transportation infrastructures (as railroads), can also cause them. Still, the overwhelming majority is caused by highway construction. New connections are frequently introduced in the network to compensate the disruptions caused by these heavy infrastructures, but not always and even more rarely in a way that restores the network's previous state.

The extension of axial lines corresponds to a completely different urban dynamic. Instead of disruptions, they are actions of consolidation of the street network. They are not 'side effects' of higher-order interventions (as are the demolitions caused by highway construction), but rather purposeful and intentional actions. They tend to occur under three main types. A first and more frequent type, concerns the extension of previously short lines to become part of new roads, and is related to supra-local connection logics and not necessarily associated with building construction; a second and not so frequent type, concerns lines that are extended and integrated into new housing or industrial/logistic developments, following mainly local logics; a third and least frequent type, concerns the extension of important main streets in urban centres, corresponding to clear (and eventually long planned) intentions of urban affirmation and consolidation. The spatial distributions of these three line extension types are also different. The first two tend to occur more or less arbitrarily across the entire study area; the last type, however, occurs exclusively and by definition at the cores of existing urban centres.

The last kind of axial line alteration, trimming, is also the least frequent. For a line to be trimmed it must be quite long in the first place: short lines do not get trimmed, they are demolished altogether. That is the main reason for the rarity of this type of transformation, because long lines are also much less frequent than short lines. Like the demolishing of axial lines, trimming is usually associated with highway construction. However, this type of axial line alteration seems less arbitrary and more carefully devised, probably because the routes (and the lines) involved are potentially more important. Trimming occurs accordingly to two main types. The most frequent concerns the division in two (or the loss of a part) of a previous long line, usually severed by some new heavy-duty road infrastructure. The remaining parts (or part) of the severed line are usually reconnected among themselves or to the surrounding grid, by new road sections (always entailing the loss of the linearity and continuity that the previous axis provided). A second type of trimming, much less frequent, concerns the division of a long line into several parts, in order to upgrade some of the resulting sections as stretches of some new, higher-order road infrastructure, while the other sections are reconnected to different points of the surrounding grid. This type of network transformation is, of course, the product of considered transport planning decisions. It is also very rare, occurring only three times during the entire study's time span.

We can also quantify the frequencies of the abovementioned transformations by time interval, in order to see if they vary. In Figure 50 we show three plots describing this. The demolishing of axial lines (a) is rare during $t_{[1,2]}$, but quickly increases during $t_{[2,3]}$ and becomes maximum during $t_{[3,4]}$. This is a direct consequence of the prevalence of highway construction during the last two periods; as mentioned before, these infrastructures are the main cause of axial line obliteration. The same is valid for the trimming of axial lines (c), even if these type of transformation is in general much rarer and shows the same frequency during $t_{[2,3]}$ and $t_{[3,4]}$. The extension of axial lines, however, shows an almost constant frequency through time (b). This type of axial line transformation seems insensitive to variations in the intensity of urban growth (which, as Figure 45 shows, is not constant), and it also seems to be a permanent phenomenon through time. This suggests that axial line extension or, in other words, the linear extension of streets, is indeed a particular form of grid growth on its own, deliberate and independent of historical circumstances.

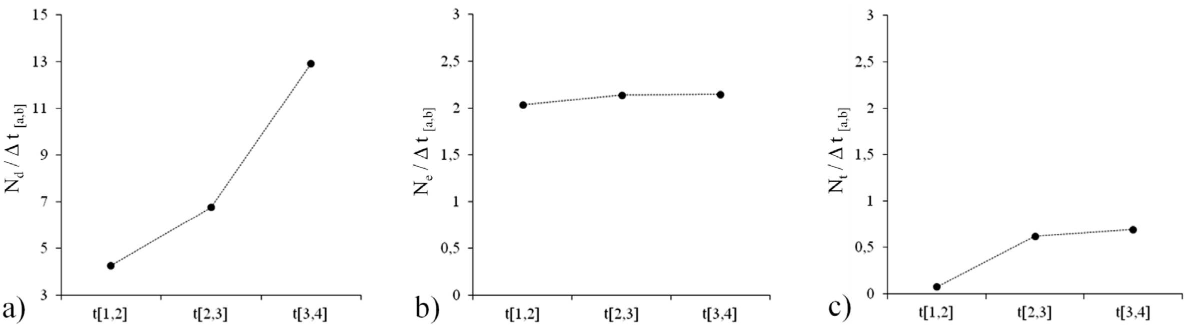


Fig.50 – The frequency by time interval of: a) demolished lines (N_d), b) extended lines (N_e) and c) trimmed lines (N_t), normalized by the number of years in each time interval ($\Delta t_{[a,b]}$). Note that the vertical scale is equal in the N_e and N_t cases (0 to 3) but larger in the N_d case (3 to 15), due to the much higher frequency of N_d.

However carefully planned or essentially casuistic, the described additions and transformations made to the spatial network through time, are never evaluated from the point of view of their impact on the evolving metropolitan spatial structure (or even on its local spatial structure). Yet, such knowledge could be useful, not only regarding its relevance for the understanding of metropolitan formation but also its immediate utility to urban planning practice. Such a detailed impact evaluation is theoretically feasible through space syntax and network analysis, provided that information on the evolution of the network is available. The high level of desegregation attained by the method described here could provide that information.

3.4. IDENTIFYING INDIVIDUAL INTERVENTIONS IN THE STREET NETWORK

We will now discuss the last methodological step of the diachronic modelling exercise, namely the identification and isolation of all the individual interventions made to the street network along the study's time span. As we will try to show next, once the subsets of all the created/transformed lines in each time interval are extracted, it is just a small step to achieve such a degree of disaggregation. By individual interventions, we mean: each and every individual development operation involving the creation or transformation of streets and roads, realized within the time interval considered in this study[58]. Such a definition is rather comprehensive and can encompass many types of urban development, so we must first characterize briefly the main types occurring in Oporto's metropolitan area.

In Portugal, metropolitan development has been almost exclusively market-led. Even if the entire national territory is today covered by municipal master plans[59], their function is primarily that of zoning general land-uses and their densities, leaving to the private sector all new urban development initiatives. In order to develop a parcel of land that has been zoned as potentially urbanisable, a private agent should make use of a rather simple planning instrument, the so-called "Projecto de Loteamento" (translatable to English as "land parcellation project"). This instrument defines the new structure of land-tenure (i.e. the new plots), the basic characteristics of buildings (e.g. foot-prints, heights, number of floors) and the layout of new streets and other public open spaces (which will be, in the end, transferred to the public domain). Public agencies (municipalities in this case) have the responsibility of lending legal support to the project. But, most often than not, they limit their role to determine whether it meets the general land-uses and density indexes set out in the municipal master plan. Beyond their traditional urban centres, Portuguese cities are mainly made up of this type of urban developments (be they residential, tertiary or industrial/logistic), restricted to the limits of their original land parcel (most often ex-rural) and quite oblivious of the broader spatial network of which they are part. Parcel by parcel, always on a piecemeal basis, these urbanization projects produce a patchwork landscape of more or less disconnected urban fragments, mingled with agricultural and natural remains (Figure 51).

Fig.51 – *Loteamentos* (land parcellation projects) colonizing rural parcels at Oporto's metropolitan area. Note the haphazard and individualistic character of the several interventions.

The process is so common and general, that the term "loteamento" (originally meaning only "land parcellation") has become the colloquial designation for that specific type of urban development initiatives. Likewise, in Oporto's metropolitan area, this incremental process is by far the main responsible for the expansion of the street network. The street grids produced by each of these private-led projects are the most common examples of the individual street network interventions recognized in this study.

Beyond their land-use regulatory function, public agencies have also the responsibility of defining and providing urban infrastructures and facilities[60]. These are planned at the municipal or national levels[61],

[58] Not including, therefore, urban operations involving only the creation or transformation of buildings. In fact, some of the mentioned interventions do not involve building construction.

[59] Municipal master plans (PDM - Plano Director Municipal) are the central instruments in the Portuguese planning system. Being the only instrument of compulsory elaboration, they have provided the basis for the systematic planning of the entire national territory. Also, their stipulations are legally binding, not only for public agencies but also for the private initiative.

[60] Among other responsibilities, of course. We mention only those that have immediate impacts on urban form.

not always in a coordinate way, both between and within governmental tiers. Municipalities act only within their administrative limits, focusing much on intra-municipal issues and little on inter-municipal cooperation, even though this tends nowadays to change within metropolitan areas. They manage the street and road networks under their jurisdiction (i.e. all municipal pathways, streets and roads, up to the national road system level) mainly through maintenance and upgrading actions. Network expansions of municipal initiative are sporadic and mainly reactive. They usually consist in the creation of new intra-municipal and local connections, trying to sew and to consolidate the ever-growing patchwork of small, private-led developments. There are also clearly public interventions at the urban cores of each municipality, but those are less common. The public and municipal origins of such operations are not difficult to ascertain. In the first case, because they do not have an obvious association with the construction of buildings or plots (unthinkable in a private development). In the second case, because they occur at the very core of urban areas and show a degree of intentionality that reveals their public nature. And, in both cases, because they occur under municipal jurisdiction. Altogether, these municipal initiatives constitute a second type of the observed interventions in the street network. A third and last type is the introduction of infrastructures belonging to the national road system (i.e. national and metropolitan highways, or other inter-regional roads). These are centrally planned and emanate directly from the national government level, even if they are many times articulated with municipalities. They are a completely different type of intervention, changing deeply both the landscape and the spatial structure of the metropolitan region. Their identification and individualization are therefore simple, because they are constructed in all their length usually at once and their physic characteristics are quite obvious.

These three basic types of urban intervention describe the large majority of all the additions and transformations made to the street network along the study's time span. However, they do not aim at being systematic or exhaustive, but to serve as illustrations of the reality over which we have worked, when trying to identify each individual intervention observed in the street network. A much more detailed study of these interventions will be presented on Chapter 6.

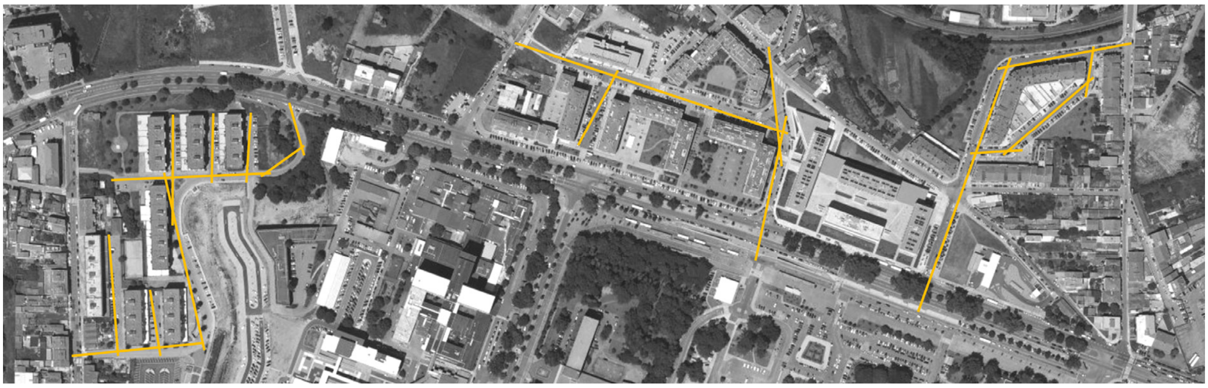


Fig.52 – Close-up on the sub-set of axial lines created or altered during the $t_{[3,4]}$ interval, layered over a current orthophotography (t = 4, 2011).

Starting with the three sub-sets of axial lines produced or altered during each time interval $t_{[a,b]}$ (see Figure 46), we introduce a new attribute column called [INT_ID] (standing for 'intervention identification') in order to record, for each new/transformed line, the individual intervention to which it belongs. We then begin by visualizing the sub-set of axial lines corresponding to the last (or more recent) time interval, $t_{[3,4]}$, layered over the current orthophotographies (Figure 52). Note that we are

[61] In Portugal, the regional level of administration does not exist. Metropolitan administration, albeit with some implementation tentatives, is still ineffective and powerless. In practical terms, the territorial administration is shared by the municipal and the national government levels.

only looking at the lines that were created or altered during $t_{[3,4]}$ and not at the entire axial system; therefore we can be sure that only the structures represented by these lines correspond to the interventions made during that time interval. The challenge is to identify them, and to allocate each line to each intervention.
As Figure 52 shows, the task of visually identifying each separate intervention is quite simple. The large majority of new axial lines in each time interval appear in relatively isolated clusters. Through the visual inspection and comparison of the physical characteristics of the built structures associated with each of these clusters (e.g. the shape of buildings, type and colour of roofing, design style, pavements, etc) one can easily recognize the individuality of each urban development operation. As mentioned before, in every time interval the bulk of new axial lines correspond to *loteamento* projects. The individualistic nature of this type of developments (particularly exacerbated in the more recent versions) actually makes the task even easier. The lines thus identified as constituting an individual intervention are then selected and their [INT_ID] attribute is modified, in order to register the number of the intervention to which they belong. This value is of course categorical, without any meaning in true numerical terms; its order and value are therefore indifferent, provided that the number of each intervention is unique. We simply start with 1 at one point of the study area and proceed with sequential integers until all the interventions of the $t_{[3,4]}$ interval are identified and their axial lines encoded with the correspondent [INT_ID] value.

Again we must make clear that what we are identifying are interventions of expansion / transformation of the street network, not of building construction. In fact, many of such interventions do not show associated buildings in the orthophotos, either because they were not yet been built or because the intervention at stake do not allow buildings in the first place[62] (Figure 53, next page). Moreover, the majority[63] of these are public initiatives, which are less spatially contained and whose individuality is not so evident. But also in these cases their discrimination is not difficult. Whenever the clusters of new interconnected lines are well separated (which is the most frequent case), one may simply assume that they belong to different interventions. For our purposes, what matters is not if such interventions were produced by the same administrative decision, but the fact that they occur in clearly separated parts of the network, in such a way that they could perfectly be executed in different moments of the same time interval $t_{[a,b]}$ without creating logic inconsistencies (e.g. the temporary creation of unconnected nodes in the graph). Furthermore, their simultaneous visualization with the orthophotos is enough to dissipate any doubts remaining about the belonging to the same intervention of lines that are not fully interconnected, but also not too far apart. Also here the visual appearance of the structures represented by the axial lines is quite enough to relate them. In the case of very long interventions, as the construction of entirely new roads or highways, we have aggregated the lines that make them up using the simple *gestalt* principle of good directional continuity[64], separating them into different interventions whenever such infrastructures show clear directional divergences. In the cases of interventions that imply the demolition, extension or trimming of previously existing lines (often the case of highways, but not exclusively) we have also encoded those lines as belonging to the same intervention (see figure 56).

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62 As it is the case of highways.

63 There are also a significant number of private developments of the *loteamento* type, which appear in the orthophotos without anything built besides the street layout (i.e. still with all plots undeveloped). But these are easily differentiable for their particular characteristics.

64 The *gestalt* laws of grouping are a set of basic rules in psychology, based on the observation that humans naturally perceive certain distributions of objects as organized patterns. This happens because of the mind's innate disposition to do so when exposed to certain visual stimuli, known has perceptual organization (or grouping) principles. One of them is the 'good continuation principle', which states that we tend to group lines or curves that follow an established direction over those defined by sharp and abrupt changes in direction. The importance of such principles in cartography and, particularly, in map generalization has long been recognized. Thomson and Richardson (1999) provide a full review on this subject.

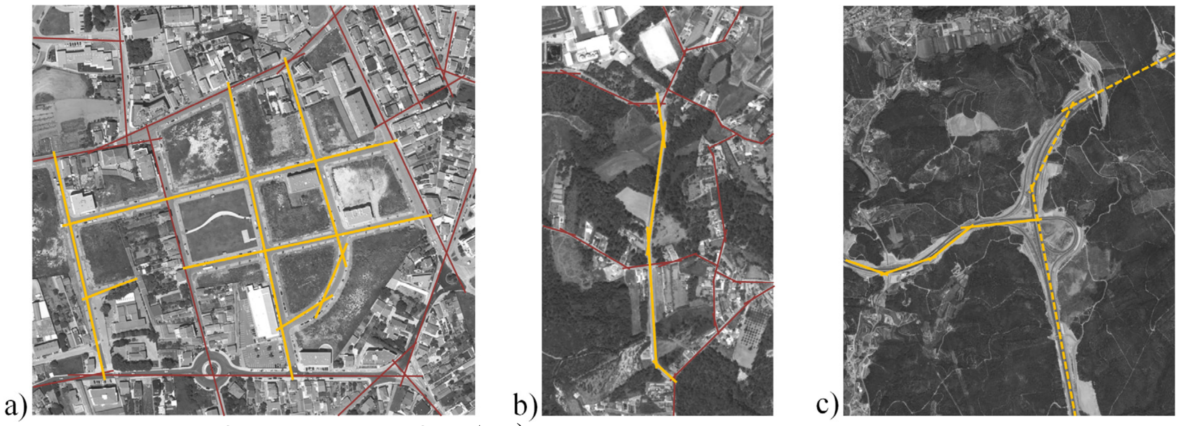

Fig.53 – Examples of interventions (all from $t_{[3,4]}$) without associated building construction: a) a large *loteamento* operation with almost all plots vacant; b) a new municipal connection; c) two highways classified as different interventions due to their clear directional divergence. $t_{[3,4]}$

Fig.54 – Three situations in which the allocation of axial lines to their respective interventions is not simple. The time interval is $t_{[2,3]}$; the thicker lines and the several colours indicate the final classification.

The situations in which it becomes really difficult to distinguish between different interventions arise only when these occur side-by-side (or even intermingled) during the same time interval (Figure 54). In general, even though the totality of the observed network expansions is capable of creating large areas of continuous urban tissue, the separation by time interval is enough to break them up into individualized parts. But, in some cases (particularly during the $t_{[2,3]}$ interval), urban growth is so intense that entirely new areas of continuous urban tissue arise. On those situations we had to make a strong interpretation effort of the orthophotos, using all the available visual information; i.e. the building and road characteristics, but also the degree of plot-occupancy, the shape and size of plots, and the type and orientation of the street grid. Such areas are particularly laborious but, in the end, a satisfactory result was usually achievable. In the few situations where the photographic information was indeed insufficient to decide if a certain cluster of lines ought to be divided or not, we have always opted for considering a single intervention, trying to limit noise in the classification to the minimum.

Once the totality of axial lines created or transformed in the $t_{[3,4]}$ interval is allocated to their respective interventions, we repeat the same process with the sub-sets of lines produced or altered during the other two time intervals, $t_{[2,3]}$ and $t_{[1,2]}$. In the end, we recognized a totality of 4170 individual interventions along the study's time span. Figure 55 shows a (possible) visual depiction of the final classification.

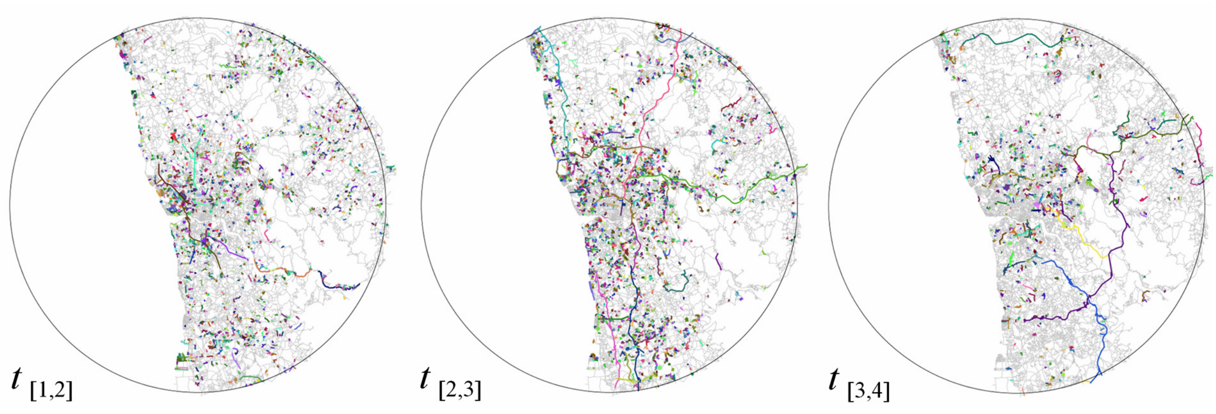

Fig.55 – A visual representation of the 4170 individual interventions identified, each one coloured randomly.

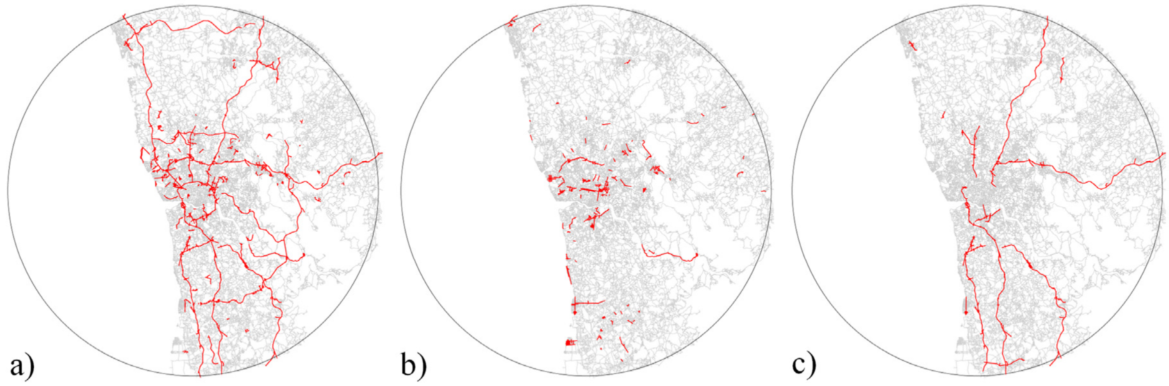

Fig.56 – a) Interventions with demolished lines; b) interventions with extended lines; c) interventions with trimmed lines.

The utility of the simultaneous encoding of the demolished, extended or trimmed lines, together with the intervention that causes them, is demonstrated in Figure 56. We can query the database so as to obtain only the interventions possessing transformed (and not only newly created) axial lines. This allows inspecting which interventions are causing which type of axial line transformation. As figure 56 shows, the demolitions of axial lines are almost exclusively caused by the construction of highways. There is not a single example of such interventions without demolished lines, even if other types of interventions also possess them. Trimming is also almost exclusively associated with that type of intervention. The extension of axial lines is associated with large interventions in the local grids, occurring mainly at urban centres.

These 4170 interventions, as represented by their axial lines, we will be the raw material for the micro-structural analysis phase of this work. They will allow for the morphological exploration of the micro-components of metropolitan form. In what follows, we will only demonstrate some statistic regularities of the identified interventions, which strongly support the robustness of our classification.

We start by looking at three thematic maps depicting the total line length[65] of the individual interventions of each time interval $t_{[a,b]}$ (Figure 57, next page). Each one is coloured according to a five-level classification (using Jenks' natural breaks) of the totality of interventions' lengths. These maps make obvious the non-normal distribution of these lengths: there are innumerous interventions in the lowest class (less than 1003 meters of line length) and very few in any of the other 4 classes. This

[65] Obviously, the total line length of each intervention is proportional to its total road length.

might seem as a bias of the classification, perhaps a tendency for over-disaggregating the clusters of new lines in each period. However, a more attentive inspection of the distribution of lengths reveals a quite different picture (Figure 58).

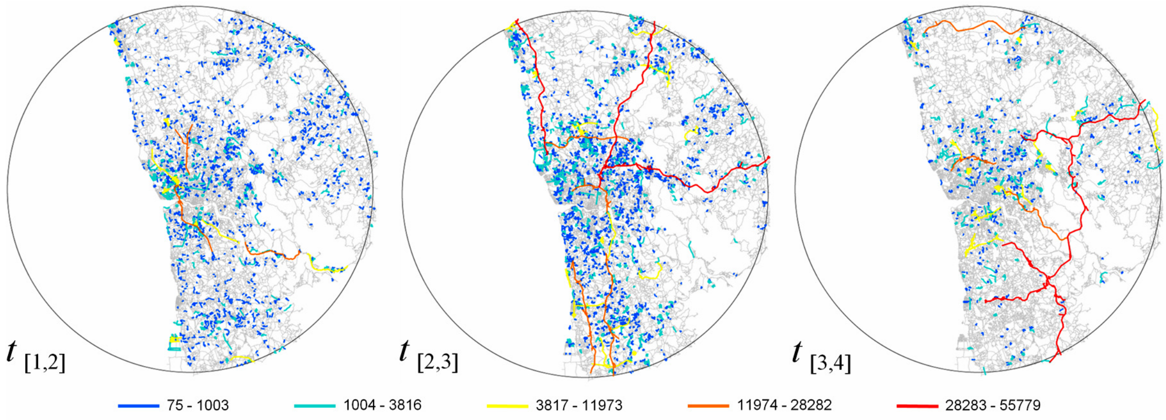

Fig.57 – Thematic maps showing the length of the individual interventions in each time interval. The colour scale was established for all interventions together (classification is Jenks natural breaks).

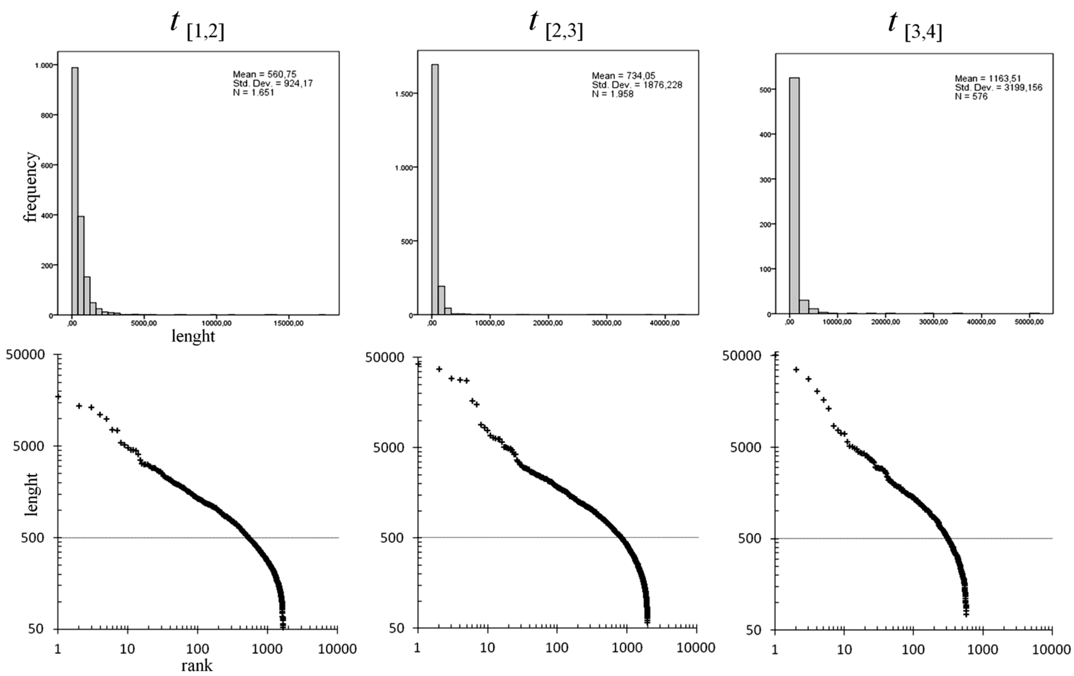

Fig.58 – Histograms and rank-size log-log plots of the lengths of the individual interventions in each time interval (ranks in reverse order, from the largest to the smallest values). Power-law scaling for the length of interventions is observable in all time intervals, roughly above 500 meters.

In fact, the histograms in Figure 58 (depicting the frequencies of interventions lengths in each time interval) all show heavy-tailed distributions, of the log-normal or power-law types. The overwhelming majority of interventions are short (less than 1000 meters), but the distribution of lengths continues until much larger values (albeit with small frequencies), up to more than one order of magnitude (i.e. around 50000 meters). It would be very uncanny for this type of statistical distribution to emerge by chance or by error. If there were a bias in our classification, it ought to manifest itself around some typical value, and not through distributions with ill-defined means.

In Figure 58 we also show three log-log plots of the interventions' lengths of each time interval, against their respective ranks[66]. Above a certain threshold (roughly 500 meters) the plots reveal clear power-laws[67] in the rank-size distributions. Furthermore, the three curves have very similar slopes, meaning that they are defined by not very different exponents. However, the number of lines is different in each time interval, as well as the ranges of their lengths and ranks, so the curves are not immediately comparable. We therefore normalize[68] the lengths and ranks dividing them respectively by the mean length and the maximum rank in each time interval, and plot them together in Figure 59. Indeed, the three curves collapse roughly around the same master curve, even if they show very small differences in slope. In Figure 59 b), we plot only the most visually linear parts of the curves (i.e. below a normalized rank value of 0,5). The power-law fits are clear (R2 equal to 0,98 and 0,99), but what is more interesting is that the exponents are very similar. In fact, the $t_{[1,2]}$ and $t_{[2,3]}$ curves have roughly the same regression equations, while $t_{[3,4]}$ shows only a slight divergence. Why this might be so, will be a theme for exploration in the following chapters. But now what we want to highlight is the fact that these statistical regularities are produced by completely independent sets of axial lines, created in different moments in time. Therefore, such regularities cannot be spurious or the product of measuring the same thing twice. They must reflect real properties of the sizes of the interventions made to the street network along time; and they also strongly suggest that our classification must be, in general, correct.

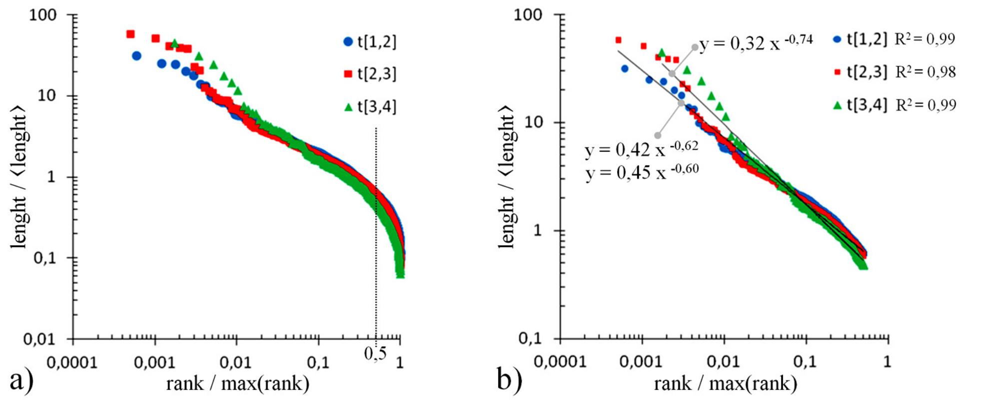

Fig.59 – Rank-size log-log plots for the interventions of each time interval, with normalized length and rank values. a) The complete sets of each interval's interventions. b) Power-law fits for the interventions with a normalized rank value less than 0,5.

[66] This type of plot is known as a Zipf plot. The ranks are in reverse order, from the largest to the smallest length values.

[67] A power-law is a mathematical scaling relationship between two quantities (x and y) of the type $y = ax^{-\beta}$. Power-laws are commonly found in many natural phenomena, notably in the rank-size distribution of cities (Batty 2008); but also in things as diverse as the intensity distributions of earthquakes or wars. In a log-log plot, a power-law manifests itself as a straight line in the graph.

[68] We follow here the same procedure adopted by (Carvalho and Penn 2004).

4

EMPIRICAL VALIDATION OF THE SPATIAL NETWORK MODEL

ABSTRACT

The spatial network model and the graphs derived from it will be the main objects of analysis in this study. But if we intend to extrapolate the present state of the network to the past, we need first to validate it against empirical observations of today's urban phenomena. For this purpose, we will use four datasets of recent vehicular movement counts obtained from official sources. If the current state of the network model shows clear correlations with actual movement patterns, then we can expect its past states to be also reliable descriptors of previous urban workings.

The empirical validation of the model raises further methodological questions that this chapter will also address. In fact, any axial map can be automatically converted into a segment map, another possible kind of spatial representation used in space syntax. The graphs derived from axial and segment maps are rather different, allowing for also different conceptualizations of distance and of scale (or radius) of analysis. Thus, the empirical testing of the spatial network model will also serve to ascertain the performance of each type of graph (axial or segment) and of each metric of distance/radius definition (topological, angular or Euclidean) at postdicting current metropolitan movement flows.

We start with a preliminary characterization of the basic structure of the axial and segment graphs, followed by the study of how distance percolates through them from a given central node. This will allow a better understanding of the three distance concepts, but it will also lead to the definition of a scale of equivalent topological, angular and Euclidean distances (a necessary requisite for producing comparable analytical results). With this transversal scale, it will then be possible to correlate the abovementioned movement counts with the results of a multi-distance and multi-scale centrality analysis, carried out on both axial and segment graphs.

4.1. STRUCTURAL CHARACTERIZATION OF THE AXIAL AND SEGMENT GRAPHS

Throughout this work we will permanently deal with axial and segment graphs extracted from the diachronic network model, described in the previous chapter. A general structural characterization of these two graphs is therefore necessary. We will start by introducing some basic properties of graphs, commonly studied in network analysis. Next, we will quantify these properties for the axial and segment graphs, as well as for comparable randomly produced graphs. The comparison of real networks with their random counterparts is a common procedure in network analysis, as it allows gauging the extent to which their structures differ from aleatory triviality. If a self-organized, real-world network (as a street network) shows strong structural divergences with random graphs with similar sizes and connection topologies, one may infer that some non-random processes must underlie its growth and organization, presumably with functional significance.

Through a simple and automatic transformation[69], an axial map can be converted into a segment map. Axial lines are simply broken into segments at each axial intersection and the resulting segments are encoded into the nodes of the subsequent segment graph. Nodes representing adjacent segments are linked by edges (Hillier and Iida 2005). The segment graph is very different from the axial graph, however. Firstly, its order and size (i.e. the number of nodes and edges) are, of course, much larger. As we shall see, the connectivity of nodes and its distribution is also very different from those of the axial graph. Secondly, the segment graph is weighted, i.e. its edges are valued according to a variable distance cost, which may be topological (as in the axial graph) but also angular or Euclidean (which we will discuss later on). Segment maps and graphs allow a finer-grained analysis (at the level of the street segment) and the use of different distance and radii metrics in the same model. There is some accumulated evidence (Hillier and Iida 2005, Barros et al. 2007) that segment maps perform better than axial maps when predicting urban movement, which is supported by evidence from cognitive science (Allen 1981, Hochmair 2002) of why this should be so. But, as stated before, there is also relevant information contained in the axial graph that is lost in the axial/segment transformation, so we will for now keep both models and study them side-by-side.

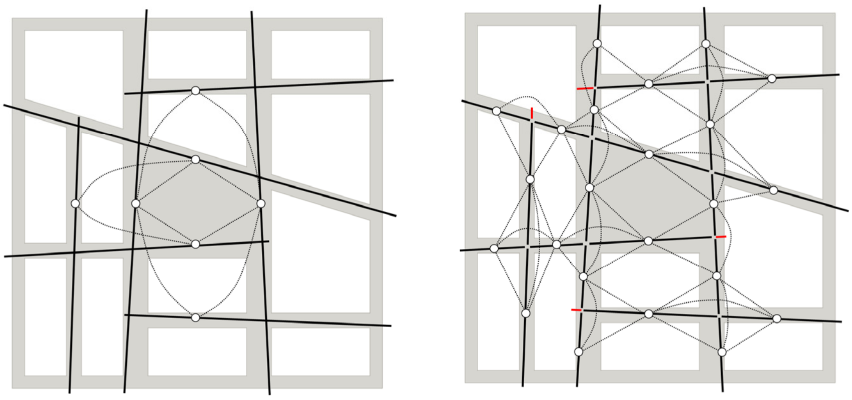

Fig. 60 – The transformation of an axial map into a segment map. Axial lines are broken at intersections and the resulting segments are encoded into the nodes of the segment graph. Edges encode adjacency relationships between segments. Note that the end ‘stubs’ of axial lines (in red, on the right) are discarded in the segment map and not encoded in the segment graph. This is not absolutely necessary, but greatly reduces the analysis’ computing time.

Axial lines and segments can be encoded as the nodes $V = \{1, \dots, N\}$ of an undirected graph $\boldsymbol{G}(V, E)$, in which any pair of lines/segments, $i \in V$ and $j \in V$, are held to be adjacent, $i \sim j$, when they intersect on the axial or segment maps. The adjacency relations between all lines are encoded by edges $(i, j) \in E$, if and only if $i \sim j$.

In an undirected graph, the *degree* (or connectivity) of each node is the number of other nodes directly adjacent to it; or, in axial/segment terms, the number of intersections each line/segment makes with other lines/segments. This is the most basic topological property of a graph. Formally, in an undirected graph $\boldsymbol{G}(V, E)$ the degree *k* of a node $i \in V$ is,

$$k_i = \sum_{i,j \in V: i \sim j} d_{ij} \tag{1}$$

[69] The transformation of axial into segment maps is implemented in UCL Depthmap V10, the software for configuration analysis that we will use throughout this work, and is fully automated.

In the previous equation, d_{ij} stands for the distance between the node in question and each one of its direct neighbours (which is always 1, when purely topological distance is considered).

The *degree distribution* of a graph (i.e. the statistical distribution of the degrees of all its nodes) is an important description of its structure. Such distributions usually assume different forms in real and in random networks. In fact, the connection topology of a theoretical graph is usually assumed to be either regular or completely random. But many biological, technological and social networks lie somewhere between these two extremes (Watts, Strogatz 1998). As we shall see, that is also the case with urban spatial networks. The average degree $\langle k \rangle$ of a graph is another important parameter. The average degree of a graph is simply the mean of the degrees of all its nodes,

$$\langle k \rangle = \sum_{i \in V} k_i \frac{1}{v} \tag{2}$$

where *v* is the number of nodes in the graph, also called its *order*. Another commonly used indicator of graph connectivity is the so-called *alpha index*, evaluating the number of cycles[70] in a graph in comparison with the maximum possible number of cycles for a graph with the same order. The alpha index varies between 0 (in an acyclic graph, as a tree[71]) and 1 (in a completely connected graph). The higher the alpha index, the more the network is connected (i.e. the higher the number of edges between its nodes). This index is useful because the relevance of $\langle k \rangle$ depends on the degree distribution being approximately normal, which is not always the case. In non-planar graphs[72] (as the axial or segment graphs) the alpha index is calculated by the following expression (where *e* is the number of edges in the graph, also called its *size*).

$$\alpha = \frac{e - v}{\frac{v(v-1)}{2} - (v-1)} \tag{3}$$

Clustering coefficients are other measures of the general connectedness of a graph. They evaluate the probability that, if two nodes A and B are connected and B is connected to C, then C will also be connected to A. This property is related to the presence of a high number of triangles in the network, a property know to occur in a higher degree in natural and real-world networks than in random generated graphs (Bocaletti et al. 2006). The global clustering coefficient of a graph (also called *transitivity*) can be quantified by,

$$C = \frac{3 \times number\ of\ triangles}{number\ of\ connected\ triples} \tag{4}$$

"connected triple" is a node with two edges incident in two other nodes. In fact, *C* measures the fraction of triples that have their third edge filled in to complete the triangle (Newman 2003). A local version (i.e. concerning each node of the graph) of the clustering coefficient was proposed by Watts and Strogatz (1998) in their famous paper on small-world networks. It quantifies how close a node's immediate neighbours are to being a *clique* (a completely connected sub-set of nodes). Given the number of nodes k_i in the neighbourhood[73] N_i of any node in an undirected graph, the *local clustering coefficient* for that node can then be defined as,

$$C_i = \frac{2 \times \left|\{e_{jk} : v_j, v_k \in N_i, e_{jk} \in E\}\right|}{k_i(k_i - 1)} \tag{5}$$

[70] In graph theory, a cycle is a closed path containing at least three nodes, starting and ending in the same node.

[71] A tree is an undirected graph in which any two vertices are connected only one path. Any connected graph without cycles is a tree.

[72] A non-planar graph is a graph that cannot be drawn in a plane without any intersection between its edges. In other words, it is a graph impossible to embed in the plane.

[73] That is, the set of nodes directly connected to it.

In the previous equation $|\{e_{jk} : v_j, v_k \in N_i, e_{jk} \in E\}|$ stands for the number of edges actually existing among the neighbours of the node in question. A mean value of the local clustering coefficient for the entire graph (Newman 2003) is given by,

$$\bar{C} = \frac{1}{v}\sum_{i=1}^{v} C_i \tag{6}$$

All these measures are concerned with direct connectivity relationships between graph elements (i.e. between elements that are adjacent). Thus, in topological terms, the distance between these elements is always 1. If not adjacent, the distance between two nodes is considered to be the shortest possible[74], also called *geodesic distance*. Distance in the axial graph is purely topological, regardless of the real metrical lengths of axial lines or of any weighting whatsoever of the edges that encode their intersection. In the segment graph the edges are weighted and distance can be topological, angular or Euclidean, but for this initial structural characterization we will only consider topological segment distance.

One important basic graph property based on distance is its *diameter*, *D*, or the longest geodesic between any pair of nodes. This gives us an idea of the graph compactness (small diameters imply a compact graph, albeit the opposite might not be true). Another relevant indicator is the *average shortest path length* (also known as characteristic path length), or the mean of all geodesics between all pairs of nodes. This gives us the average minimal trip length between any two origin-destination pairs, induced by the structure of the graph. It is denoted L and given by the expression,

$$L = \frac{1}{v(v-1)}\sum_{i,j \in V} d_{ij} \tag{7}$$

These measures will serve for a first exploration of the graphs generated by the axial and segment maps. We have quantified them for the contemporary versions of those graphs and also for their random counterparts, i.e. random connected graphs with the same order, size and degree distributions. Because transitivity, diameter and average path length are affected by the size of the graph, their values were normalized by the order of the correspondent graphs (i.e. divided by v), in order to be comparable. Table 2 (next page) summarizes these values.

The random counterparts of the axial and segment graphs have been generated[75] accordingly to an algorithm proposed by (Viger, Latapy 2005) that is able to produce random graphs with a given degree distribution which are assuredly connected. This aspect is important, because traditional algorithms for the generation of random graphs (as the Bernoulli or the Erdös-Renyi algorithms), even if run for the same number of nodes and edges, do not guaranty the respect for a given degree distribution (just for a given mean degree) and usually produce disconnected graphs[76]. Thus, even if widely used in many fields, such algorithms are not suitable for generating random graphs which are to be compared with real street networks, because these are connected by definition (there is no such thing as a street that is not connected to another street). The adopted algorithm ensures that randomness is restricted to the connections between nodes, while guarantying the same number of nodes and edges, the same degree distribution and a resultant connected graph.

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[74] If the graph is not acyclic, which street graphs very seldom are, there can be many paths between two given nodes and, among these, several minimum paths. Geodesics are these minimal paths, selected from all the possible paths.

[75] We have used a free piece of software - GenGraph - which implements the mentioned algorithm, made available by the first author (Fabien Viger) at http://fabien.viger.free.fr/liafa/generation/.

[76] A graph is disconnected if it possesses at least two nodes such that no path has those two nodes as endpoints. In other words, a graph is disconnected if it is composed by more than one component (i.e. by more than one set of connected nodes), but those components are not connected between themselves.

		Axial graph	Random axial	Segment graph	Random segment
Order	v	68409		141560	
Size	e	99704		257231	
Mean degree	$<k>$	2,9		3,6	
Maximum degree	$k_{\max}$	47		7	
Alpha index	α	$1{,}34 \times 10^{-5}$		$1{,}15 \times 10^{-5}$	
Mean clustering coeff.	$\bar{C}$	0,17	$0{,}23 \times 10^{-4}$	0,41	$0{,}28 \times 10^{-4}$
Transitivity	C	0,21	$0{,}19 \times 10^{-4}$	0,43	$0{,}23 \times 10^{-4}$
normalized C	Cn	$3{,}07 \times 10^{-6}$	$2{,}78 \times 10^{-10}$	$3{,}04 \times 10^{-6}$	$1{,}62 \times 10^{-10}$
Diameter	D	264	27	348	19
normalized D	Dn	$3{,}86 \times 10^{-2}$	$3{,}91 \times 10^{-4}$	$2{,}46 \times 10^{-2}$	$1{,}34 \times 10^{-4}$
Average path length	L	73,2	11,5	97,7	10,5
normalized L	Ln	$1{,}07 \times 10^{-3}$	$1{,}68 \times 10^{-4}$	$6{,}90 \times 10^{-4}$	$7{,}42 \times 10^{-5}$

Tab. 2 – Summary of the values of 12 graph parameters, quantified for the axial and segment graphs, and for their random counterparts.

For the first five parameters (order, size, mean and maximum degree, alpha index) the values are the same for the actual graphs and for their random counterparts; this is because the Viger-Latapy algorithm uses the same number of nodes and edges of the original graphs (hence the same alpha index), but also the same degree distributions (hence the same mean and maximum degrees). What matters here is just the comparison between the values of the real axial and segment graphs. Regarding order (v) and size (e), the transformation from axial to segment graph actually doubles the number of nodes and almost triples the number of edges. Roughly speaking, one can say that it produces a segment graph that is twice as large as the axial graph. Their mean degrees (‹k›) are not very different, however: 2,9 and 3,6 for axial and segment graphs, respectively. But the maximum degree ($k_{\max}$) is much larger in the axial than in the segment graphs (47 and 7, respectively), suggesting different degree distributions. As for the alpha index (α), both graphs show similar values albeit extremely low (five orders of magnitude lower than a completely connected graph).

These values provide a first impression on the basic structures of the axial and segment graphs. Their absolute size is different, the segment graph being considerably larger. One would expect this increase in size to correspond to an also larger informational content in the segment map. However, the degree distributions of both graphs are also different, apparently with greater range and variance in the axial graph. These are also factors of structural richness, so one can say that the two graphs have different sizes but not that one is actually structurally more complex than the other. In fact, their alpha index suggests this, being similar in both graphs. Still, this parameter indicates extremely sparse graphs, very far from maximum connectedness. This is undoubtedly a consequence of the spatially-constrained nature of both axial and segment graphs. As both represent the spatial morphology of streets and how streets are connected to each other, they also encapsulate the strong lacunarity of street systems. Indeed, at the metropolitan level, the street network has enormous voids and is by no means homogeneously dense, but rather denser in some areas and very sparse in others.

The last four parameters in Table 2 (mean clustering coefficient, normalized transitivity, normalized diameter and normalized average path length) have different values for the real graphs and also for their random counterparts. We can thus ascertain the divergence from structural randomness of the real graphs. Both the axial and segment graphs show high values of local clustering and transitivity (i.e. $C, \overline{C} \gg 0$), but these are higher in the segment graph. Also, the values are similar in the segment graph (i.e. $C \cong \bar{C}$), but the axial graph shows a higher global clustering value (i.e. $C > \bar{C}$). In any case, both parameters are much lower in the random graphs than in the real ones (four orders of magnitude lower). This means at least two things. Firstly, that both segment and axial graphs possess strong internal *modularity*, which is not present in the random graphs. In network analysis, the property of modularity refers to the existence of internal sub-structures made of highly interconnected sets of nodes, which have also relatively weak external connections. This is a non-trivial property typical of spatial networks (Barthélemy 2010), which are strongly geographically constrained[77]. Secondly, that the axial graph, even if also highly modular, has a weaker local structure (i.e. local modules are not so interconnected as in the segment graph, because $\bar{C}$ is lower in the axial graph). This means that the segment graph may be a better descriptor of the local structure than the axial graph.

Regarding the last two parameters (normalized diameter and normalized average path length), both axial and segment graphs show also very different values from those of their random counterparts. The diameters are more than two orders of magnitude larger in the real networks. The average path lengths are also significatively larger. Again, these are typical properties of spatially-constrained networks. Diameters and average path lengths are long, because the actual spatial embeddedness of street networks simply forbids the existence of arbitrarily long links, which may be present in networks existing only in abstract mathematical space (as the random ones, considered here). Obviously, the non-normalized values of diameter and average path length are larger for the segment map, because the axial/segment transformation entails roughly the doubling of the size of the original axial graph. However, the segment graph has shorter normalized diameter and average path length. This means that, in spite of its larger size, the segment graph is actually less deep than an axial map of comparable size.

We now inspect the degree distributions of both axial and segment graphs (Figure 61, next page). Even if the number of nodes is doubled in the segment graph, it is easy to see from the histograms that the range of connectivities is much larger in the axial graph (range [1,47]) than in the segment graph (range [1,7]). Furthermore, the distributions are completely different: normal in the segments' case but highly right-skewed in the axial case (as shown by the Q-Q plots[78] on Figure 61). In fact, if we plot the absolute node degree frequency of the axial graph on a log-log plot (Figure 62, next page), the power-law nature of the degree distribution becomes apparent. The fit is clear (R2=0,99) for the range [3,23], i.e. excluding $k \in \{1,2\}$ and the noisy end of the tail[79].

This shows how the axial graph encapsulates important structural information that is not present in the segment graph. While the segment graph constrains the degree of nodes to a small range and to a trivial distribution (because it expresses the trivial fact that the number of streets in a junction has an actual physical limit), the much larger range of connectivities of the axial graph (expressing the very different fact that urban space, in terms of linear extension, has a wide range of variability) is able to relate the morphological structure of street networks to the more vast phenomenology of scale-free networks[80] (Barábasi 2003), even if these tend to occur without spatial constrains[81]. Actually, and in

[77] The modularity of spatial networks is fostered by the heterogeneous spatial distribution of nodes and by spatial constrains to the establishment of very long links.

[78] A quantile-quantile (Q-Q) plot is a graphical technique for determining if a sample is compatible with a certain test distribution (normal, in this case). The reference line indicates the expected concordance with that distribution. The greater the departure of the actual data points from this line, the greater the divergence from the test distribution.

[79] Nodes with k=1 are dead-ends and nodes with k=2 are lines/segments connected in a thread. Both degrees do not represent real street junctions.

[80] Networks with power-law degree distributions are sometimes said to be scale-free, or scale-invariant. This is because a power-law distributions have no defined mean or, in other words, no typical scale. Nodes with extremely large values (or hubs) are rare, but they do exist. In fact, they are vital for the cohesion of the network, which collapses if a few of them are deleted. By contrast, in a network with a normal degree distribution, the frequency of nodes with abnormally high degree quickly tends to zero and the overwhelming majority cluster around the mean, which is well defined and effectively characterizes the network, endowing it with a characteristic scale.

[81] Power-laws have been found in the degree distributions of many real networks. For example: in social networks (as scientific collaborations in journal papers, or the collaboration of movie actors in films), in digital networks (as the World Wide Web) and even in biological networks (as the protein-protein interaction network inside the cell). But all these networks are very little constrained or even free from the contingencies of space.

spite of the seemingly indifference of the axial graph to geometric properties, it is clear that it internalizes (in the degree of its nodes) much of the non-trivial geometric properties of urban space, namely the highly-structured variation of the linear lengths of streets (Hillier, 1999).

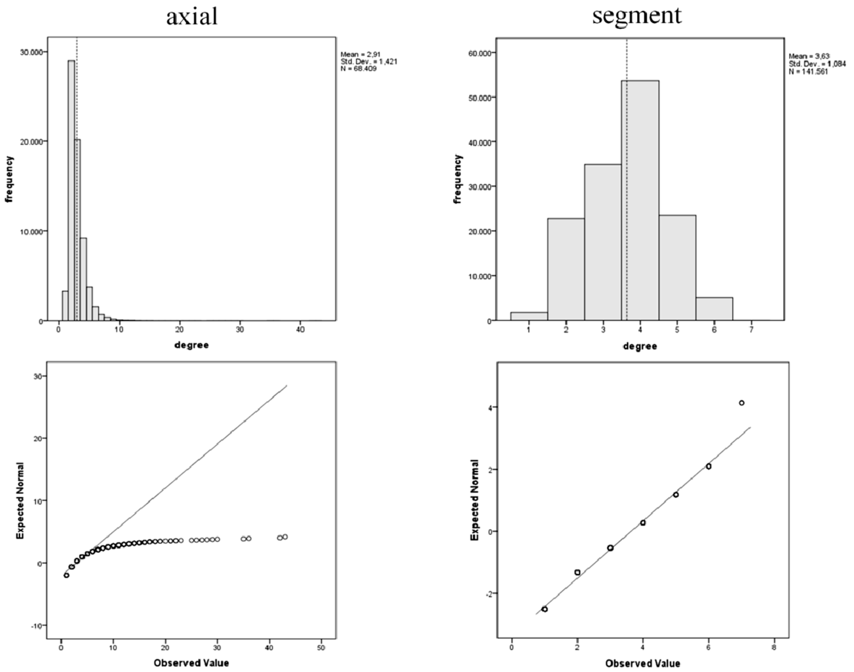

Fig. 61 – Histograms of the degree distributions of the axial and segment graphs and respective Q-Q plots.

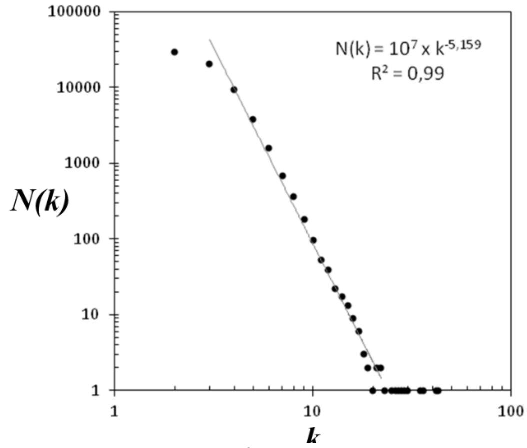

Fig. 62 – Log-log plot of the absolute node degree frequency in the axial map. The power-law fit includes only the $2 \leq k \leq 23$ interval and not the entire range of *k*.

This relation between the degree of nodes in the axial graph and the linear length of urban space can be further illustrated by a baffling morpho-structural property of cities. It has been suggested by Hillier (1999) and later demonstrated by Carvalho and Penn (2004) that axial lines capture in their length distributions deep and seemingly universal properties of general urban form. The latter authors have used a large database of axial maps[82] to show that the lengths of axial lines have universal scaling properties, largely independent of city-size or of cultural and geographical contexts, and are governed solely by a certain range of scaling exponents. In other words, the probability of occurrence of an axial line of a given length is merely a function of that length, no matter the location or the size of the city. The findings of these authors explain why axial graphs are capable of developing scale-free degree

[82] The database included 36 cities from 14 different countries.

distributions. Because axial line lengths distributions are also scale-free (i.e. short lines are very frequent but very long lines, albeit rarer, do occur) the connectivity of axial lines (i.e. their degree as nodes in the axial graph) tends to be a function of their length (Hillier 1999, 2002; Carvalho and Penn 2004). In what follows, we corroborate these findings but show also something new: that the same scaling behaviour also holds for the length of segments and that the scaling exponent ruling the lengths of axial lines and segments in our maps.

In principle, the length of segments has no clear relation with the length of axial lines (Figure 63), because segment lengths simply express the linear distance between two street intersections (or, alternatively, the lengths of the sides of urban blocks) and not the linear extension of roughly convex street stretches (as axial lines do). As Figure 63 shows, the correlation between the length of axial lines and the length of segments (produced by each axial line) is very low (R^2=0,104). This is due to the highly variable and heterogeneous connectivity of the street network, with some axial lines with no intermediate intersections (thus producing just one segment) and others with many (thus producing many segments). Obviously, no segment can be longer than its 'host' axial line, the reason why the points in the scatter are restricted to the area below a straight diagonal boundary, corresponding to lines and segments with the same length (i.e. to lines that were not broken into segments during the transformation, because they have no intermediate intersections). But, below that boundary, a great deal of variation between line and segment lengths is evident.

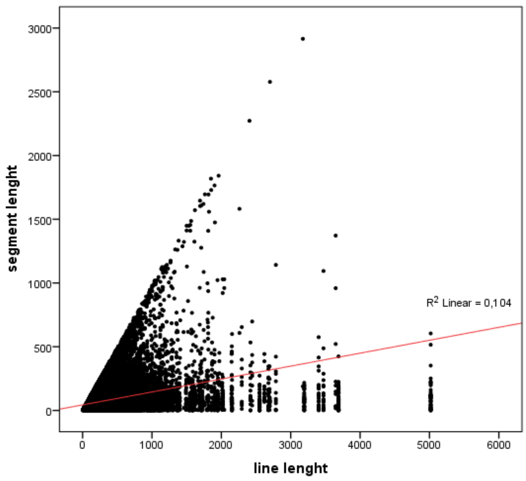

Fig. 63 – Correlation between lengths of axial lines and lengths of segments.

However, if we represent street and segment lengths against their respective ranks[83] in Zipf plots[84] (Figure 64, next page), it becomes clear that the distribution of sizes of both axial lines and segments are by no means random, but rather obey to scaling laws of the type $L_i = A \cdot R(L_i)^{-\gamma}$, where L_i is the line / segment length, $R(L_i)$ its rank, A a constant and γ the scaling exponent. In other words, two power-laws: showing that the number of lines and segments of a certain size is merely a function of the order of that size in the rank lists. Below a certain cut-off (here we choose 100 meters), this principle no longer holds, as line and segments enter a range of rather small and improbable lengths. But it applies to the entire upper tails of the distributions, spanning over four orders of magnitude on the rank axis.

[83] Ranks are in descending order, from the highest to the lowest values. Ranks are simple ordinal values, as the number of ties is insignificant.

[84] Zipf plots (named after the American linguist George Zipf) are log-log graphs, with the axes being log(rank order) and log(frequency). Zipf used them to study the relative occurrence of words in several languages.

What is more surprising is that the slopes of both curves seem to be roughly the same, which means that they may have approximately the same scaling exponent[85] (i.e. the sizes of axial lines and segments might be defined by the same scaling rule, in spite of their different natures). If we plot only the most evidently linear parts of the curves ($L_i \geq 100$), we can ascertain this more clearly (Figure 65). In fact, both curves are almost parallel, with exponent $\gamma \cong -0{,}4$, (γ_{axial} = -0,44 and $\gamma_{segment}$ = -0,39). Following (Carvalho and Penn 2004), we rescale the lengths of lines and segments by dividing each by their means (Figure 65, on the right). The individual exponents remain the same, of course, but both curves collapse onto roughly the same master curve, with $\gamma \cong -0{,}4$. This suggests that the probability of occurrence of an axial line or of a segment of a certain size might be governed by the same scaling principle.

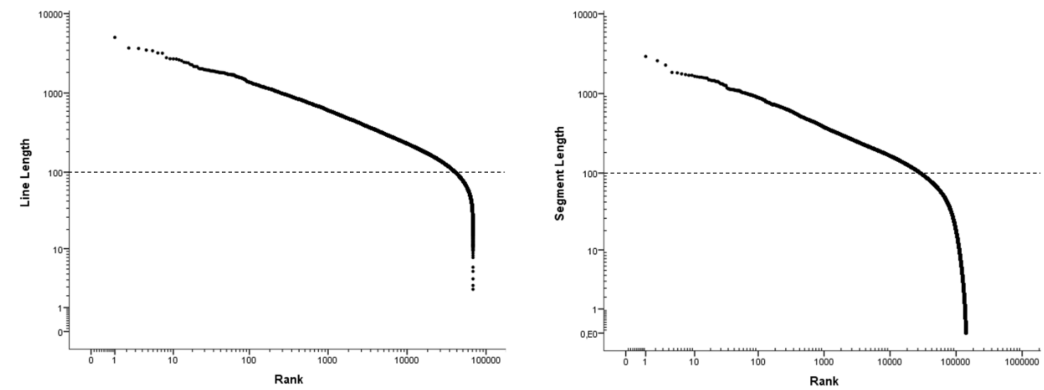

Fig. 64 – Log-log plots showing the rank-size distributions of axial line lengths (left) and segment lengths (right).

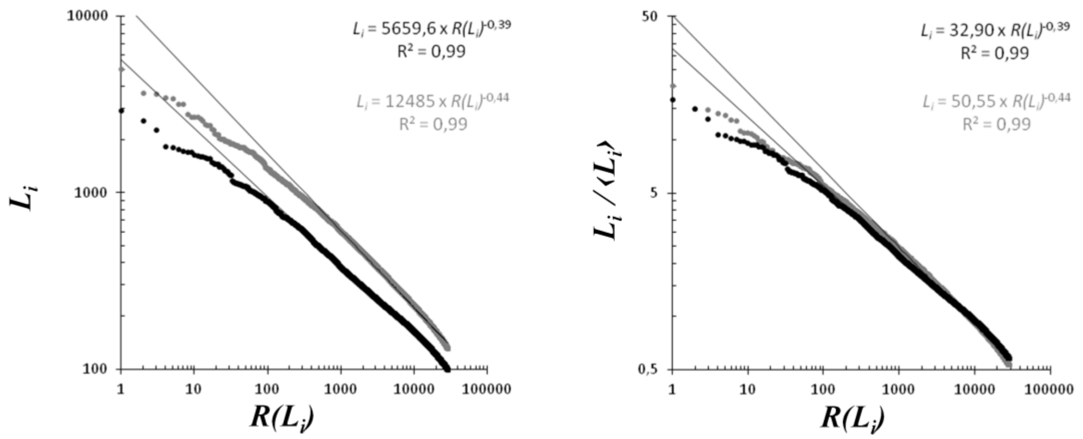

Fig. 65 – Log-log plots showing the rank-size distributions of axial line and segment lengths for L_i>100 meters (left), and with L_i rescaled (right).

What is interesting about these statistical regularities is that they seem to unite into the same descriptive framework two initially unrelated morphological properties - the lengths of axial lines and segments - describing *a priori* rather different things. Moreover, this type of auto-similarity is by no means an exclusive attribute of cities. In physics, it is well known that many systems, albeit greatly different, may exhibit strong similarities when close to their critical point (e.g. a phase transition). Near the critical point, microscopic properties and interactions are no longer relevant, because the system becomes self-similar across all scales: its organization principles, determined by a small number of global parameters, are all that matters. What is more remarkable is that such global parameters happen to be the same in very different natural phenomena - hence the term *universality*,

[85] The exponent of a power-law characterizes entirely the phenomenon at stake, because scaling the argument x by a constant factor c in $f(x) = ax^k$ causes only a proportionate scaling of the function itself. That is, $f(cx) = a(cx)^k = c^k f(x) \propto f(x)$.

used in physics to characterize such ubiquitous behaviour. Similarly, cities are critical systems, highly dynamic and far-from-equilibrium, although the relatively slow pace of such dynamics might lead us to think otherwise (Batty 2007). The scale-invariance and the universal classes discovered by Carvalho and Penn (2004) for the lengths of axial lines are indeed the hallmark of self-organized systems at the critical state (Bak et al 1987). Here, we take a small step in the same direction showing that segments lengths are also scale-invariant and, apparently, under the same scaling exponent of axial lines.

We cannot claim any generalisable conclusions from these results, as well as from the ones previously stated in this section, because they pertain only to the case under study. But they serve nonetheless to better understand both our axial and segment graphs and to show that they are able to disclose deep structural properties of the morphology of the metropolitan spatial system under study; and thus are indeed potentially fecund bases for our research.

4.2. Topological, angular and Euclidean conceptualizations of distance

The progressive advance of a fluid trough a porous material is known as *percolation*. By analogy, in a graph, the progression of the increasing distance values from a certain node to all the others may be seen as the 'percolation' of distance through that graph (Figure 66). When a fluid percolates, its movement rate depends on the material's porosity and on the fluid's viscosity. Likewise, the rate of distance 'percolation' in a graph depends on the graph's structure (its 'porosity') and on the type of metric used to define distance within it (determining distance's 'viscosity'). One can evaluate this by studying the distribution of the lengths of the geodesics from a given node to all the others, according to different distance metrics. This type of exercise is known in space syntax as 'step-depth' analysis, and is normally used to study the embeddedness of a certain node (or set of nodes) in the entire graph. Here we will do the same, but with a different purpose. Our interest is not on the particular node from which distances are measured, but rather on the distribution of the distance values themselves. In other words, we are interested in the 'percolation' pattern produced by each type of distance metric.

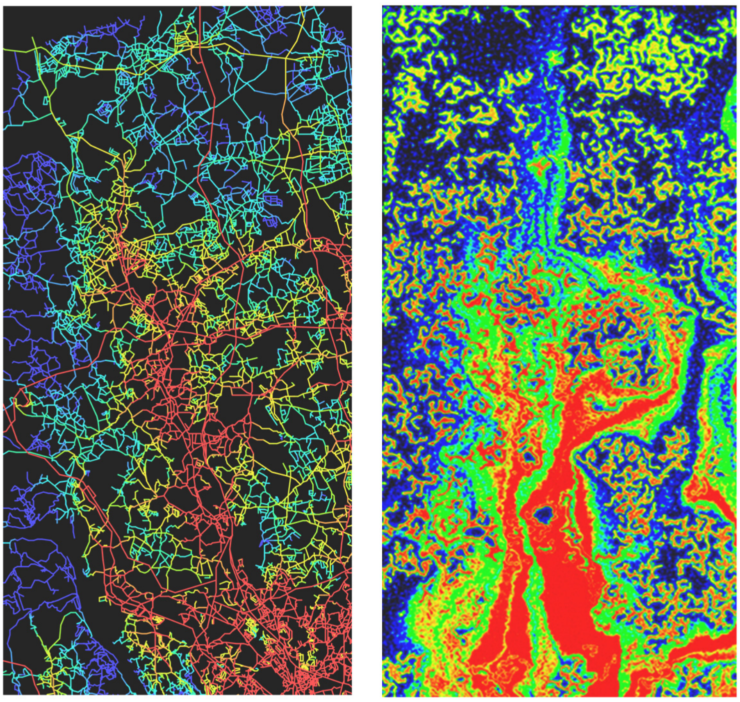

Fig. 66 – The analogy between the progressive increase of distances from a given node in a spatial network (left) and the percolation of a fluid (right; source: http://fluidflowvisualization.sandia.gov/trans_light_tech.html).

The objective of this analysis is twofold. First, we want to understand the behaviour of each distance metric when applied to the axial and segment graphs. As mentioned before, there is some consensus in the space syntax literature regarding angular distance (used in angular segment analysis, or ASA), as being a better predictor of urban movement than the topological or Euclidean distance concepts. This is usually taken for granted, but we will test this assumption nevertheless, to choose with appropriateness which type of model and distance metric to use later. Secondly, the definition of the radii of analysis (a very important aspect of syntactic analysis, explained below) also implies a choice on distance metrics. In order to compare the predictive value of the two models and the different possible distance and radii metrics, we need to create a compatible scale relating them. This will also be done in this phase, through the study of distance percolation.

On the axial graph distance is purely topological, being always 1 between adjacent nodes. The distance between a pair of non-adjacent nodes is the shortest topological path between them. But distance can assume diverse natures on the segment graph, where edges can be weighted accordingly to three different distance concepts: topological, angular or Euclidean. In the segment graph, topological distance is similar to the axial graph. The distance between two adjacent segments/nodes is always 1, except if they were produced by the same axial line (i.e. are completely co-linear), in which case it is 0. Thus, if not radius-constrained (see below), topological distance in the axial or segment graphs is equal.

Angular distance is quite different; it is proportional to the angle of incidence between two intersecting segments. In other words, for each edge between each pair of nodes in the segment graph, a value between 0 (no turn) to 2 (180º turn) is assigned, representing the angle of incidence of the two segments[86]. Thus, in angular distance terms, the shortest path between two non-adjacent nodes is not that with fewest turns, but that with the minimum amount of total angular turn. In a sense, angular distance reproduces topological distance whenever the angle between segments is 0º or 90º (the distance cost in these cases being respectively 0 and 1). But it also allows for a continuous variation in the interval [0,2] according to the angle of incidence between segments, therefore producing a more fine-grained analysis. The rationale behind this is that people, when moving in urban spatial networks, naturally try to minimize angular distance (choosing the straightest path) more than minimizing topological distance (fewest turns) and even more than Euclidean distance (shortest path). This might seem unlikely at first, thus it is important to note again that there is evidence from cognitive science suggesting that this is so. It seems that people do try to minimize travel distance in urban systems, but in a way that is constrained by the visual, geometrical and topological properties of urban spatial networks (Hillier Iida 2005). On reflection, this seems in fact rather more plausible than to assume that we can ascertain with accuracy Euclidean distances in complex spatial systems.

The last type of distance metric is normal Euclidean distance, but measured through the network between the midpoints of each segment (i.e. not as the crow flies). Again, the Euclidean distance between two non-adjacent segments is simply the shortest path in meters (or any other Euclidean distance unit) between them. Figure 67 (next page) summarizes these three distance metrics and their implementation in the axial and segment graphs.

At this point we need to introduce yet another analytical concept used in space syntax, that of radius of analysis. It is clear that urban space is used and perceived at different scales, from the short walk in the neighbourhood to car trips of tens of kilometres. Accordingly, urban spatial structure should be analysed in a manner that captures both its local and global properties, independently of whatever the

[86] This angle is measured according to the direction in which the path is being calculated and always forwards (i.e. without allowing turning back which could, in some circumstances, produce a smaller sum of angular turn). The direction of turn is immaterial and the turn angle is always positive.

metric used for accounting distances. This is achieved by calculating the centrality of each node, not only in regard to all the other nodes in the graph (global analysis) but also to all those within a variable neighbourhood around it (local analysis). This neighbourhood, or radius, can be defined using the same distance metrics mentioned before. Thus, each line/segment/node can have varying centrality values, according to the radius at which analysis is carried out and to the way such radius is defined. The number of possible radii is potentially very large, because the analysis can be run sequentially, from the most local to the global levels.

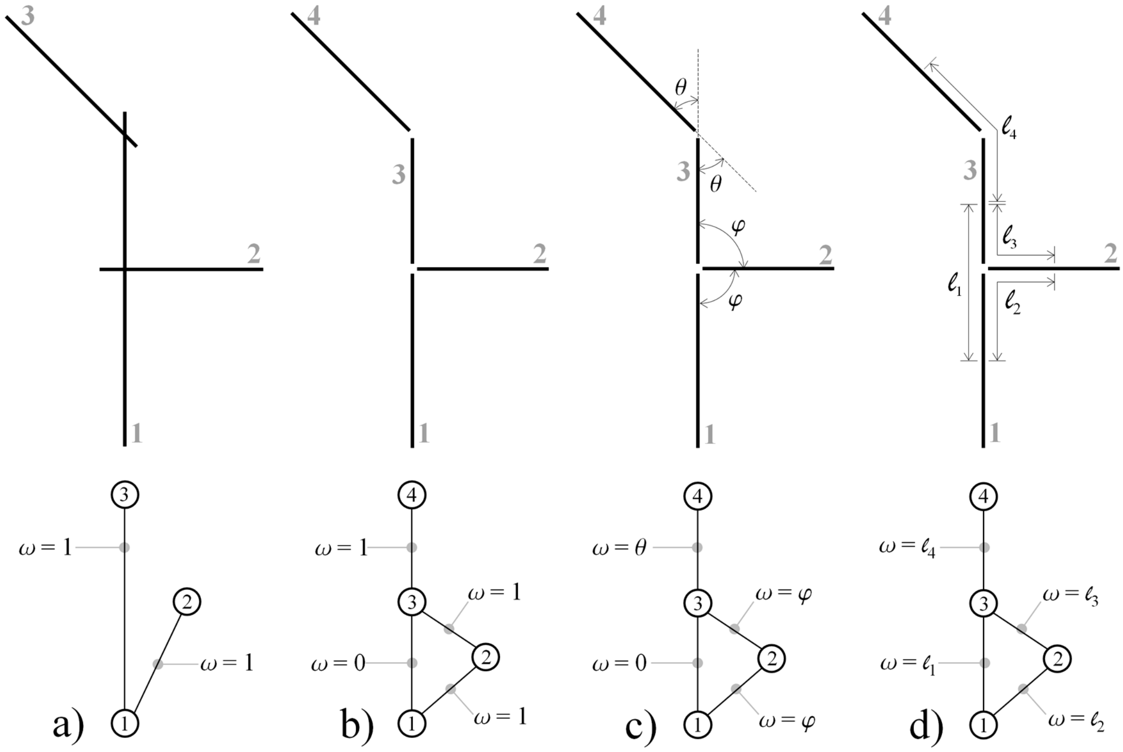

Fig. 67 – The four possible distance conceptualizations in space syntax, applied to the axial and segment graphs. a) A system of four axial lines and its respective unweighted axial graph; distance is purely topological, i.e. the cost of moving from one node to the other (ω) is always 1, and the shortest paths are those with the minimal number of changes of direction (least turns). b) The same system transformed into segments and the corresponding weighted segment graph; topological distance is similar in the segment graph, but ω is zero between co-linear segments (as between nodes 1 and 3). c) Angular distance weights each edge of the segment graph with ω proportional to the angle of incidence between segments; shortest paths are those with minimal amount of angular turn. The value of ω varies within [0,2] and is defined so that the distance gain will be 0 when there is no angular change, 1 when the turn is a right angle and 2 if it is a 180º turn. d) Euclidean distance weights each edge with ω equal to the real Euclidean distance separating the midpoints of each segment, measured along the segments themselves; shortest paths are those with minimal metric length.

The technique of restricting the calculations to a certain radius around each node is also useful to mitigate a problem characteristic of configurational analysis known as 'edge-effect', or sensitivity to boundary conditions. When a certain area, which is part of a continuous system, is isolated for modelling, it is expectable that spaces near the edge of the model will show very low centrality levels when assessed from the point of view of the entire graph. This happens not because those spaces are truly less central, but solely because the limit of the model bounds them to be so.[87] The use of a restricted radius of analysis greatly limits edge-effect, because then all nodes are being analysed in

[87] That is, nodes near the edge of the graph are logically less connected and more distant from all the other nodes, than those located deep within the graph.

respect to an averagely equal neighbourhood. Of course, the edge-effect is only artificial when the actual spatial system is larger than the model and where the limit is artificially imposed. Otherwise, it is quite natural and corresponds to the actual segregation of peripheral spaces.

Summarizing, we have two types of graph (axial and segment) and three possible definitions of distance to assess (topological, angular and Euclidean). In order to do this, we have chosen the closest line/segment to the centre of the circle that bounds our study area, as the origin of the step-depth analysis that we will perform for each type of distance metric.

In Figure 68 (next page) we show the graphic depiction on the segment map[88] of the distances of all nodes to the origin node (marked with a cross), using the three distance metrics mentioned before. The chromatic range varies between red (nearest) to blue (farthest). Topological and angular distances produce similar patterns, but with subtle differences. Topological distance spreads out more evenly, while angular distance emphasizes the straightest paths, with distance increasing fast beyond them. Topological distance is not so sensitive to path straightness (although these paths are also privileged) and increases clearly slower. In both cases, distance percolation is strongly non-uniform, producing a star-like pattern (more evident in the angular case), following the main radial roads emanating from the centre of the study area. The distributions of distances (depicted in the histograms and box-plots[89] of Figure 68, on the right), even if approximately normal, are clearly right-skewed with many outliers at maximum distances, particularly in the angular case. This seems a strong sign of edge-effect, with the farthest nodes showing abnormal depth values when compared to the rest of the distribution.

Euclidean distance produces a completely different pattern. It percolates quite uniformly through the segment graph, producing concentric rings of increasing distance values. Unlike the previous two metrics, it seems insensitive to any particular structural differentiation in the network, aside from variations in road-density. In fact, the histogram shows a bi-modal distribution with a strong decrease in occurrences between distances 12000 and 24000 meters. This corresponds to a less dense area of the street network (indicated in Figure 68 c) between dashed lines), particularly to the north and east parts of the study area, due to the presence of some significative reliefs (north-east) and of intensive agricultural areas (north). However, it is interesting to note that Euclidean distance seems much more robust to edge-effect than topological or angular distances. The distribution is not right-skewed and there are no outliers, meaning that extreme distances do not increase at such an accelerated pace as they do for the previous metrics. This suggests why Euclidean distance is probably the best way to define the radius of analysis, as it is indeed current practice in recent space syntax studies (Turner 2007, Hillier 2009). Unlike topological and angular distances, which favour very long lines or very straight paths, Euclidean distance is insensitive to these structural particularities. A radius defined in a topological or angular way, can suffer from distortions caused by nodes that connect much more readily than other nodes to remote parts of the graph (e.g. very long lines or almost straight threads of segments), making it difficult to constrain the system in a uniform way. In contrast, Euclidean distance always constrains the neighbourhood of each node to a nearly uniform circle, therefore being a more constant way of defining the radius boundary. But it seems quite incapable of detecting any meaningful spatial structure, when compared to the two other metrics.

[88] Here we use here only the segment map, because for this purpose (step-depth analysis) and regarding topological distance, the axial and segment graphs are equivalent.

[89] Box-plots depict datasets as vertical or horizontal bars (or boxes), delimited by the upper and lower quartiles of data, and with the mean represented as a line on the bar. Additionally, minimum and maximum values are represented as lines, extending beyond the box. Outliers can also be represented on the diagram.

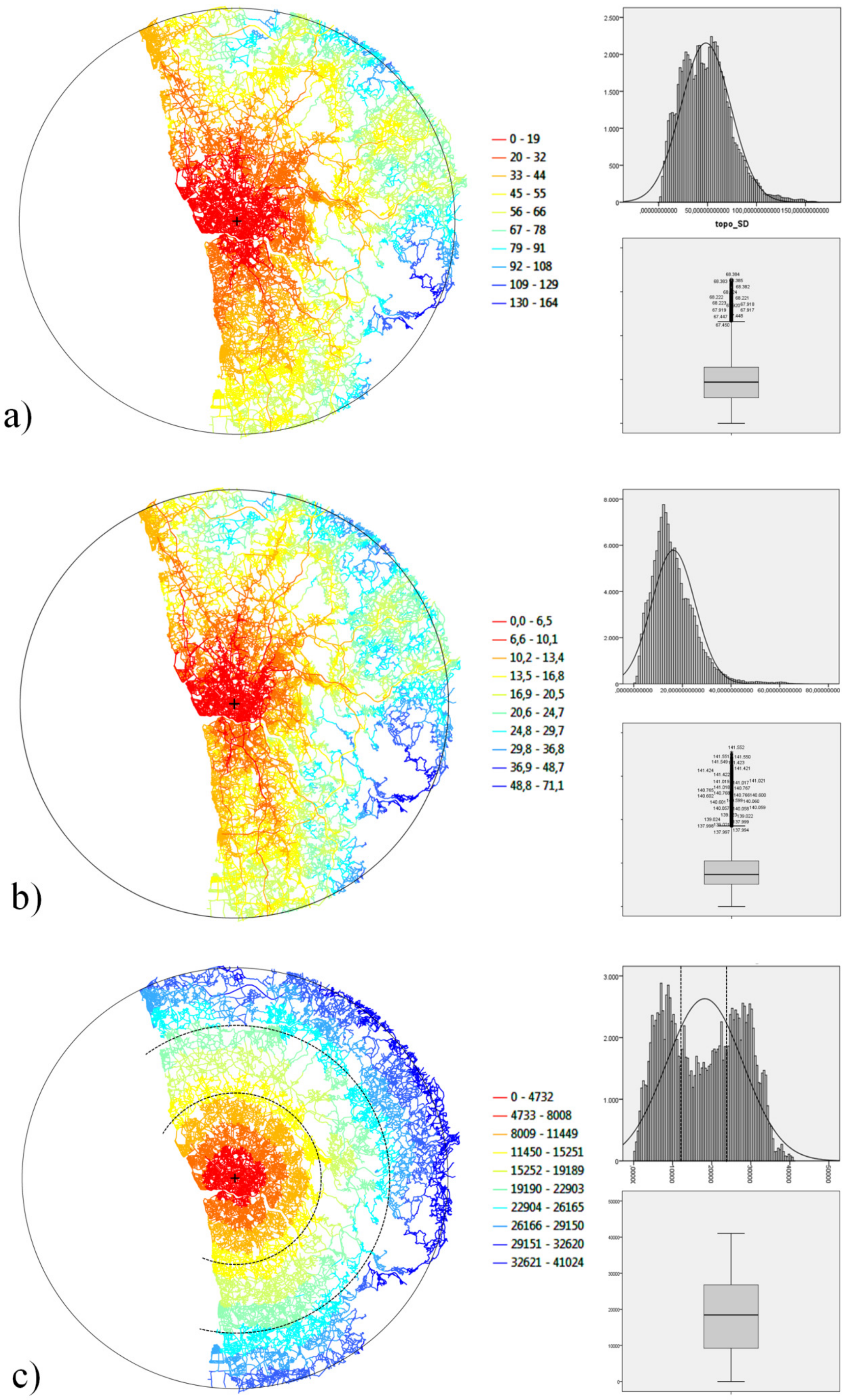

Fig. 68 – Topological (a), angular (b) and Euclidean (c) distance patterns, produced from a node localized in the centre of the study area (the small crosses in each map on the left). Histograms and box-plots of the distance values of each type of metric (right).

All these properties can be further explored by plotting the distance values against their respective ranks[90] (Figure 69, next page). This type of plot is useful here, for it makes clear the progression rate of distance through the graph. Several things become evident at once. Firstly, all three distance metrics show the same type of progression: a short, fast-growing start, followed by a long linear progression and a sharp, exponential-like increase at the end. The similarity among the progression curves suggests that it is indeed possible to establish some kind of common scale between the three distance metrics. Secondly, the distance from which edge-effect begins to take place becomes clear, as represented by the transition from the linear to the final exponential phase. From a certain point on, distance begins to increase at an accelerated pace in relation to rank, because distance increases continuously but fewer and fewer nodes are found at each distance level and, therefore, the rank increases slower and slower[91]. In other words, when the number of nodes at each distance level begins to decrease with increasing distance, edge-effect begins to take place: the number of nodes diminishes solely because the graph's limit is drawing near[92], increasingly restricting the number of nodes at each distance increment. Thus, the break in the linearity of the distance/rank progression is caused by the limit imposed on the graph through the definition of an arbitrary boundary.

This conclusion allows us to define with certainty the maximum distance beyond which analysis will be no longer valid for each metric; but it can also serve as a general method for detecting edge-effect in general configurational analysis. It is also important to note that in our model the topological radius-radius[93] distance is 49; much less than the acceptable maximum distance, which is 70 (beyond which edge-effect starts). Thus, it seems that radius-radius is just another distance in the range of possible radii and that it might be convenient to significatively extend the analysis beyond that level. On the other hand, radius N[94] seems to have only a theoretical interest because, in practical terms, it is the radius most prone to edge-effect.

For all distance metrics, the onsets of the progression curves exhibit power-law behaviour. To make this clear, in Figure 69 we have isolated the initial tail of each distance progression in small inset log-log plots. In fact, it is known that in networks with strong geographical constrains the sizes of neighbourhoods grow according to power-laws (Lämmer et al 2006; Csányi, Szendröi 2004). In particular, (Csányi, Szendröi 2004) studied the western US power network, the Hungary water network and the London Underground network, showing how they all exhibit power-law neighbourhood grow. Here we study the number of nodes at each distance level and not the growing size of neighbourhoods, but the two quantities are obviously proportional and thus we find the same effect. It is common practice in space syntax studies to consider a greater density of radii at closer distances than at longer ones. There are implicit reasons to do this (e.g. to scan more thoroughly the range of walking distances) but they were never formally discussed or theoretically supported. However, here we provide an additional finding suggesting why this should in fact be so. If a node's neighbourhood increases initially as a power-law, a greater variance of its centrality values is to be expected at closer distances than at longer ones. Therefore, an initial higher density of radii should indeed be considered, in order to fully capture the potentially more variable short-range spatial structure.

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[90] Ranks are in ascending order, from the smallest to the largest values. Tied values are resolved by fractional ranking, i.e. they acquire the mean of the values they would have under simple ordinal ranking. Thus, the increase of rank values is proportional to the number of occurrences at each distance level.

[91] This can also be observed in the histograms of Figure 68, as the continuous decrease of occurrences beyond a certain distance.

[92] Obviously, if the graph were infinite, the number of nodes at each distance level would increase indefinitely.

[93] Radius-radius is equal to the mean depth of the most integrated node. It is normally regarded as the greatest distance at which edge-effect is expected to be negligible, albeit here we argue otherwise.

[94] Radius N, or radius infinity, is equal to the graph diameter (i.e. the longest possible distance).

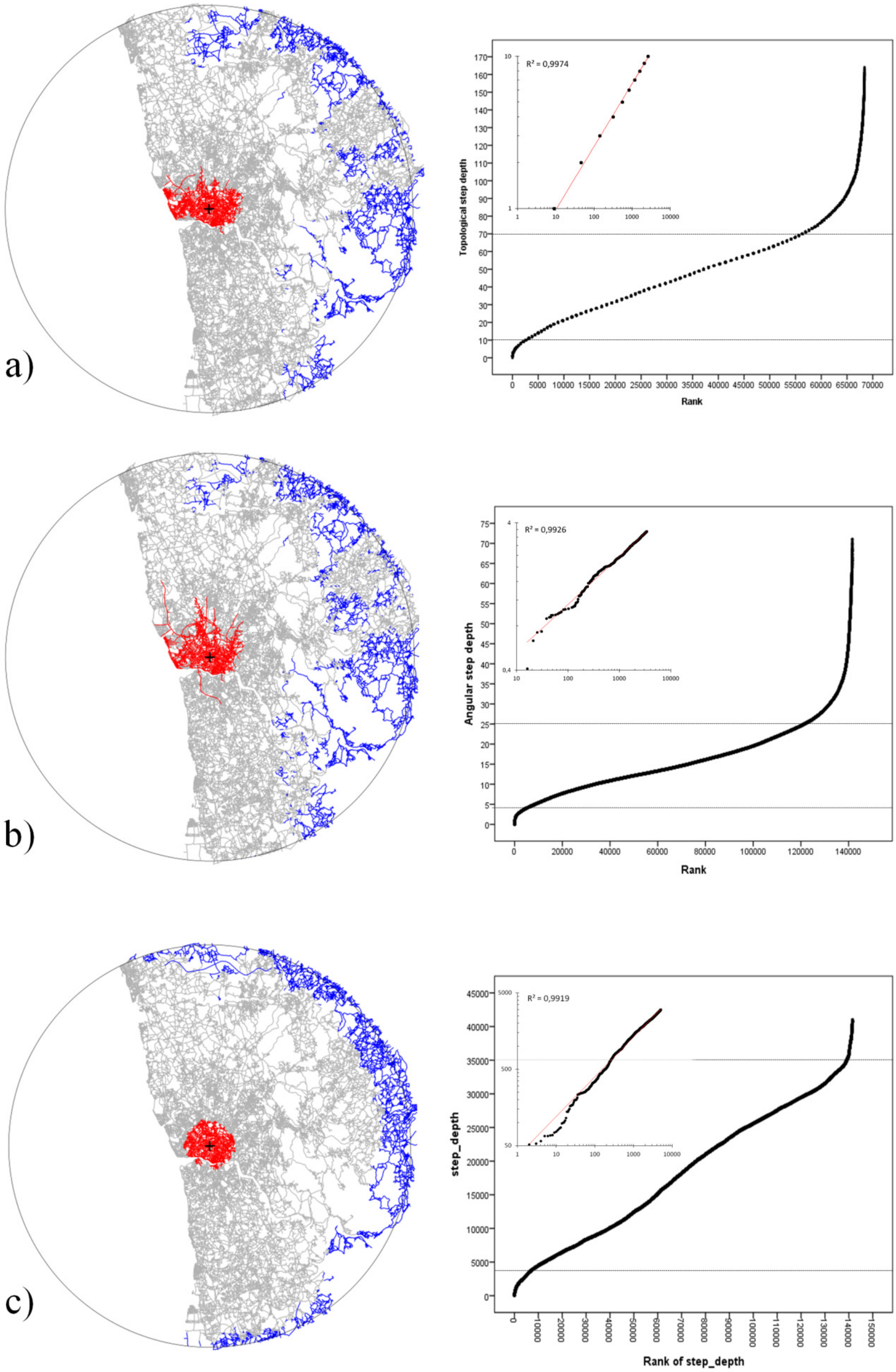

Fig. 69 – Distance/rank plots, showing the progression of distance values from the origin node: a) topological, b) angular and c) Euclidean distances (right). The inset log-log plots show the power-law behaviour during the initial increase phase (below the lower dashed line in each plot). The maps on the left depict the three phases of distance progression: in red (initial power-law phase), grey (linear phase) and blue (final exponential phase).

In Figure 69 we show all these effects, depicted in the distance/rank plots and also directly on the segment map. The chosen cut-offs between the power-law start, the linear phase and the final exponential phase, are represented by dashed lines on the plots. The segment/nodes above and below these cut-offs are coloured in the segment maps in red (below the first cut-off), grey (between cut-offs) and blue (above the last cut-off). Thus, the red area is where distance progresses as a power-law, the grey area the linear progression zone and the blue area the exponential progression zone, subject to edge-effect.

The similarity between topological and angular distances is again quite clear. For both these metrics and beyond a certain distance, the edge-effect is very pronounced, not limited to the edge of the model and penetrates areas with lesser node density and connectivity. These are particularly deep areas of the graph, where one can say that edge-effect is real, i.e. it is not caused by an arbitrary boundary definition, but by real physical barriers (in this case rivers and pronounced reliefs). On the other hand, it is interesting to verify that there are also other areas close to the boundary which are not affected by edge-effect, because they are reached long before the moment when distance progression starts to be constrained by the boundary of the model. In other words, they benefit from being dense and highly connected, but especially for being made easily accessible by the structure of the network. As for the areas below the first cut-off, i.e. those where distance progresses as a power-law, they are also similar for topological and angular metrics. A further progression along certain straightest paths is visible for angular distance, but the concerned areas are rather similar, encompassing the entire city of Oporto and even some zones outside its administrative limits. This initial distance progression behaviour should indeed be taken into account, for it can extend itself over considerable areas.

Again, with respect to Euclidean distance, things are slightly different albeit with the same general behaviour. The edge-effect phase is shorter, but now solely caused by the limit of the model, as it can been seen by the almost perfect blue contour along its edge. Furthermore, the interior areas that were deep when topological and angular distances were considered appear now in grey on the map, i.e. within the main linear progression zone, which is also more extensive. The initial power-law progression is also present, but now the area concerned is smaller and perfectly circular. All this reinforces what has been said before, regarding the adequacy of Euclidean distance as a radius-defining metric, but also in regard to its inability in revealing meaningful urban spatial structures. This is reflected by the fact that there are no areas with accessibility differences, as there were with topological and angular distances.

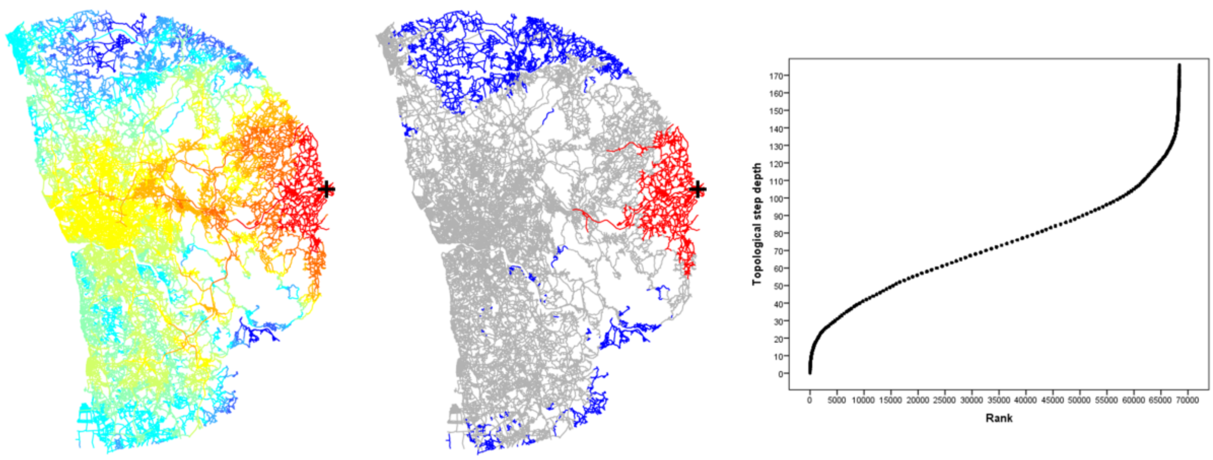

Fig. 70 – Topological distance pattern from a very peripheral node.

We have tested these findings also with peripheral nodes (i.e. near the model's boundary), in order to ascertain if they were still valid or just a consequence of studying distance percolation from a very central and interior node. In Figure 70 (previous page) we show an example of the same exercise, but now done with a peripheral node and just for topological distance. The result is similar even if the initial phase of the progression is longer. This is undoubtedly due to the fact that the grid is much sparser here than at the centre of Oporto and to the proximity of the model's boundary. These two factors concur to make the number of nodes at close distance quite low and, consequently, to produce a slower initial evolution of the rank values.

We now turn to the problem of finding a similar scale of radii for the three distance concepts. This will make possible their subsequent comparative assessment, through the correlation of their analytical results with observations of real urban movement. The previous analysis has shown that the behavior of the three distance metrics is comparable, so we begin by correlating the distance values produced by the three metrics among themselves. We take topological distance as the central metric for comparison purposes, because its values are always integers while the values of the other metrics are real numbers and vary continuously. As topological distances cannot exist out of the set of natural numbers, they are a convenient basis for establishing a uniform scale.

In Figure 71 (next page) we show two scatter plots comparing the topological distances from the origin node, with angular (a) and Euclidean (b) distances. As suggested by the previous analysis, topological and angular distances are highly correlated (R^2=0,93) but the correlation between topological and Euclidean distances is also strong (R^2=0,79). The reason for the patterns in the scatters being clouds of points rather than single curves is due to the fact that topological distance values recur quite often, while angular and Euclidean values vary continuously. Thus, for each integer value of topological distance, there are many non-integer values of angular and Euclidean distances. However, because the correlations between the three metrics are so high, we can make a drastic simplification without the risk of grossly deviating from the actual relation between variables. We simply take the mean of all continuous angular and Euclidean distances occurring at each integer value of topological distance and plot them against the latter to obtain two single curves (Figure 71, c and d).

These two curves make clearer what was already guessable from the previous scatter plots: that there is a range of high collinearity between topological and angular / Euclidean distance values, beyond which the linear relationship changes and becomes noisy. Furthermore, the transition point occurs roughly at the same distances that we have identified before as the beginning of edge-effect, which suggests that the observed noise can clearly be related to it. We can thus isolate the most linear part of the two curves (Figure 71, c and f), in order to obtain two regression equations, which describe the relationship between topological and angular/Euclidean distances.

With these two equations we can finally build a radii conversion table, taking integer topological distances (as x values) and producing the correspondent angular and Euclidean distances (as y values). The final scales of radii to be used in further analysis are summarized in Table 3. As stated before, we consider an initial higher density of radii (every two topological steps) below topological distance 10, in order to cope with the higher initial variability of each node's neighborhood. From topological distance 10 on, we consider a radius every 5 topological steps, up till distance 70, around which we have observed the beginning of edge-effect. This scale of topological radii is then converted into angular and Euclidean distances, through the equations of Figure 71. We rounded the resulting Euclidean values to the nearest hundred to obtain more graspable numbers, because distances in meters are more familiar than sums of angular turns. But the maximum deviation from the actual value is 50 meters, which is a rather negligible distance in urban terms. In Figure 72, three scatter plots combining the three radii scales show that they are, in fact, equal.

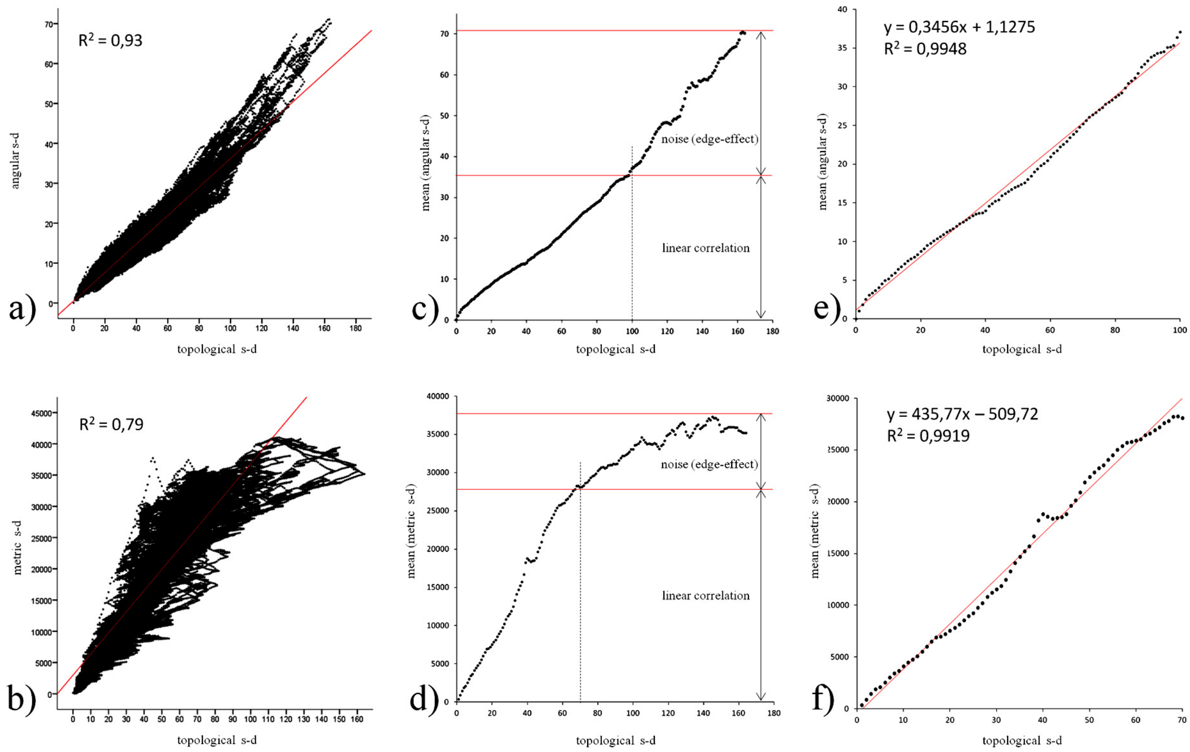

Fig. 71 – Correlations between the three distance metrics: a) angular and topological; b) Euclidean and topological; c) mean angular and topological; d) mean Euclidean and topological; e) mean angular and topological, up to topological distance 100; d) mean Euclidean and topological, up to topological distance 70.

Topological	2	4	6	8	10	15	20	25	30	35	40	45	50	55	60	65	70
Angular	1,8	2,5	3,2	3,9	4,6	6,3	8,0	9,8	11,5	13,2	15,0	16,7	18,4	20,1	21,9	23,6	25,3
Euclidean	400	1200	2100	3000	3800	6000	8200	10400	12600	14700	16900	19100	21300	23500	25600	27800	30000
Euclidean (not rounded)	362	1233	2105	2976	3848	6027	8206	10385	12563	14742	16921	19100	21279	23458	25636	27815	29994
error	38	-33	-5	24	-48	-27	-6	15	37	-42	-21	0	21	42	-36	-15	6

Tab. 3 – Selected distance values for topological, angular and Euclidean radii of analysis.

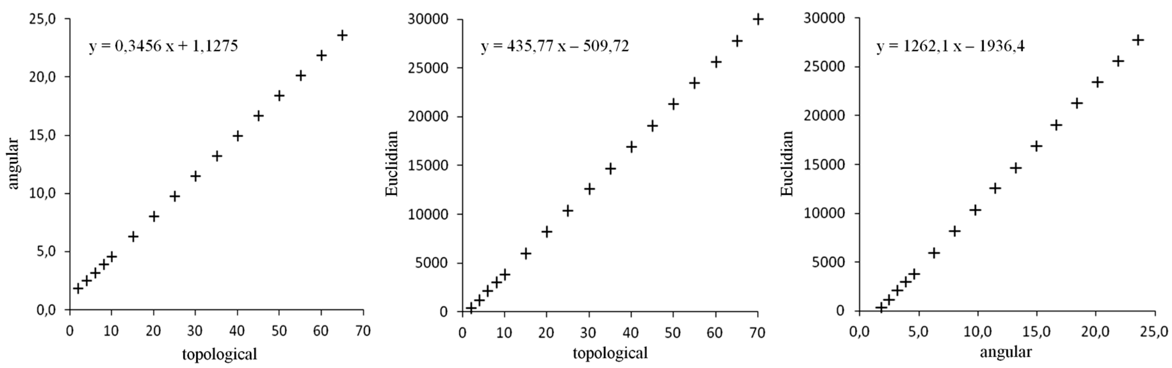

Fig. 72 – Correlation between the selected distance values for topological, angular and Euclidean radii. Correlation is absolute (R^2 = 1) for all cases.

4.3. NETWORK CENTRALITY MEASURES: INTEGRATION AND CHOICE

Having reached this result, we now have everything we need to compare the posdictive performance of each graph (axial and segment) and of each distance and radii definition metrics (topological, angular and Euclidean). However, we first must introduce the two main measures of centrality used in space syntax to evaluate the relative importance of each node in the network. Up till now, we have only studied distances from a given node or much aggregated graph properties, as average shortest path lengths. But the main assumption of space syntax analysis is that a node's potential as an attractor of urban movement and activity is a function of its centrality regarding all the other nodes in the graph (or all the other nodes within a sub-set of the graph, defined by a certain radius). At the basis of that type of analysis are two centrality measures borrowed from graph theory and social network analysis, know as *closeness* and *betweenness* centralities, studied and defined by Linton Freeman (1977; 1979). The introduction of these measures into space syntax has led to their development and slight modification, including the terms used to designate them. Within space syntax they are known as *integration* and *choice*, respectively.

Integration measures the relative proximity of each node to all the other nodes, according to one of the distance criteria enunciated before. It is therefore a measure of a node's *accessibility*, when regarded from all the other nodes in a graph. Integration is a standardized version of a simpler measure (which is actually equal to the closeness centrality of general network analysis), called *mean depth* in space syntax. In a connected undirected graph ***G***=*(V,E)* the mean depth of a node $i \in V$ is given by the expression,

$$MD_i = \frac{1}{v-1} \sum_{i,j \in V} d_{ij} \tag{8}$$

where v is the total number of nodes in V (or, alternatively, in the sub-graph defined by a certain radius around i) and $\sum d_{ij}$ the sum of the geodesics between i and all the other nodes in V (or within radius), measured according to topological, angular or Euclidean distances. In order to standardize mean depth between zero and one, Hillier and Hanson (1984) proposed a variation of the measure, called relative asymmetry (RA). The expression used to calculate the RA of a node i is,

$$RA_i = \frac{2(MD_i - 1)}{v-2} \tag{9}$$

Because RA values are smaller for more accessible nodes and larger for less accessible ones, the reciprocal of RA is normally used[95]. This is, finally, what space syntax calls the integration value of a node.

$$Integration\ (i) = \frac{1}{RA_i} \tag{10}$$

The measure of integration was initially developed only for axial graphs (ASA is a more recent development in space syntax). The measure actually used then was slightly different from the one stated above, because a normalization process was still carried out after the calculation of RA[96]. In fact, the RA values of graphs of very different sizes are not comparable, because MD (as the name indicates) is a mean and not a normalized value. All that the formula does is calculating the mean of

[95] The reason for this is that urban movement and functions correlate negatively with RA, because more central spaces have lesser RA values. In order to obtain positive correlations (which are intuitively more graspable than negative anti-correlations) integration is used instead.

[96] The normalized value of RA (real relative asymmetry, or RRA) was used instead. RRA was calculated by dividing RA by the RA of the root of a diamond-shaped graph with the same number of spaces (called D-value). The rationale behind this is that such a graph has a guaranteed normal distribution of depths independently of size, and therefore can serve as a common 'yardstick' for making values comparable. See (Krüger 1998) for details on the normalization procedure.

all geodesics from a given node; and this value can of course assume different orders in systems of very different sizes[97]. Thus, even if RA is bonded to vary in the [0,1] interval, its mean is still prone to vary with the size of the system. This is only relevant in systems varying greatly in size and structure, but it constituted a problem for the comparative analysis of cities and therefore a hindrance for research. However, such normalization procedure is not applicable to segment graphs, even if we consider only topological distance (unlike RA, which remains valid for the segment graph and for all types of distance). Given that ASA has become the main analytical procedure in syntactic urban analysis, the use of normalized axial integration has simply become obsolete (Hillier 2012).

In what concerns this study these issues are not so relevant, because we are dealing only with one spatial system, even if in different states of development. But all comparative analysis between different temporal moments of the system (described in the following chapters) will involve several numerical precautions in order to cope with the possible lack of comparability between values. In any case, for the current exercise (which is carried out solely with the present state of the network) the only care that we should take is to guarantee that the radii used in the analysis are comparable, so that each type of graph and distance definition may be evaluated accurately.

Betweenness centrality (or choice, as it is called in space syntax), measures a rather different node property. Betweenness is the most direct expression of the idea of centrality: it measures the degree to which each node is part of the shortest paths between all the others (i.e. is in-between all the others). It can be seen as a measure of the overlapping of such paths on each node. It depends on two things: the number of geodesics passing through each node and the possible existence of multiple geodesics connecting each pair of nodes. Thus, when there is only one geodesic between a given pair of nodes j and k, each node i on that geodesic acquires the betweenness value $b_{jk}(i) = 1$; if there is more than one geodesic between j and k, $b_{jk}(i)$ is proportional to the presence of i on those geodesics:

$$b_{jk}(i) = \frac{n_c(i)}{n_c} \ : \ j \neq i \neq k \tag{11}$$

where n_c is the number of geodesics between j and k and $n_c(i)$ is the number of geodesics between j and k containing the node i. The betweenness centrality $C_b(i)$ is then the sum of the values acquired by i in each geodesic passing through it,

$$C_b(i) = \sum_{j=1}^{v} \sum_{k=1}^{v} b_{jk}(i) : j \neq i \neq k \tag{12}$$

The values of $C_b(i)$ depend strongly on the size of the network, but a normalized version of the measure was also proposed by Freeman (1979). It is given by the ratio between the value of $C_b(i)$ and the maximum possible value a node could acquire in a graph of the same order[98]. This is the formula used in space syntax to calculate the choice value of a given node i,

$$Choice\ (i) = \frac{2C_b(i)}{v^2 - 3v + 2} \tag{13}$$

Again, the shortest paths between each pair of nodes $j, k \in V$ can be defined topologically, angularly or metrically. And as for integration, the choice value of each node i can be calculated regarding the shortest paths between all nodes in the graph (global choice), or only for those within a certain radius around i (local choice). The caveats mentioned for integration on comparing values of very different

[97] The mean distance between all the spaces of a village is obviously different from the mean distance between all the spaces of a metropolitan region.

[98] Freeman (1977) proved that the maximum value possible for $C(i)$ is achieved only by the central node of a star graph and given by $(v^2 - 3v + 2) / 2$.

graphs (in size and in structure) apply also for choice, not least because Freeman's normalization was devised for unweighted graphs using only standard topological distance. But also the remarks made before for integration, regarding this study in general and the current exercise in particular, are valid for the choice measure.

These two centrality measures have acquired different functional meanings in space syntax. Both have proven to be strongly correlated with levels of actual urban activity (e.g. movement flows, functional diversity and intensity) as the literature on the subject shows (Penn et al. 1998, Hillier 2012). But they are also seen as describing quite different things (Figure 73). Because spaces with high integration are more near (or more accessible) to all the others, integration is thought as describing the potential of a certain node to act as a destination. Highly accessible locations naturally 'attract' and concentrate centrality functions, which then act as further attractors of urban movement and activity. Thus, integration is related with *to-movement*, or the potential of a node to generate movement which is directed to it. Choice, for its part, is thought as describing the potential of a certain node to act as a channel for movement between other locations. Because a high choice value means that a node is virtually 'in the middle' of all the others, it also means that it is frequently a part of the routes between all the others. Therefore, a space with a high choice value attracts *through-movement,* i.e. passing-by movement from various origins to various destinations. It may also then attract urban functions that profit with visibility and seek the exposition to strong urban flows, or others that profit by being strategically located in-between urban centers (Hillier 1996). From all this, it follows that spaces with both high integration and choice values, are also spaces that beneficiate from both attributes, i.e. being frequent destinations as well as frequent channels.

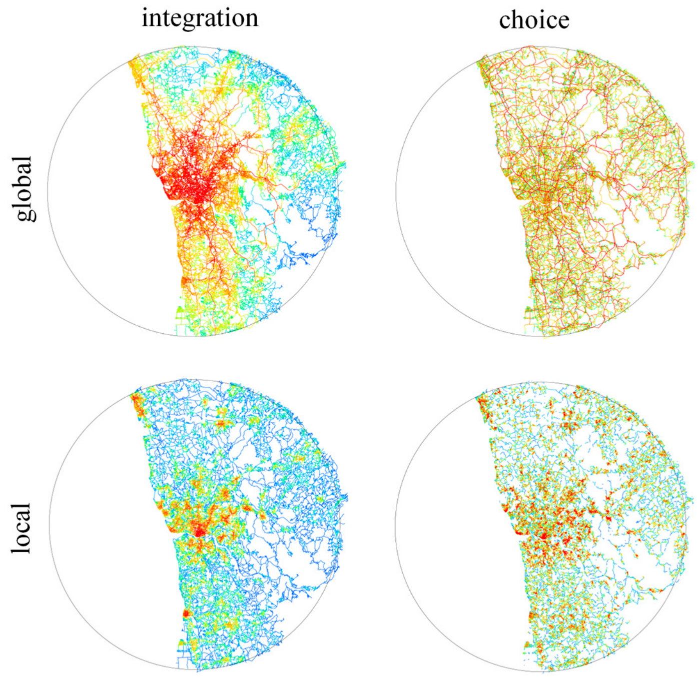

Fig. 73 – General patterns of integration and choice, at the local and global scales.

What is more interesting about these functional translations of the integration and choice measures, is that they capture the two basic elements in each urban trip: selecting a destination from an origin - integration - and choosing a route, and so the spaces to pass between origin and destination - choice (Hillier 2012). Thus, the two centrality concepts seem able to encapsulate the elementary phenomenology of urban movement. And because both integration and choice can be calculated for each node regarding a very large range of radii around it, these two basic elements (destination/route) can also be assessed at varying spatial scales. For example, a local integrated area might reveal an active local neighborhood and a street with high local choice might turn out to be a neighborhood's high street. In the same way, a globally integrated area may correspond to the core of an urban system and a street with high global choice to an important urban thoroughfare.

This dialectic relationship between the centrality measures and their functional significance and impact on urban movement is central in space syntax's theory of the city and will be further developed in the following chapters. But here we will not dwell longer on them, because our main objective is just to validate empirically the spatial network model. That is the theme of the next section.

4.4. CORRELATIONS WITH URBAN MOVEMENT FLOWS

We now reach the last stage of this chapter's exercise: the correlation between observed urban movement flows and the centrality patterns produced on the two possible types of graph (axial and segment), using the three types of distance and radius definition metrics (topological, angular and Euclidean) and the two centrality measures (integration and choice). In order to do this, we will use four datasets of vehicular movement observations, obtained from independent official sources. These are the "National Institute for Road Infrastructures" (INIR), the public company "Portuguese Roads, SA" (EP), the "Laboratory for Traffic Analysis" (LAT) of the Faculty of Engineering of Porto University and the Municipality of Valongo[99] (CMV).

A very brief description of the organization of the Portuguese National Road System (SRN) is necessary, in order to make clear the different geographical scopes and traffic types of the four data sets. The SRN is divided in two tiers: the National Core Network (RNF - comprising the Principal Itineraries[100], IPs) and the National Complementary Network (RNC - comprising the Complementary Itineraries[101], ICs; the National Roads[102], ENs; and the Regional Roads[103], ERs). The SRN includes also the "National Motorway Network" (RNAE), comprising only roads of that type[104]. The RNAE is a transversal class of the SRN, being composed by both IPs and ICs (when these assume the form of motorways). All the road infrastructures not included in the SRN (e.g. the street networks in urban areas) belong to Municipal Road Networks (RVMs) and are managed and maintained by municipalities.

The first two data sources (INIR and EP) provide public access traffic data[105], the former regarding the RNAE and the latter regarding the remainder of the SRN. The data provided by both entities are recorded continuously by automatic devices installed on the network and made public through annual reports. The data comes in units of annual average daily traffic (AADT), being produced by exactly the same calculation methodology[106]. The datasets provided by these sources (INIR and EP) can

[99] Valongo is a municipality of the first suburban ring around Oporto.

[100] IPs are the communication pathways of higher national interest. They support the entire national road network, providing the links between urban centers with supra regional importance, and from these to the major ports, airports and borders. They are almost exclusively roads of the motorway type.

[101] ICs are the pathways that establish the links of greater regional importance as well as the main ring and access roads in the metropolitan areas of Lisbon and Porto. Their function is to ensure the links between the fundamental network and the urban centers of municipal or supra municipal importance. They are usually motorways, but not always.

[102] ENs fulfill the same functions of ICs, albeit at a lower hierarchical level, being standard roads many times embedded in urban areas.

[103] ERs are similar to ENs, but they serve areas of touristic interest and ensure the links within acknowledged territorial units formed by several municipalities.

[104] That is, roads with dual-carriageways and central reservation, not allowing property access or at-grade intersections and exclusively for motorized traffic

[105] INIR traffic data can be accessed at: http://www.inir.pt/portal/RedeRodovi%C3%A1ria/Relat%C3%B3rios/tabid/142/language/pt-PT/Default.aspx. EP traffic data can be accessed at: http://telematica.estradasdeportugal.pt/pls/alqueva/f?p=105:1:0.

[106] Until recently, both entities (INIR and EP) were the same. Thus, they share many methodological procedures.

therefore be merged and used as a single one. The third source (LAT) kindly provided us with data gathered by the "automatic management smart system" (SIGA) of Oporto's Municipality, which controls the traffic light system. Such data, pertaining only to traffic flowing within central Oporto's urban grid, are gathered by automatic devices in the street pavement or by cameras, being also recorded continuously and provided in AADT units. The last source (CMV) has kindly provided us with vehicular counts carried out for the realization of the municipality's noise map[107]. This dataset comes in units of average hourly traffic (AHT), but the count and AHT calculation methodologies were not provided. The data sources and the basic characteristics of each dataset are summarized in Table 4.

Data source	No. observations	Date	Data type	Surveyed netwks.
INIR/EP	43	2010	AADT	RNAE+RNF+RNC
CMV	28	2010	AHT	RNC+RVM
LAT	52	2011	AADT	RVM

Tab. 4 – Summary of the datasets of vehicular movement flows.

If the INIR and EP datasets share the same data treatment methodology and can therefore be merged (called hereafter INIR/EP), the same is not true about the other two datasets (CMV and LAT). In fact, the former datasets are the only for which we could access the calculation methodology for estimating AADT values. Moreover, the CMV dataset comes in AHT diurnal values, whose range is completely different. Figure 74 shows a plot of the observations of the three datasets sorted by ascending order. We have rescaled the CMV dataset by multiplying its values by 24 (the hours of the day), in order to make it minimally comparable with AADT values. Figure 74 shows also a plot of a logarithmic transformation of the values, which stabilizes their variance and linearizes their rank curves. It seems evident that all datasets have rather different scales and variability ranges, and that therefore should not be mingled, but correlated separately with the network's centrality values.

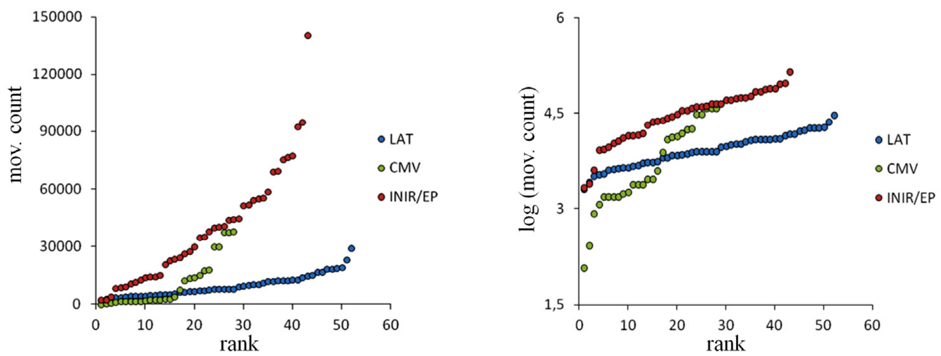

Fig. 74 – Rank ordered traffic counts of each movement dataset (non-logged, left; logged, right).

In fact, each of the three datasets (INIR/EP, CMV and LAT) corresponds to a different mix of vehicular traffic. In figure 75 (next page) we show the spatial distribution of the measurement locations (a total of 123, for all datasets). All observations in the INIR/EP dataset are made either on the RNAE, RNF or RNC networks, and its observation points are rather well distributed over the whole study area. Thus, this dataset represents regional and trans-regional traffic, ranging the entire metropolitan area and beyond, flowing in the spatial network's 'super-structure' of motorways and main roads. On the other hand, observations in the CMV dataset are restricted to the Municipality of Valongo, an area of the first suburban ring of the metropolitan region. They are made both in the RVM and in the RNC networks, therefore representing not only local but also trans-municipal traffic.

[107] The realization by municipalities of "noise maps" has recently become mandatory in Portugal, as part of Municipal Master Plans (PDMs).

Therefore, the CMV dataset allows gauging the model's performance when postdicting movement on a suburban area and on a meso-scale of metropolitan trips. Finally, observations in the LAT dataset occur exclusively in the RVM network and in the metropolitan region's central core. This dataset therefore represents local and inter-municipal vehicular movement, in a highly dense and central urban area.

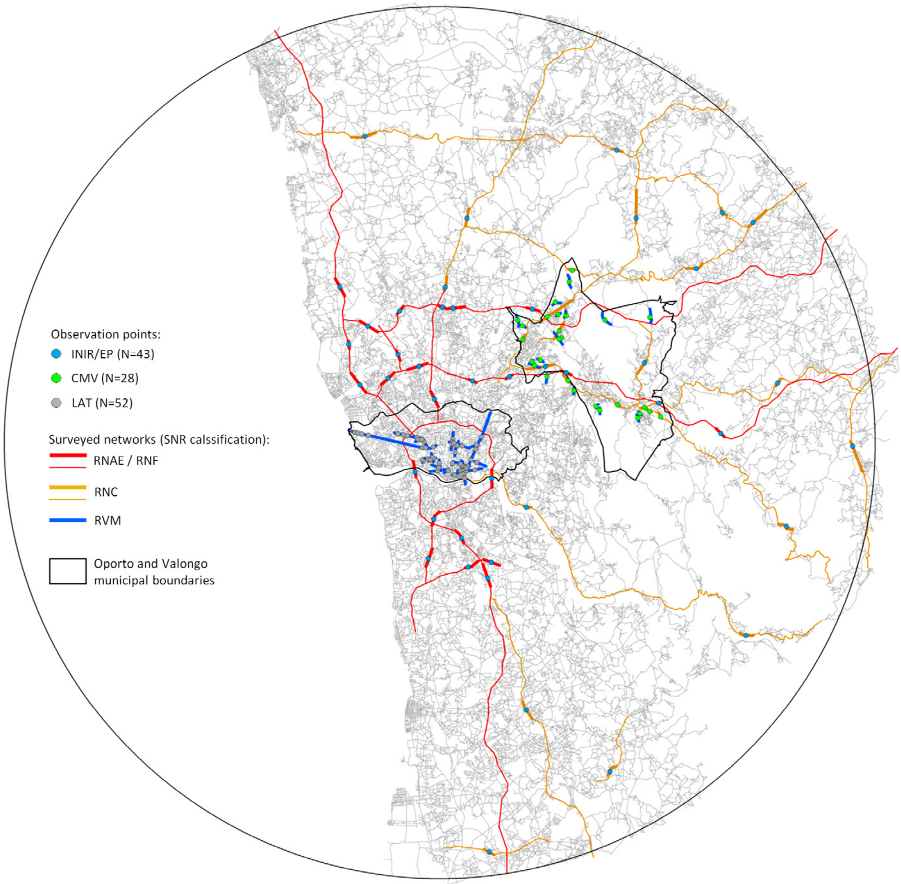

Fig. 75 – Spatial distribution of each dataset's observation points on the study area.

What we will probe, therefore, is the capability of each graph (axial and segment) and each distance/radius definition metric (topological, angular and Euclidean) to postdict vehicular movement at different scales and in different geographical and morphological areas of the metropolitan spatial network. Figure 76 (next page) shows for each of the three movement datasets as well as for a logarithmic transformation of each one, their histograms, Q-Q plots and box-plots. Clearly, all datasets deviate from normality, particularly in the upper parts of their distributions (i.e. they are right-skewed). Moreover, the LAT and INIR/EP datasets have outliers at their maximum values. Both these characteristics are detrimental to a standard Pearson product-moment correlation exercise, such as the one we intend to conduct. But the logarithmic transformation is enough to regularize that. All the transformed datasets are clearly normal (points following close the expected line in the Q-Q plot, and without clear defined pattern around the horizontal line in the detrended Q-Q plot), without outliers and within similar ranges. We will therefore use the logged values of movement counts. Centrality values have also varying statistical distributions. Integration (or closeness) values are known for being typically normally distributed, but choice (or betweenness) values are known for being typically very right-skewed, usually of the log-normal or power-law types (Blanchard and Volchenkov 2009). Therefore we will also always transform choice values logarithmically, but keep integration values as they are.

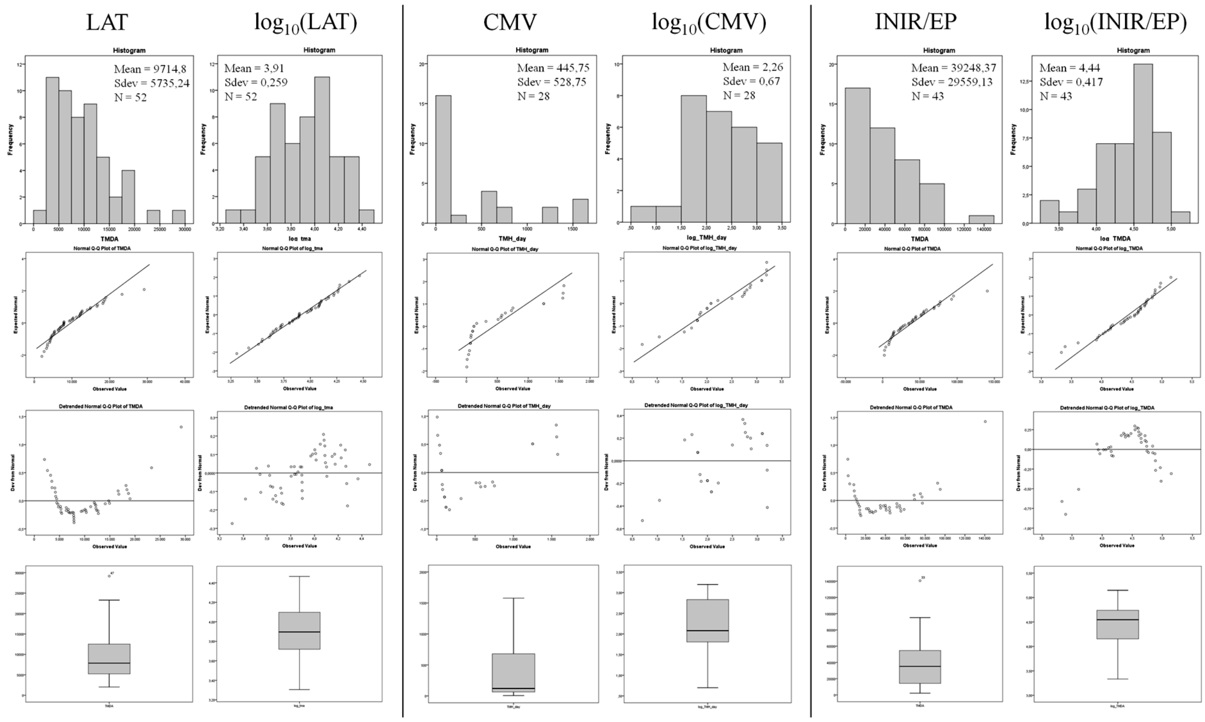

Fig. 76 – General descriptive statistics of each movement dataset.

We used the UCL DepthMap (Turner 2001, 2004) software for computing the graphs' centrality values, as we will do for all configurational analysis in this work. From the possible nine combinations of distance and radius metrics, only six are available in DepthMap (Euclidian distance with topological or angular radii and topological distance with angular radius, are not available). For all these, integration and choice values were computed, using the 17 radii defined in section 2.2. Topological distance constrained by topological radius will be calculated in the axial graph and all the other combinations in the segment graph.

The method for producing the correlations is simple. Centrality values of integration and choice at 17 different radii are calculated for each of the possible combinations of distance/radius, producing 5 different versions of the segment graph/map and 1 of the axial graph/map. These elements are loaded into a GIS platform together with the points of the three movement datasets. The maps are then over layered with the points, and through a simple join operation the centrality values for each line/segment are acquired by the points they intersect. Thus, each movement observation point (a total of 123, containing the correspondent observed traffic volume) acquires 204 new attributes, corresponding to the centrality values of integration and choice produced by the 6 possible combinations of distance/radius metrics (2 centrality measures x 6 distance/radius combinations x 17 radii = 204 attributes). The resulting tables are then exported to a statistical analysis platform and the bi-variated correlations between the points' centrality values and the observed traffic volumes are calculated.

In Figures 77, 78 and 79 (pages 119-121) we report the results of the exercise for each of the three movement datasets, LAT, CMV and INIR/EP. Each figure shows 12 linear plots, one for each centrality measure (integration and choice) and for each analysis type (distance/radii combination). The plots depict on the *y* axis the correlation value (Pearson's r, varying between -1 and 1) and on the *x* axis the 17 selected radii (from the most local to the most global). We draw attention to the fact that the *x* scale is comparable across all plots, as demonstrated in section 2.2. What the Figures show then, is the varying postdictive performance (r-values, y axis) of the several distance/radius combinations, across a wide range of equivalent spatial scales (or radii, x axis). The charts also indicate the correlation values that are statistically significant (i.e. have an associated p-value less than 0,01) through the different colours of the resulting curves (light-red for p>0,01 and red for p<0,01). Also, the maximum correlation values and respective radius are marked on each graph.

These Figures can be read at least in three different ways: independently (i.e. by dataset), vertically (i.e. by centrality measure) and horizontally (i.e. by distance/radii combination). We will adopt this methodology and proceed with their analysis using these three types of reading: by dataset (LAT, CMV and INIR/EP), by centrality measure (integration and choice) and by analysis type (six possible distance/radius combinations, noted hereafter as: Top/Top, Top/Met, Met/Met, Ang/Met, Ang/Top and Ang/Ang, where “Top” stands for topological, “Ang” for angular and “Met” for metrical or Euclidean).

If we look at the results of each dataset, it is noticeable that correlations are generally low in the first one (LAT), stronger in the second (CMV) and very strong in the third dataset (INIR/EP). Maximum significative correlations are r=0.67 for LAT (Integration Ang/Met, radius 6000), r=0.73 for CMV (Choice Ang/Met, radius 21300) and r=0.93 for INIR/EP (choice Ang/Met, radius 30000). This seems to indicate that, all other things being equal, our spatial network model generally performs better when postdicting larger-scale vehicular movements, even if the LAT dataset also shows some significative correlations (especially regarding the last three analysis types, Ang/Met, Ang/Top and Ang/Ang). Nevertheless, the spatial scales at which the maximum correlations are attained are consentaneous with the traffic characteristics of each dataset. Thus, for LAT the maximum correlation (r=0.67 for integration Ang/Met) is attained at 6000 meters, an intra-urban scale; for the CMV, the maximum correlation (r=0.73 for choice Ang/Met) is attained at 21300 meters, an inter-urban scale; and for INIR/EP, the maximum correlation (r=0.93 for choice Ang/Met) is attained at 30000 meters, which is the radius of the study area and therefore represents the entire metropolitan region. Because all datasets pertain to vehicular (and not to pedestrian) movement, the correlation results for the most local radii are overwhelmingly non-significant. This is also consentaneous with the type of movement data used here, but it does not mean that such scales are functionally irrelevant. It simply means that the data are not related to them (which would not be the case if pedestrian movement flows were taken into account). Another general conclusion to be drawn from the results of each dataset, is that radius infinity (or radius N) shows quite often a drop on the correlation value, confirming the remarks made in section 2.2 about the edge-effect that such scale of analysis entails.

If we read the results vertically, looking now at the behaviour of the two centrality measures (integration and choice) no striking pattern is noticeable, with both measures producing equally significant correlations. Still, integration seems to perform better at postdicting micro-scale traffic (LAT, Ang/Met) and choice seems to perform better at postdicting meso-scale (CMV, Ang/Met) and macro-scale (INIR/EP, Ang/Met) traffic. Integration also tends to produce more variable correlation curves with also varying degrees of significance; while choice tends to attain an early plateau in the correlation values and to stabilize after that. This is particularly noticeable regarding integration Ang/Met in the INIR/EP dataset, which shows a significant *negative* correlation at low radii (r=-0.43 for choice Ang/Met at radius 2100 meters). This is a very realistic result, because the spaces surveyed in this dataset (motorways and highways) are indeed global-scale oriented, unavoidable for longer trips but less used for shorter ones.

We now look at the results of each analysis type for all datasets and centrality measures. The several analysis can be divided in two groups, one constituted by the first three distance/radius combinations (Top/Top, Top/Met, Met/Met) and another by the last three (Ang/Met, Ang/Top, Ang/Ang). The first group shows systematically lower correlations, in several cases without any statistical significance; while the second group shows always better results. This is evident in the LAT and CMV datasets and to a lesser extent also in the INIR/EP dataset. The common characteristic between the analysis types of the second group is that distance is angular in all of them. What this means is that the angular conceptualization of distance is indeed a more realistic and effective model of human perception of distance than the Euclidean or even the topological concepts, as it has been frequently claimed by Hillier (Hillier and Iida 2005, Hillier 2012). Indeed, at the level of short-range trips, topological distance (Top/Top and Top/Met) seems less able to produce good results (even if the same is not true for long-range trips). As for Euclidean distance (Met/Met), whatever the scale considered, is in all cases the worst postdictor of urban movement. In all datasets, integration calculated with Euclidean distance is not able to produce a single significant correlation. As for choice, only in the CMV and INIR/EP datasets the Euclidean weighted version of the measure produces some results, but still among the weakest. Even if this confirms previous findings from the space syntax field it is nonetheless surprising, because Euclidean distance is still and by far the most commonly used distance-cost in urban spatial network analysis, not only in practical applications but also in academic research (Porta et al. 2006, 2008, 2010). But it truly seems an inadequate distance concept, when applied to urban phenomena. The assumption of angular distance as the preferential distance metric has yet another consequence: turning the segment graph into the preferential descriptor of urban spatial structure, since angular distance is not applicable to axial maps.

Regarding the analysis types in the second group (Ang/Met, Ang/Top, Ang/Ang), correlations are always significant for all datasets. Since in all these analysis distance is always angular, what we are in fact comparing here is the type of radius definition. Euclidean radius produces always the best correlations with the choice measure, which also outperforms integration in two of the three datasets (CMV and INIR/EP). Integration seems less sensitive to the way radius is defined: higher correlations are attained with different radius deffinitions in each dataset. But if we look at the shapes of the correlation curves and also at the significance of their values, further details become apparent. The way the correlation varies across spatial scales is different for each type of radius definition. The measures constrained by Euclidean radius seem to produce more variable correlation curves, with also variable significance. Whereas the other radius types (topological and angular) produce curves that become flat after an initial rise, i.e. more homogeneous and monotonous curves. This seems to indicate that Euclidean constrained measures have a greater precision in identifying the spatial scale with which a certain phenomenon correlates. In fact, this is noticeable not only with Euclidean constrained angular analysis (Ang/Met) but also with topological analysis (Top/Met), especially in the INIR/EP dataset. Looking at the moment and significance level of the correlations, it becomes apparent that the Euclidian radius is also more descriminant. The higher correlation usually appears as a distintic peak, while with other radius definitions it is usually just another value in a more-or-less flat curve. Moreover, Euclidean radius is also able to produce significant negative correlations, which have a clear relation with the nature of the datasets employed here and thus a realistc translation. On the other hand, the more homogeneous and monotonous curves produced by the other types of radius deffinition seem to indicate a lesser sensitivity to structural differentiation, producing unrealistic continuous correlation values.

Thus, we may say that the empirical validation of the spatial network model has attained satisfactory results, allowing us to use it as a reliable representation of the evolving metropolitan spatial structure. The segment graph, using angular distance constrained by metric radius is undoubtedly the best option for further work. Even if the samples of vehicular movement used here are small, they pertain to different scales of metropolitan traffic and to different geographical contexts of the metropolitan region. For all these samples significant correlations with the model structure were found: the model emulates very well ($r=0,93$) long-range vehicular movement, satisfactorily ($r=0,73$) mid-range vehicular movement and somewhat less satisfactorily ($r=0,67$) short-range vehicular movement.

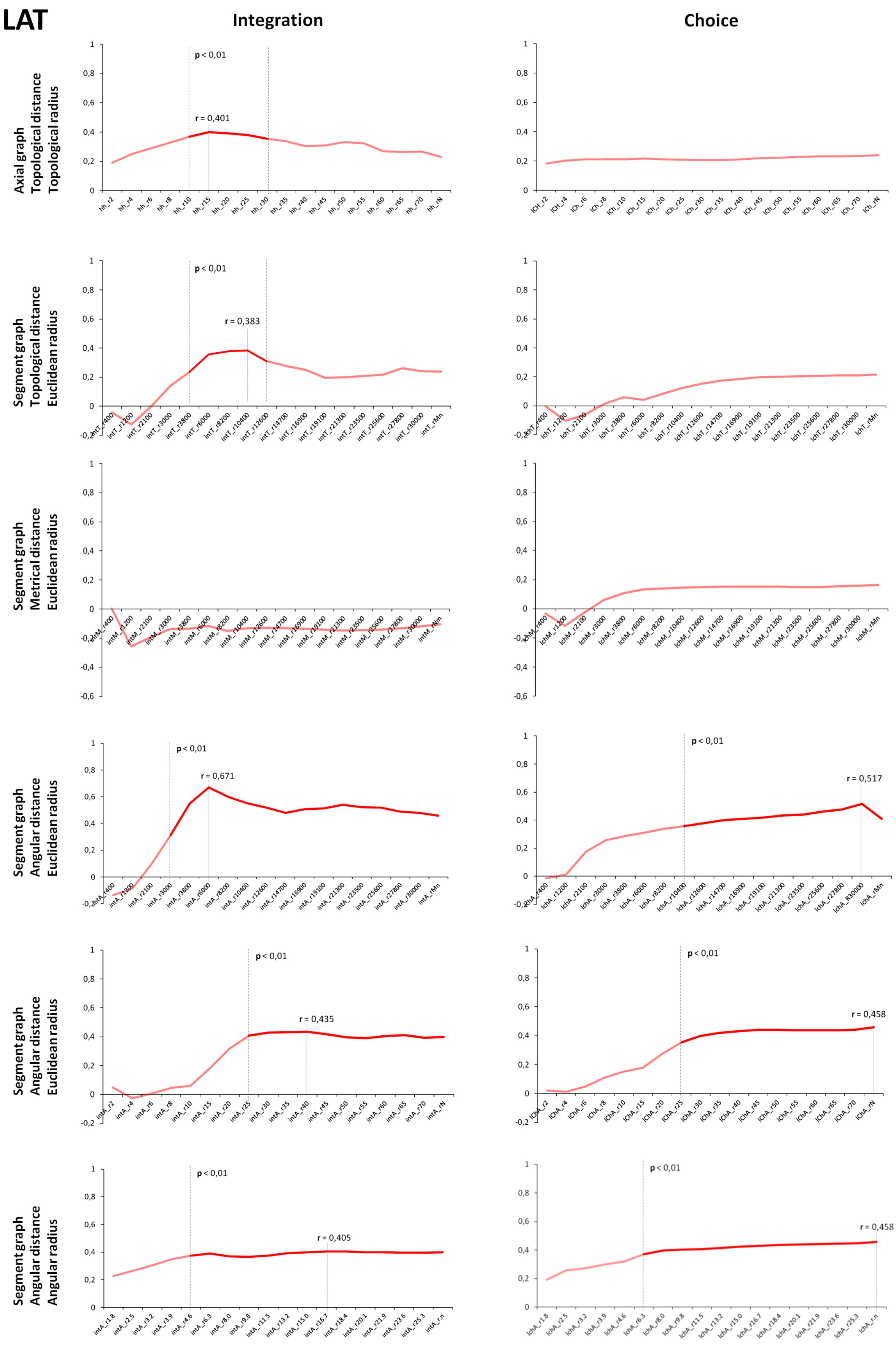

Fig. 77 – Correlations for the LAT dataset.

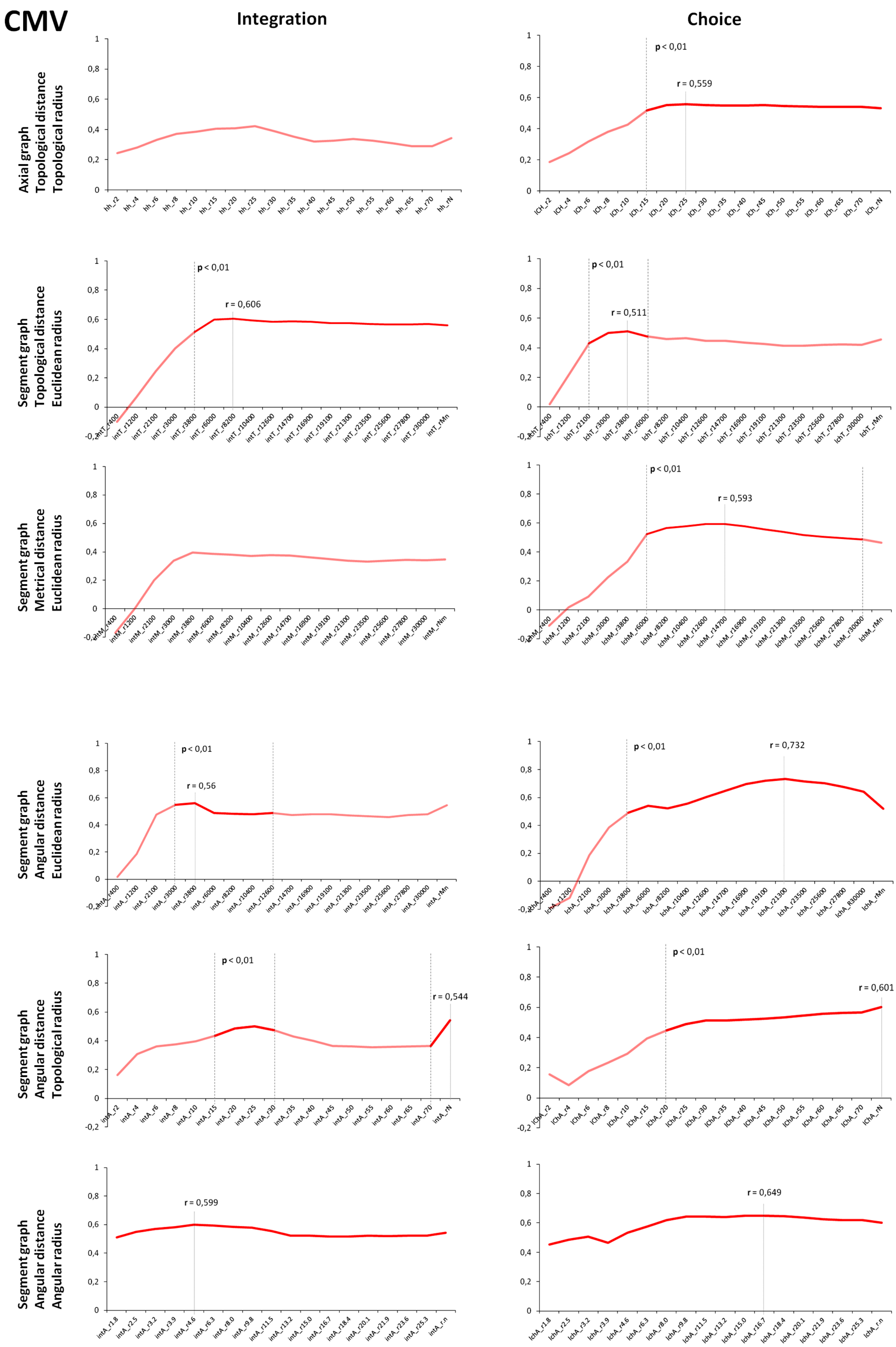

Fig. 78 – Correlations for the CMV dataset.

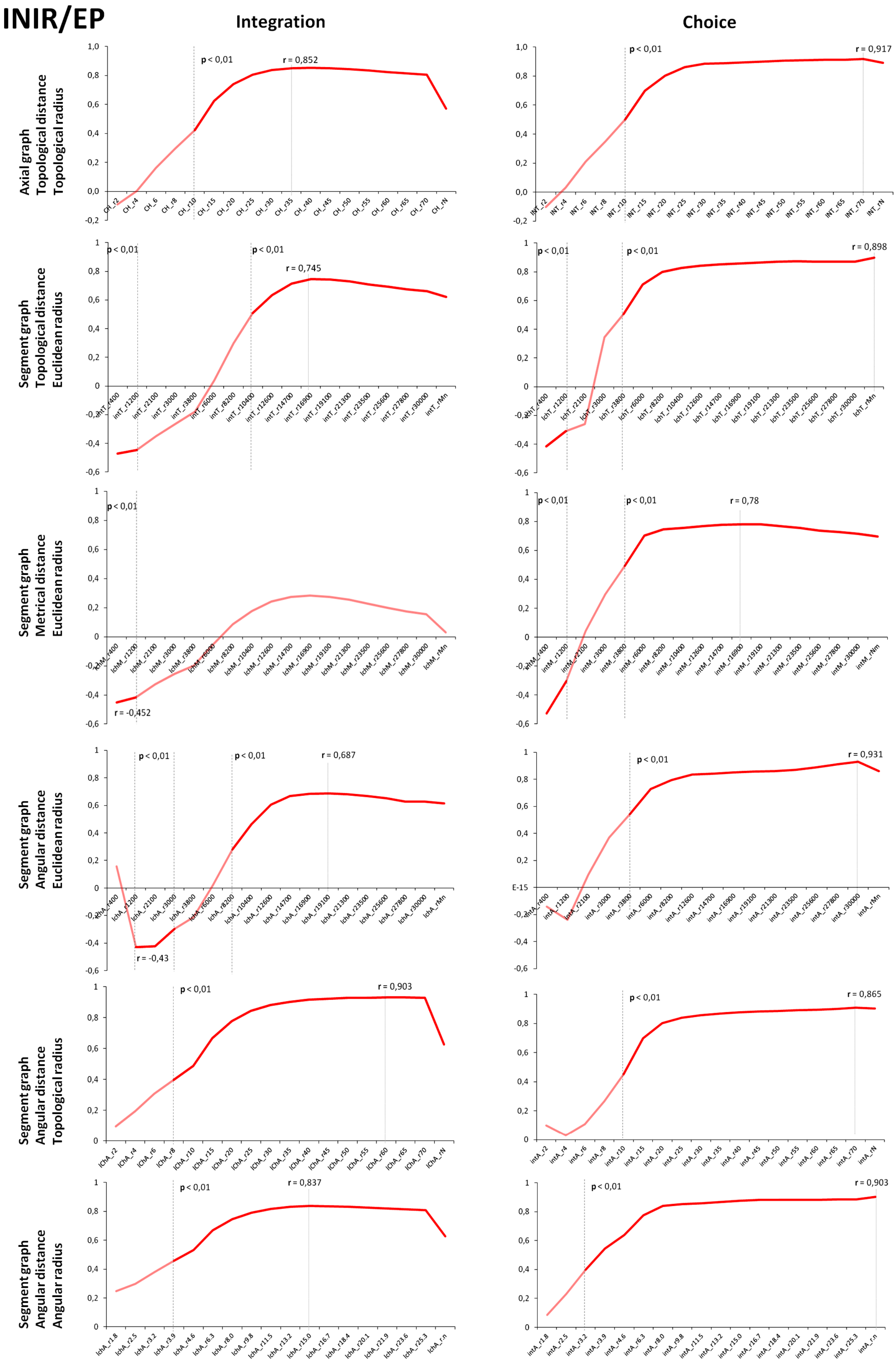

Fig. 79 – Correlations for the INIR/EP dataset.

5
MACRO-STRUCTURAL ANALYSIS

ABSTRACT

In this Chapter we perform a detailed structural analysis of the metropolitan spatial network throughout time. We start by acknowledging the large-dimensionality problem that the analysis of such huge network entails. In doing so, we also identify and define a new representational concept of metropolitan spatial structure - the metropolitan centrality palimpsest - in which the centrality variability of each space in the network, along the entire spectrum of spatial scales, is taken into account. When extended over time, the metropolitan centrality palimpsest becomes a large tri-dimensional data cube, to whose exploration we dedicate the remaining of the Chapter.

We start by searching latent general scales within the metropolitan centrality palimpsest, through the use of principal component analysis. Three fundamental centrality regimes are identified: those of the region, of the city and of the neighbourhood. These three centrality regimes, described by three principal components of integration and three others of choice, are able to encapsulate the variability of those measures over the entire range of metropolitan spatial scales; while at the same time revealing deep and temporal-independent centrality modulations within it. We explore and visualize the evolution of the network's centrality patterns produced under those three fundamental centrality regimes, obtaining several insights on the nature of such evolution.

We then explore potential regularities in the behaviour of all network's spaces through time, as described by integration and choice at the three previously defined centrality regimes. For this, we use non-hierarchical and hierarchical cluster analysis, which enable us to classify the huge number of individual spaces in the network into a restricted number of clusters, containing spaces with similar centrality behaviours. We recognize in the resulting clusters different spatial structures, which can be seen as types of metropolitan 'places' and 'paths'. These types are remarkably stable over time and liable of being organized into a spatio-structurally derived typology, which we subsequently define through hierarchical clustering.

We end the present Chapter by unpacking the metropolitan centrality palimpsest as two integrated taxonomies of places and paths, organized according to a hierarchy of fundamental centrality 'families' (or taxonomic classes), which may be unfolded into several levels of progressive structural specificity. These two taxonomies, derived only from the structure of the spatial network itself, constitute novel descriptions of the metropolitan region's intimate structure, revealing its intrinsic constituent parts and how these are nested within each other. We conclude by suggesting that these taxonomic descriptions allow for a quick and comprehensive understanding of the spatial structure of Oporto's metropolitan region and thus are useful instruments, both for research as well as for operational planning purposes, within this or any other contemporary metropolitan context.

5.1. THE METROPOLITAN CENTRALITY PALIMPSEST

With the validity of the spatial network model ascertained, we may now use it to study the evolution of the spatial structure of Oporto's metropolitan region through time. This will be done through the syntactic analysis of its centrality patterns, as defined by the integration and choice measures, at each observation moment $t = \{1,2,3,4\}$ and along a variety of spatial scales, or radii of analysis. For this we will use the type of analysis identified in Chapter 2 as the best descriptor of movement in the metropolitan street network (segment angular analysis constrained by Euclidian radius) and the range of radii also defined on that chapter.

The objective of such exercise is to reveal what we will call the 'centrality palimpsest[108]' of the metropolitan region and its temporal evolution. Spatial centrality is a multi-dimensional issue. The centrality pattern of an urban spatial network is not the same at the local or global scales, or at any other scale between these two. It changes with each different radius at which analysis is carried out. A certain space may be central at a local scale but peripheral at a global one, and vice-versa. More specifically, a space may assume highly variable centrality values over the range of all possible spatial scales, enclosing several functional roles whose disclosure depends on the scale from which we look at it.

Naturally, this changing behaviour is not a mere product of different analysis types: it describes a real phenomenon, corresponding to the many scales at which urban space is used and perceived, be it for movement purposes or for any other type of activity. For example, it is well known that different urban functions cater for different 'costumer basis', from the neighbourhood's local shop to the metropolitan shopping mall (to mention only commercial functions). Such functions exploit different scales of urban space, seeking locations that are central at the scale that best serves their commercial intentions: perhaps a major highway interchange for the shopping mall and a neighbourhood's high street for the local shop. In the same way, the routes we choose when moving through the city depend largely on the desired destination: if it is far away we might prefer to use the highway system or the main grid of urban thoroughfares, if it is near we may well choose some shortcut through the local grid; because the highway system may be highly central at large urban scales but irrelevant at shorter ones, whereas the local shortcut may show high values of local centrality but surely not that high at the whole metropolitan scale.

Thus, spatial centrality changes not only from place to place but also within the same place, accordingly to the scale at which its centrality is evaluated. This implies that a space incorporates a multitude of centrality values, which are actually infinite when centrality is evaluated in a continuous scale of distances (as it is the case with Euclidian distances). Moreover, these varying centrality values are not mutually exclusive, but rather coexistent and independent of each other. It is as if each space of the urban grid was in fact a multi-dimensional entity - a 'centrality manifold' - containing all the centrality states that it could assume at each scale of the metropolitan spatial spectrum. The overlaying of all these states for all the spaces of the spatial network produces what we call the metropolitan *centrality palimpsest*: a thick, multilayered structure enclosing all possible centrality states of all the spaces composing the metropolitan spatial network (Figure 80, next page).

The multi-dimensional nature of the centrality palimpsest, exacerbated in networks with the size of the one we are studying, raises a new operational problem. How shall we unpack such a complex and extensive structure, in a way that is both feasible and meaningful for study purposes? In fact, in the

108 A palimpsest is a manuscript page of an old book (often made of parchment), from which the text has been scrapped or washed in order for the page to be used again. With time, the faint remains of the former text may appear underneath the later text (or may be revealed by modern techniques). A palimpsest may contain dozens of superimposed texts. The term has come to be used as a metaphor in a variety of disciplines, notably in architectural archeology, to designate the superimposition over time of different built structures.

case under study, for each of the 120.000 nodes/segments (on average) composing the spatial network at each $t = \{1,2,3,4\}$, we want to study two continuously varying centrality measures (angular integration and angular choice), over a range of 17 spatial scales (or radii[109]). This amounts to 16.320.000 different centrality values. Of course, these values are actually divided into several sets, each one representing the centrality pattern of the network produced by each centrality measure, at each analysis moment. But they amount to a total of 136 centrality patterns (2 measures x 17 radii x 4 analysis moments), which is still a rather intractable number, in terms of their detailed visual and numerical analysis[110]. Moreover, even if the centrality values vary between spatial scales, they do not vary abruptly. They change gradually instead, with the values of close radii being typically highly correlated (albeit not equal), turning the visual analysis and comparison of the 136 coloured segment maps rather dubious and difficult. Besides, we are not exactly interested in the values of each particular spatial scale, but on how these values change across scales and time. What we would need was something as 'natural' centrality scales among the range of all possible scales, or perhaps meaningful combinations of these. Furthermore, we would like to be able to perceive and to identify areas with different centrality behaviours; that is, areas locally or globally central, but also areas with any possible variation behaviour of their centrality values, over the range of the 17 different radii. In other words, what we need is a method for unpacking, analyzing and visualizing the structure of the metropolitan centrality palimpsest at each observation moment.

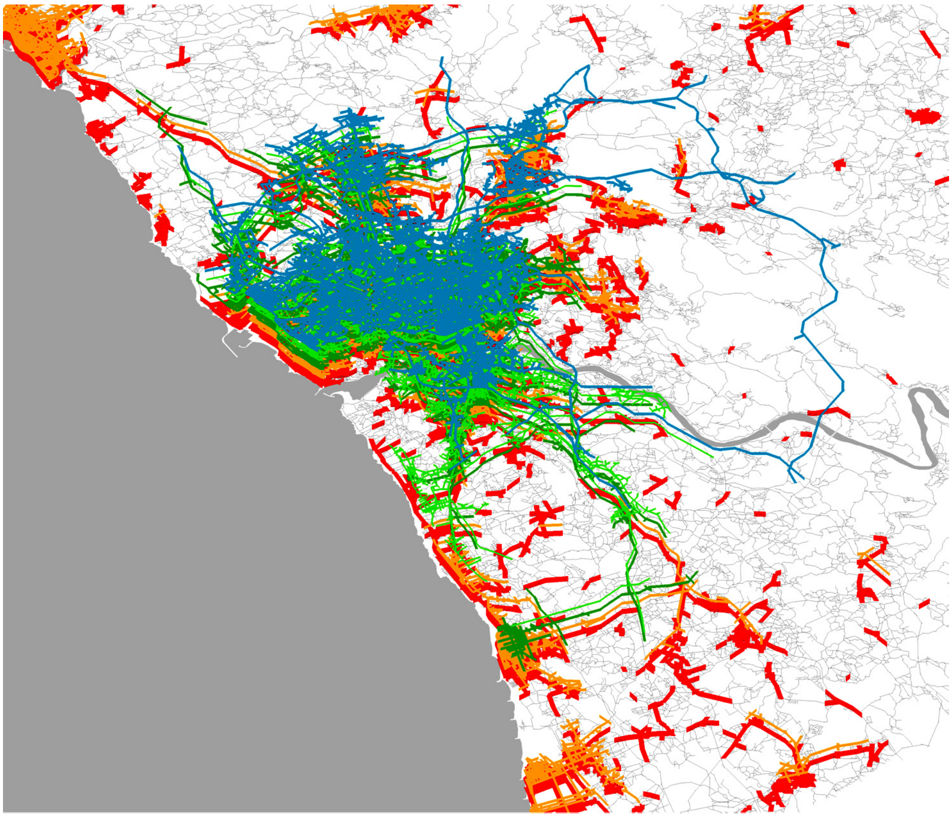

Fig. 80 – The metropolitan centrality palimpsest, showing the 10% highest values of five centrality analyses (integration) conducted at different spatial scales, layered over each other. There are spaces that are only locally central (in red), others that are locally but also supra-locally central (in red and orange), and others that are only globally central (in blue), and still others that are central at many spatial scales (in red, orange, green and blue).

[109] These 17 radii were defined in Chapter 3 and are the following (in meters): 400, 1200, 2100, 3000, 3800, 6000, 8200, 10400, 12600, 14700, 16900, 21300, 23500, 25600, 27800, 30000.

[110] Each centrality pattern can be described both in tabular and graphical formats, i.e. the values themselves or their depiction on the segment map.

5.2. THE USE OF UNSUPERVISED DIMENSION-REDUCTION AND CLASSIFICATION TECHNIQUES FOR TACKLING THE LARGE DIMENSIONALITY OF METROPOLITAN SPATIAL NETWORKS

The data produced by the processing of the segment graphs of each $t = \{1,2,3,4\}$, accordingly to two centrality measures (angular integration and choice) at 17 different Euclidian radii, results in a three-dimensional data cube[111], composed of four tables (one for each *t*), each with 34 columns and 120.000 lines (on average). On each table, the lines represent segments in the map or nodes in the graph (i.e. the objects: $N_1, \dots, N_n$) and each column represents a centrality measure (integration or choice) at each analysis radius (i.e. the fields, or objects' attributes: $d_1, \dots, d_{34}$). Thus, each table has (on average) 4.080.000 cells. This three-dimensional data cube encapsulates in its 16.320.000 cells all the information describing the variability of the metropolitan centrality palimpsest at four different moments in time. The task is to extract that information in a meaningful and graspable way. Or, in other words, to *mine the data cube* describing the temporal evolution of the metropolitan centrality palimpsest.

Data mining is the colloquial term for the computational process of discovering patterns or regularities (or, still, structures) in large datasets. It has been theorized by (Fayyad et al. 1996) as an advanced analytical step of a broader process, known as "Knowledge Discovery in Databases" (KDD), which is based on the idea that relevant and unsuspected patterns may be hidden within the incommensurable amounts of data, produced today across a wide variety of fields; and that those patterns may be discovered, interpreted and distilled into knowledge, which may be relevant not only for the concerned fields but also for science in general. On the KDD process, the goal of the data mining step is to extract information from a dataset and transform it into an understandable structure for further use. Data mining applies a series of exploratory statistical techniques to discover relevant and previously unknown patterns in data. We will use some of these techniques to explore the data cube describing the metropolitan centrality palimpsest, in search of its complex and subtle structure, and how that structure has evolved over time.

We will approach the cube in three ways: by focusing on dependency relations between variables (using principal components analysis), on structural relations of similarity between objects (using cluster analysis), and by studying the way all these potential regularities evolve over time. Regarding the variables (i.e. the centrality measures of angular integration and choice at each radius) we want to know if they are related among themselves and may be reduced, or if they are independent and all necessary to explain the variability of data. In other words, we will be looking for 'natural' centrality scales in the network, i.e. for the existence of strong modulations within the complete metropolitan spatial spectrum (as described by the 17 radii), which may reveal deeper, simpler and more general spatial scales of the metropolitan centrality palimpsest. Regarding the objects (i.e. each segment, as described by its 34 centrality values), we want to know if they are all more-or-less different or if, on the contrary, they show structural similarities and may therefore be grouped into a number of meaningful clusters, each one representing a specific regularity in the occurrence of centrality values; or, in other words, a certain 'centrality profile'. These different centrality profiles could lead to the establishment of a typology of metropolitan centrality structures, directly extracted from that multi-layered and complex structure: the metropolitan centrality palimpsest.

Both principal component analysis (PCA) and cluster analysis are *unsupervised* exploratory methods (Tan et al. 2005). The term unsupervised, emanating from the machine learning[112] field, means that no

[111] Data cubes are three- (or higher) dimensional arrays of values, commonly used in computer programming and data mining contexts to describe time-series of multi-dimensional datasets.

[112] Machine learning is a branch of artificial intelligence, dealing with the study and construction of systems that can be trained (automatically or not) in order to learn from data. This is used for a wide variety of purposes as, for example, for automatically distinguishing spam and non-spam email messages.

input (besides the raw data) is given to the algorithms, and thus that there is no error or reward signal to evaluate potential solutions. As opposed to supervised methods, which depend on previous knowledge of the problem at stake (e.g. previous classification criteria for variables or objects) unsupervised methods derive solutions only from data themselves, thus being particularly indicated for finding underlying structures in complex datasets. They embody the exploratory endeavour, postulated by Stan Openshaw (1994) in the GIS context, “where the whole philosophy is to *let the data speak for themselves* and to suggest, with a minimum of preconditioning, what patterns might exist” (op. Cit. p. 48, our emphasis).

PCA is used to reduce the dimensionality (i.e. the number of variables, or fields) of the actual data, based on potential linear correlations between the data fields. It derives a number of compound measures (called principal components) whose number is smaller than that of the original fields, but which retain most of their information and can effectively substitute them. This is particularly useful in tasks involving data reduction as, for instance, audio or image compression (Tan et. al 2005). Obviously, data reduction makes sense only in the case of associated variables; otherwise the respective benefits are trivial. But in doing this, the method may also reveal underlying variability factors, obscured by redundant, marginal or irrelevant information. In other words, the method is capable of finding *latent variables* underlying a number (usually considerably larger) of actually observed variables. These latent variables are expressed as combinations of the original fields (i.e. principal components), which need to be interpreted and eventually semantically labelled, according to their respective composition (in terms of the original fields) and to the variance of data that they explain. One particular aspect of principal components is that they are by definition uncorrelated, a characteristic that makes them particularly appropriate as inputs to many other modelling techniques, including clustering (Tsiptsis, Chorianopoulos 2009).

Cluster analysis is an unsupervised classification method, which groups data objects based only on information found in the data that describes the objects. Its main goal is to find similarities between objects in order to group them into classes according to those similarities: the greater the similarity (or homogeneity) within a class and the greater the difference between classes, the better (or more distinct) the clustering solution. There are many clustering algorithms, which are usually divided into hierarchical and non-hierarchical (or partitional) methods. The main difference between these two types is that classes in hierarchical methods may be nested within each other; whereas in non-hierarchical methods they are always mutually exclusive (i.e. they constitute non-overlapping subsets). Hierarchical methods are computationally more expensive than non-hierarchical methods, and thus are normally used with (relatively) small datasets (Tan et al. 2005). Later in this work we will also use hierarchical clustering methods, but now (due to the large size of the metropolitan centrality palimpsest we aim at exploring) we will use one of the most prominent non-hierarchical methods, namely the *K-means* algorithm.

The K-means clustering technique divides the objects of a given n-dimensional dataset into a desired number of clusters; K is a user-specified parameter, namely the number of clusters to attain. Initially, K centroids are randomly chosen, each data point is assigned to the closest centroid and each collection of points assigned to a centroid is a cluster. The centroid of each cluster is then updated, based on the mean distance between the points assigned to the cluster. The assignment and update steps are iteratively repeated until no point changes clusters, or equivalently, until the centroids remain fixed. The algorithm then stops, having identified the centroids of the natural grouping of points for that number of clusters (Tan et al. 2005). The choice of K by the user in unavoidable in this procedure, but the algorithm can be run sequentially for increasing K (i.e. K=2, K=3, ... , K=n) and there are several methods (discussed in section 3.4) to approximate the optimal number of K.

These two unsupervised methods - PCA and K-means clustering - will be used to explore, respectively, the variables and the objects in our data cube, representing the evolution of the metropolitan centrality palimpsest through time. In what follows, we will provide further details and explanations on both techniques, as they become necessary. What is important to stress now, is that such analytical techniques are indeed entirely objective, semi-automatic and fully reproducible. Thus, they are not only efficient tools to deal with the overwhelming complexity of metropolitan spatial networks. We dare say they are also ways of precluding the proto-scientific habit of the mere visual interpretation of urban form, often leading to irreproducible findings or to conclusions existing only 'in the eye of the beholder'.

5.3. DISCOVERING NATURAL SCALES IN THE METROPOLITAN CENTRALITY PALIMPSEST

The centrality patterns of an urban spatial network, varying across spatial scales (or radii of analysis) from the most local to the most global, are like the individual frames of a motion picture. The frames of a movie are all different, but contiguous frames are almost equal. Likewise, the centrality patterns produced at close scales are very much alike. Sharp visual differences are only noticeable when the patterns produced by quite distant radii are compared (Figure 81). Yet, just like the almost indistinguishable frames of a movie are all necessary to produce a moving image, the slightly different centrality patterns of the entire range of spatial scales are also all necessary, if we want to get an entire picture of the metropolitan centrality palimpsest.

This is not a platitudinous comparison or just an analytical preciosity[113]. In fact, just like a movie may become unintelligible if we suppress, say, fifteen frames every each twenty[114], also the continuous structure of the centrality palimpsest becomes grossly truncated, if we only take into account a few scales of the entire metropolitan spatial spectrum. However, the totality of the 136 centrality patterns (not to mention the 16.320.000 individual values) is rather difficult to manage. What we need is a method capable of transforming all that data into simpler structures without losing, or losing very little of, the information contained therein. This is exactly what PCA does.

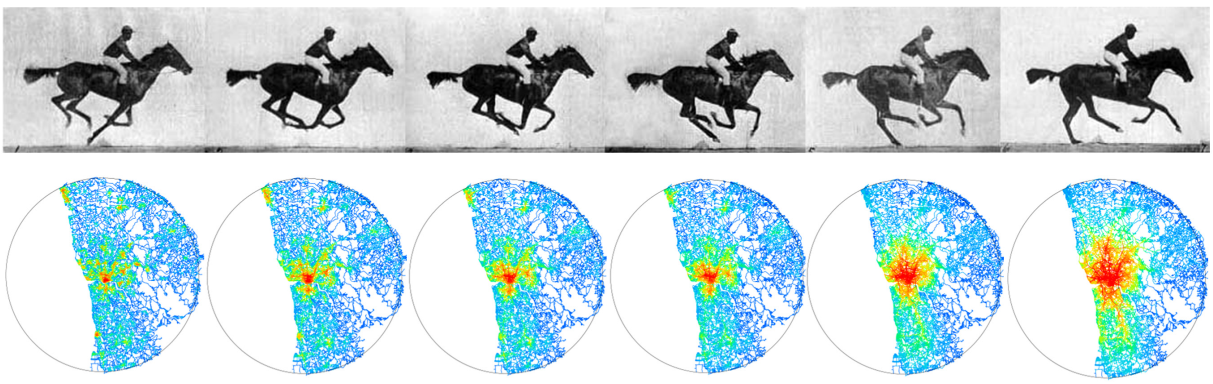

Fig. 81 – The analogy between movie frames and the varying centrality patterns of the metropolitan region across spatial scales. Above: an excerpt of the famous Eadweard Muybridge's photographic sequence "The Horse in Motion", 1878. Below: centrality patterns (integration) of Oporto's metropolitan region, at radii 1200, 2100, 3000, 3800, 6000 and 10400 meters (from left to right).

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113 Actually, the analogy is liable of being concretized. One just needs to import (as images) several sequential centrality patterns of a given street network into some video editing software and run the movie. We have tried this and the result is quite interesting, but unfortunately not possible to show here.

114 The frame rate in standard movie industry is 24 frames per second.

We start by recalling what our variables are and by inspecting their pairwise correlations. They represent the centrality values (of integration and choice) at all the 17 previously defined metric radii, of all the segments/nodes in each segment map/graph, at each observation moment. As mentioned before, the values of these variables are strongly correlated, especially when close radii are concerned. In Figure 82 we show two correlation colour maps, which make this clear (for the sake of economy, we only show the correlations for t=1, because all other periods have a similar behavior). Correlations attain values close to 1 for all contiguous radii, but high correlation values extend across all scales, except for the most distant radii (i.e. local *versus* global). This is valid both for integration and choice, albeit more evident in the former measure.

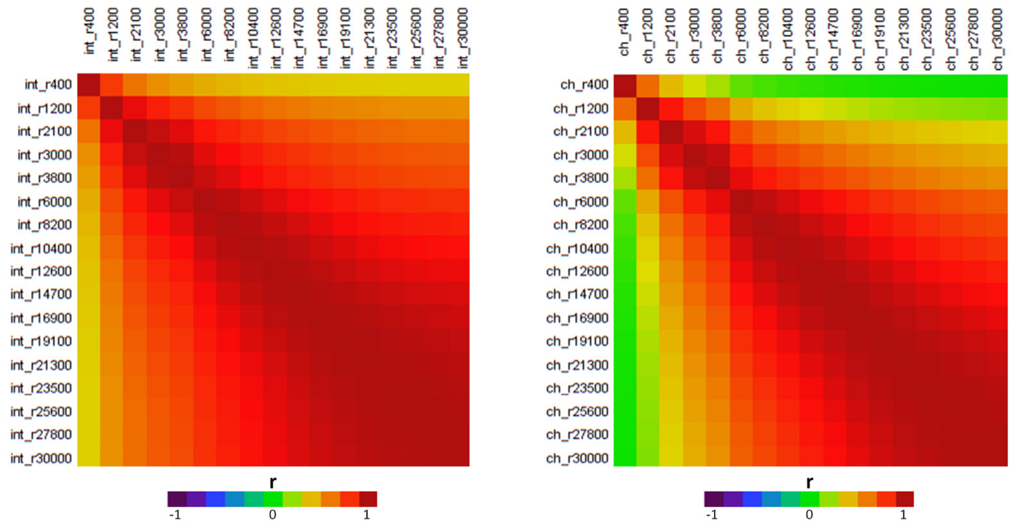

Fig. 82 – Correlation (Pearson's r) colour maps, for integration (left) and choice (right) values at t=1.

Thus, all our centrality variables are strongly collinear. One could think, then, that they are also massively redundant and that some of them could simply be ignored. However, just like a movie is not present in each of its frames, but rather *emerges* only when all the frames are quickly visualized, also these variables give rise to a composite structure that is by no means present in each one of them, but emerges only when they are taken together. That structure - the metropolitan centrality palimpsest - is also an emergent structure, arising from the fact that each space in the street network is perceived, used and traversed at many spatial scales. The high collinearity between our variables is a sign of that continuous and underlying structure; the task, then, should be to find the *latent variables* that truly characterize such structure.

A situation of multicollinearity between variables is the main pre-requisite for PCA: it makes no sense to try to find association factors between variables that are naturally dissociated. There are several statistical tests to evaluate the suitability of a given dataset to PCA, the two more common being the Kaiser-Meyer-Olkin (KMO) and Bartlett's tests (Abdi, Williams 2010). The KMO measure of sampling adequacy, tests if the variables are multicollinear or simply pairwise correlated (which is undesirable). KMO produces values between 0 and 1, with values above 0.5 indicating adequacy for PCA. The Bartlett's test of sphericity serves to rule out the null hypothesis (H_0) of the correlation matrix being an identity matrix[115]. In this case, the significance value of the test (p-value) should be less than 0.05, meaning that H_0 may be rejected. The values of these two tests are summarized in table 5, where it is made clear that all variables in each table $t = \{1,2,3,4\}$ are nicely fit for a PCA exercise.

[115] An identity matrix is a square matrix with ones in the diagonal and only zeros elsewhere. Obviously, in the case of a correlation matrix, this would indicate that the variables were only correlated with themselves and not with the others.

	Integration		Choice	
	KMO	Bartlett's test	KMO	Bartlett's test
t=1	0.927	$p < 0.001$	0.872	$p < 0.001$
t=2	0.938	$p < 0.001$	0.880	$p < 0.001$
t=3	0.935	$p < 0.001$	0.874	$p < 0.001$
t=4	0.934	$p < 0.001$	0.862	$p < 0.001$

Tab. 5 – KMO and Bartlett's tests of PCA adequacy.

PCA is based on the eigenvectors[116] (and on their associated eigenvalues) of the co-variance or correlation matrices[117] of the standardized variables. A square matrix with eigenvectors has as many of these vectors as it has dimensions (i.e. in a $n \times n$ matrix, there are n eigenvectors). The importance of these eigenvectors is that they describe the *covariability* among variables. The eigenvectors of a co-variance/correlation matrix of variables are its *principal components* and their associated eigenvalues correspond to the *variance explained* by each of these components. They act as a kind of 'lines of best fit' of all variables at the same time, indicating the main variability trends in a multicollinear dataset. The first component (i.e. the eigenvector with the highest eigenvalue) accounts for the greatest share of variance, the second component for the second greatest share of variance, and so forth until the number of principal components is equal to the number of variables and the totality of variance is accounted for. The main objectives of the method are the discovery of latent variables and the reduction of a dataset's dimensionality, so the number of components to retain should naturally be always less than the number of original variables. As stated before, these principal components have still one additional advantage: they are, by definition, orthogonal vectors, i.e. the correlations between each other are zero. Thus, besides defining the main variability trends in a group of multicollinear variables, the principal components also guarantee that those trends are defined independently of each other, thus avoiding the multicollinear problem of the original dataset.

The first analytical issue in the PCA process is the decision of how many components to retain while ensuring that a significative share of the original variance is maintained. There are several criteria for deciding this. The first, and most important one, is that the solution should be interpretable at the light of the problem at stake. From an exploratory point of view, it makes no sense to produce PCA solutions that are more difficult to interpret than the original problem. Secondly, one should choose a number of components that is capable of explaining an acceptable portion of the original variance, i.e. entailing a minimal information loss. Thirdly, principal components with eigenvalues less than 1 may, in principle, be rejected. This is because standardized variables have a variance equal to 1, so a principal component explaining less variance than a single variable may be considered of marginal importance. However, this only makes sense if the solution thus defined is considered satisfactory (i.e. meaningful in the context of the problem at stake). Fourthly, a graphical device called 'scree plot' is commonly used to ascertain the number of components to retain (Tsiptsis, Chorianopolous 2009).

Figure 83 (next page) shows the scree plots of the PCA carried out for the four tables $t = \{1,2,3,4\}$, each one with two sets of 17 variables (corresponding to the centrality values of integration and choice at each of the 17 previously defined radii). In these plots the xx axis represents the ordinal numbers of principal components and the yy axis their corresponding eigenvalues. The term 'scree plot' comes from the typical shape of the curves that these plots create and from the type of analysis to which they

[116] An eigenvector of a square matrix A (only square matrices have eigenvectors, albeit not all) is a non-zero vector v that, when multiplied by A, yields the original vector multiplied by a single number λ (called the eigenvalue of A corresponding to v), so that $Av = \lambda v$. The prefix *eigen* is a German word meaning "self" or "proper".

[117] Technically, the co-variance matrix is used when it is important to distinguish variables with different variance ranges (i.e. when a variable with greater variance is expected to have a greater weight in the PCA solution). The correlation matrix is used when variables with different variance ranges are expected to have the same weight in the solution, which is the case here.

are intended. One needs to decide where the 'mountain slope' ends (the sharp dropping part of the curve, on the left) and where the 'scree at its bottom' begins (the flat part of the curve, on the right). The flat part of the curve corresponds to principal components with eigenvalues close to zero, thus explaining very little variance, usually equated with noise. What we are looking for is a point beyond which the curve flattens or, in other words, for a strong decrease in the difference between consecutive eigenvalues. This means that no further significative variance is explained by a greater number of components.

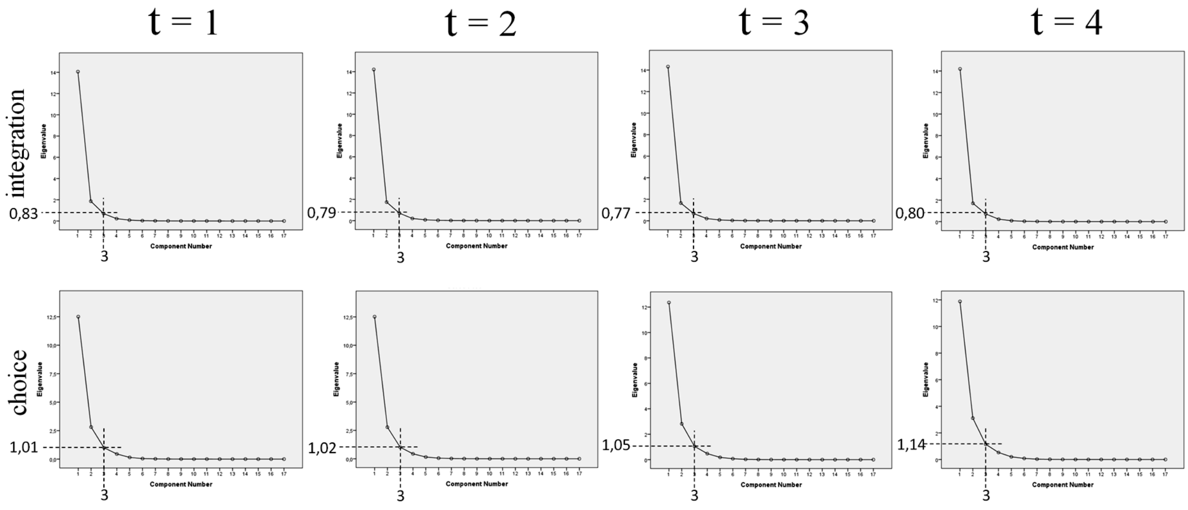

Fig. 83 – PCA scree plots for integration and choice variables, at each $t = \{1,2,3,4\}$.

The results are rather stable over time. For each of the two centrality measures, we extract three principal components at each observation moment. Regarding choice variables, this number of components corresponds to the point where eigenvalues start to decrease clearly slower, but also to the last eigenvalue above 1. Regarding integration variables, the eigenvalues of the third component are always below 1; but very close to that value, nonetheless. The difference between the second and the third eigenvalues is also always considerably larger than the difference between the third and the fourth. In all cases the amount of variance added by this fourth component is negligible. And above all, as we will see further ahead, the three-component solution produces results that are rather meaningful and revealing for the problem under study.

Our four initial data tables had 34 variables (17 integration variables and 17 choice variables); the same is to say that each of the two centrality measures was defined by 17 different axes in a 17-dimensional space. Now we have reduced all these variables to just 6 per table (3 principal components of integration and 3 others of choice). Thus, the variability of each type of centrality measure along the entire metropolitan spatial spectrum at each observation moment, is now described solely by 3 new variables; each centrality measure exists now in a (much more straightforward) 3-dimensional space and its values, covering the entire range of metropolitan spatial scales, are representable in a system of three orthogonal axes; something that we can actually visualize.

Once the number of principal components defined, a next step takes place in the PCA process. These three eigenvectors define the main variability trends of our original variables. But if we simply project their values on this new system of axes, so as to obtain new values described along those axes, the results may not be immediately interpretable. This happens because the first component usually accounts for a great share of the initial variance and the subsequent components for a significatively lesser share, or residual variance. Thus, the first component may appear associated with most of the original inputs, while the other components may seem irrelevant. This is fixed by *rotating* the principal components' axes, so that the correlation of each component with each of the original fields is either maximized or minimized[118]. This operation does not alter the structure of data. It simply makes clear the already existing associations between the principal components and the original fields. Rotation reattributes the percentage of variance explained in favor of the components extracted last, while the total variance jointly explained by the derived components remains unchanged (Tan et al. 2005).

	integration				choice			
	PC1	PC2	PC3	total	PC1	PC2	PC3	total
t=1	54,67%	31,80%	11,31%	97,77%	56,30%	30,01%	9,68%	96,00%
t=2	54,41%	31,87%	11,64%	97,92%	56,22%	30,10%	9,65%	95,97%
t=3	54,64%	31,13%	12,11%	97,88%	54,24%	31,13%	10,08%	95,45%
t=4	53,27%	32,48%	11,99%	97,73%	51,44%	32,94%	10,55%	94,93%

Tab. 6 – Percentage of variance of the original fields explained by the rotated principal components.

Table 2 shows the final percentages of variance explained by each of the rotated components for each of the centrality measures of integration and choice at each observation moment. Again, the results are very stable through time, indicating that the extracted components describe real and temporal-independent underlying structures of the metropolitan centrality palimpsest. Both for integration and choice and on all moments of observation, the three principal components are able to explain at least 95% of the original variance. On average and for both measures, the first component accounts for 54%, the second for 31% and the third for 11% of the original variance.

After the rotation procedure it is possible to start understanding what each of the three principal components represents. This is done by examining each component's 'loadings', i.e. the correlations between it and the original fields. Typically, correlations above r=0.4 in absolute value are considered to be of practical significance and denote the original fields which are representative of each component (Tsiptsis, Chorianopoulos 2009). For easier interpretation, these loadings may be plotted in sequential order, from the most local to the most global radii. Figure 84 (next page) shows such plots, one for each principal component of the integration and choice variables, with the curves corresponding to each table $t = \{1,2,3,4\}$ superimposed. We have chosen a cut-off of $r \geq 0.6$ (and not $r \geq 0.4$), in order to characterize the principal components by exclusive spatial ranges, i.e. without overlapping of the original variables. But this is just to make their differentiation easier, for these are clearly continuous structures with some overlap, whose individualization is gradual rather than sharp.

The plots in figure 84 (next page) make the meaning of each principal component immediately clear. Both for integration and choice variables, PC1 is characterized by high loadings (i.e. $r \geq 0{,}6$) on the long-range scales (i.e. 8200 to 30000 meters, with maximum at 25600), PC2 on the medium-range scales (1200 to 8200 meters, with maximum at 3000) and PC3 on the short-range scales (400 to 1200 meters, with maximum at 400). These three principal components - each one describing a different segment of the metropolitan centrality *continuum* - also inform about the amount of variability going on in each of these segments, which is related to their extent regarding the spatial scales they cover. Roughly speaking, the first component spans 65% of the original radii range (accounting for 54% of the original variance of all variables, on average), the second component spans 35% of the radii range (accounting for 31% of the original variance, on average) and the third component spans only 12% of the range (accounting for 11% of the variance, on average).

[118] There are several rotation methods, with also different purposes. In this case we used the Varimax method because it guarantees that the angle between the rotated axes remains perpendicular, resulting in uncorrelated components. This will be important for the exercise developed in section 3.4 of this chapter.

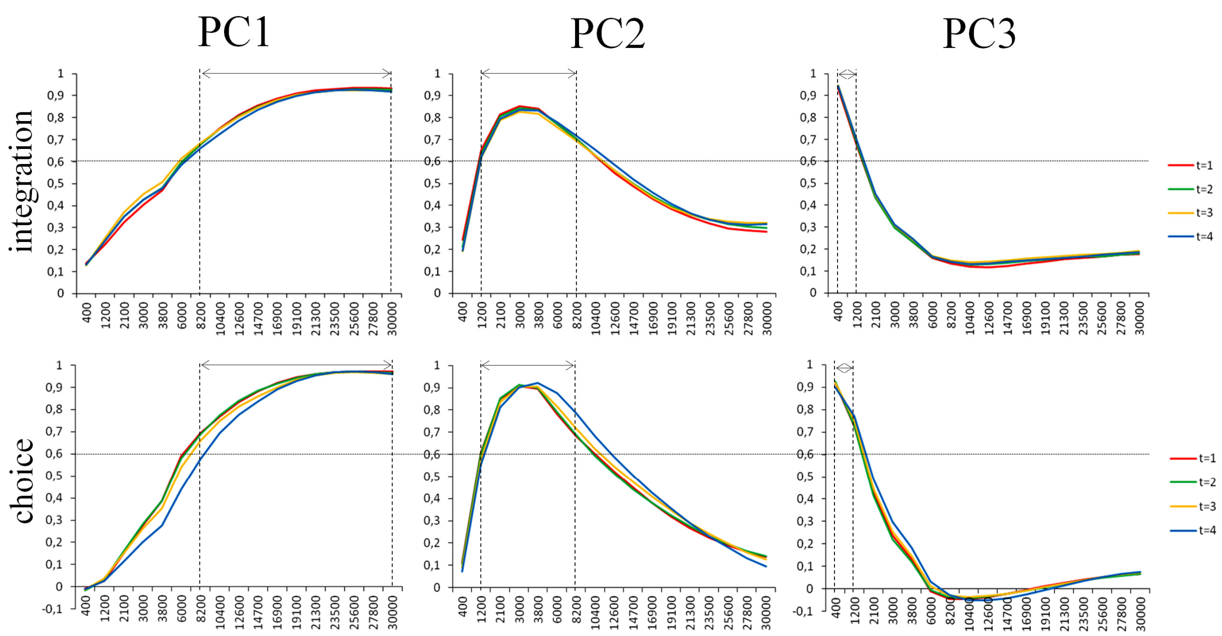

Fig. 84 – Loadings of the principal components of integration and choice variables at each t = {1,2,3,4}.

The reason for considering only three components was already discussed, but is worth saying that an additional fourth component would add, in every case, a very small amount of explained variance (particularly given the 95%, on average, already explained by three components). For instance, regarding integration variables at t=4, an additional fourth principal component would explain only 1.91% of additional variance, which is irrelevant when compared with the 10.03% explained by the third principal component. The same happens for both integration and choice variables at every observation moment. But what is more important is that the composition of this fourth component is difficult to interpret (being very similar to PC2) while the solution of three components corresponds to the intuitive idea of three general metropolitan scales: global, median and local.

The reason for the range of spatial scales being partitioned in this manner, and not in any other, is less obvious but eventually more interesting. It arises solely from correlations among the centrality variables themselves; the same is to say: from *characteristic modulations* of the centrality values, induced by the structure of the spatial network. What PCA is telling us in this case, is that the centrality variables at the radii composing each principal component (i.e. with higher loadings on each component, both for integration and choice variables) are more correlated among themselves than with those composing the other components. Thus, what this particular division of the radii range in three segments is indicating, is the existence of three basic *centrality regimes* in the metropolitan spatial network - pertaining to the scale of the *region* (i.e. between 8200 and 30000 meters), to the scale of the *city* (i.e. between 1200 and 8200 meters) and to the scale of the *neighbourhood* (i.e. between 400 and 1200 meters) - while telling us at the same time where one begins and the other ends; indeed something difficult to decide in any other manner. Therefore, from now on, we will refer to the principal components of integration and choice variables, as the region's, the city's and the neighbourhood's scales (PC1, PC2 and PC3, respectively), and base our observations on this partition of the metropolitan centrality *continuum*.

It is important to stress that these three basic centrality scales, or regimes, were found solely by the PCA process based on intrinsic relations between the original centrality variables, without any learning signal whatsoever on how they should be grouped or separated *a priori*. They were grouped in this way only because their correlations implied such grouping; or, alternatively, because such an association already existed, latently, among the variables. Their variability could well be different, more monotonous or more diverse, entailing more or less principal components. But it seems that, for all purposes, centrality varies within the metropolitan spatial network only under these three basic regimes. Furthermore, they are extremely stable over time, not changing with the growth and development of the spatial network. The only apparent temporal change (even if very slight) regards the principal components of choice variables at t=4 (the blue curve in the bottom plots of Figure 84). Particularly PC1 and PC2 seem to accentuate a bit their roles during that last period (i.e. PC1 becomes more 'global', loosing loading values at middle scales; and PC2 becomes more 'median', loosing loading values at large scales). Still this change is very marginal and hardly any conclusions can be drawn from it.

The temporal persistence of just three possible centrality regimes defies any cursory conceptualization of contemporary metropolitan development. Such immutability seems indeed very far from the common imagery of unprecedented and dystopic metropolitan phenomena. Yet, one would still expect to observe some kind of variation across time in the centrality patterns of the metropolitan spatial network. And of course such variation happens; as a matter of fact, quite intensely. Only it happens *within* these three centrality regimes, and not through the inception of new centrality scales or through the abandonment of others. Existing spaces loose or gain centrality and new spaces may assume the centrality roles of previously existing ones, but always within these three modes. And what is more remarkable is their temporal stability: in spite of the intense network growth observed before, the spatial scales involved in each centrality regime are always the same, at least within the time span addressed in this study.

Of course, new types of road infrastructures (as the current metropolitan motorway network), supporting new movement speeds and shortening travel times, have made their appearance throughout the study's time span. However, in strict spatial centrality terms, these tend to take (or even to overtake) the role of previous infrastructures, which can be potentially very old, albeit fulfilling similar general functions within the same three-mode, or tripartite regime, of spatial centrality. It is important to stress that we are not claiming that a traditional regional road is the same as a contemporary motorway. Indeed they are not the same; for they relate very differently to the neighbouring grids and they induce also different centrality patterns, as we will see later. All we are saying is that they may have similar centrality roles at the region's scale in different historical moments, because they are built to meet the same general purpose (i.e. inter and trans-regional connection).

If we were studying the temporal evolution of travel speeds or travel times, there is no doubt that the resulting picture would be different, indeed much more variant. But what we are studying here is spatial centrality across spatial scales, i.e. the proximity and accessibility of each space regarding all the others within increasingly larger neighbourhoods (or radii) - and how all this varies across time. This type of spatial property, imminently structural and prior to the material specification of built forms, is quite insensitive to travel times or speeds. It simply describes structural relations between spaces, which have been stripped of all their physical qualities, except those defining their most basic geometric and topological properties.

Thus, one may say that the speed and time of travel indeed may change, but not the territorial scopes for which road infrastructures are built. What changes is the *technology* of road construction, following the ever evolving technology of transportation; which, in turn, undoubtedly accelerates and leads further away urban movement flows, broadening the territorial scope of urban development. But this broadened urban territory is still organized, or structured, according to the same three centrality scales, for which road infrastructures are still built today, as they were before. Thus, those three main centrality scales - the region's, the city's and the neighbourhood's scales - are not a novel product of the metropolization process itself, but rather the territorial scopes at which the metropolization process occurs, taking advantage of (and ultimately expanding) the already installed centrality framework of the road network.

Once the meaning of each principal component ascertained, we can compute new values for each object in each table, describing its position in relation to those new axes. These values are called 'component scores', and are produced by linear transformations of the original fields, using coefficients that correspond to their loadings. They effectively substitute the original variables, describing each object's behaviour in relation to the mean behaviour of each component (Tan et al. 2005).

Thus, instead of the original 34 centrality values (of integration and choice at 17 different radii) previously needed to describe each space's behaviour along the metropolitan centrality *continuum* at each observation moment, we now only need 6 (3 PCA scores for integration and choice). In the same way, we only need to inspect 6 maps (instead of 17) at each observation moment, describing the centrality patterns at the scale of the region (i.e. PC1 scores), at the scale of the city (i.e. PC2 scores) and at the scale of the neighbourhood (i.e. PC3 scores). For comparison purposes, Figures 85 and 86 (next page) show the spatial distribution of the scores of the three principal components of integration and choice at $t = 4$, together with the centrality patterns of the radii loading higher in each component. The colour scale of these maps represents standard deviations of similar distributions, so they are visually comparable. Their reading should be accompanied by the inspection of the plots in Figure 84.

PCA scores may be positive or negative, oscillating around zero. Specifically, they denote how many standard deviations an object lies above or below the mean of each component. Because principal components are related to a specific set of the original variables, the scores may be also interpreted as the degree to which a particular object is described by high or low values on those variables. Values close to zero represent objects that are close to the mean of the original variables, thus to objects that are undifferentiated regarding the behaviour that a particular component is describing (these are represented in grey, in Figures 85 and 86). By comparing the upper and lower maps of Figures 85 and 86, it is possible to see that what the new score values are representing are several centrality scales (or radii) at the same time. Returning to our initial metaphor, the patterns created by the component's scores are like several contiguous frames of the same movie, overlapped and seen by transparency. Each of the lower maps in Figures 85 and 86, representing the radius loading stronger on each component, may be seen as just one of those hypothetical frames.

The higher informational content of the upper maps of Figures 85 and 86 is quite evident. Not only do they depict several strong structures (i.e. sets of spaces with high scores) which are not present in the lower maps, as they also represent what we could call 'negative-structures' (i.e. spaces with scores far below zero, denoting a centrality behaviour contrary to that of each component), also absent in the maps depicting the original radii.

These differences arise from two important properties of PCA: the fact that each principal component is a combination of several original variables, and the fact that principal components are by definition orthogonal (i.e. the correlation between their scores is zero). Therefore, they have at least two advantages over the original centrality variables. First, they are capable of gathering and revealing structures with similar variability trends, but which were dispersed throughout the original variables, in spite of being *intrinsically related*; and secondly, they guarantee that the structures observable in each component are *intrinsically different* from those of the other components (i.e. the information contained in each component is uncorrelated with the information contained in the others). We will try to make these advantages clear by dwelling for a moment on the maps depicted on Figures 85 and 86.

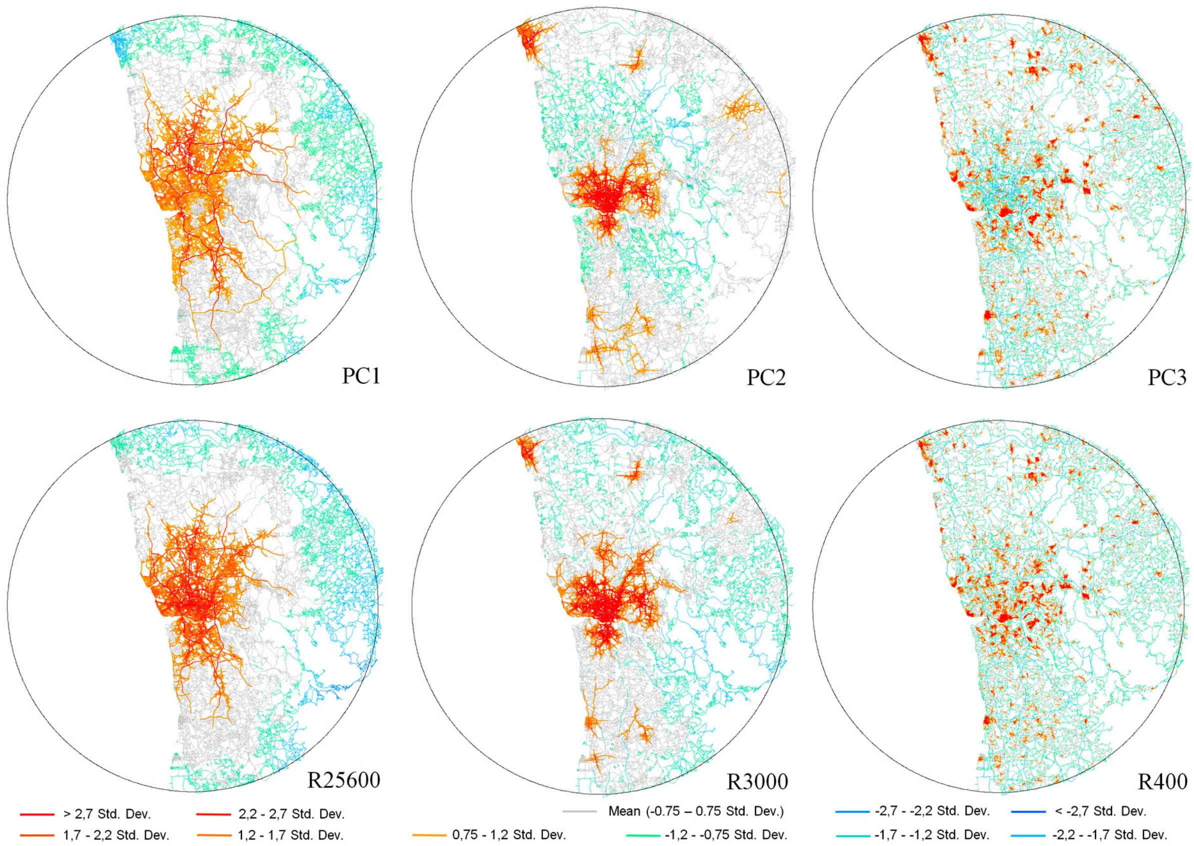

Fig. 85 – Integration, *t*=4: principal components (above) and radii corresponding to the highest loading (below).

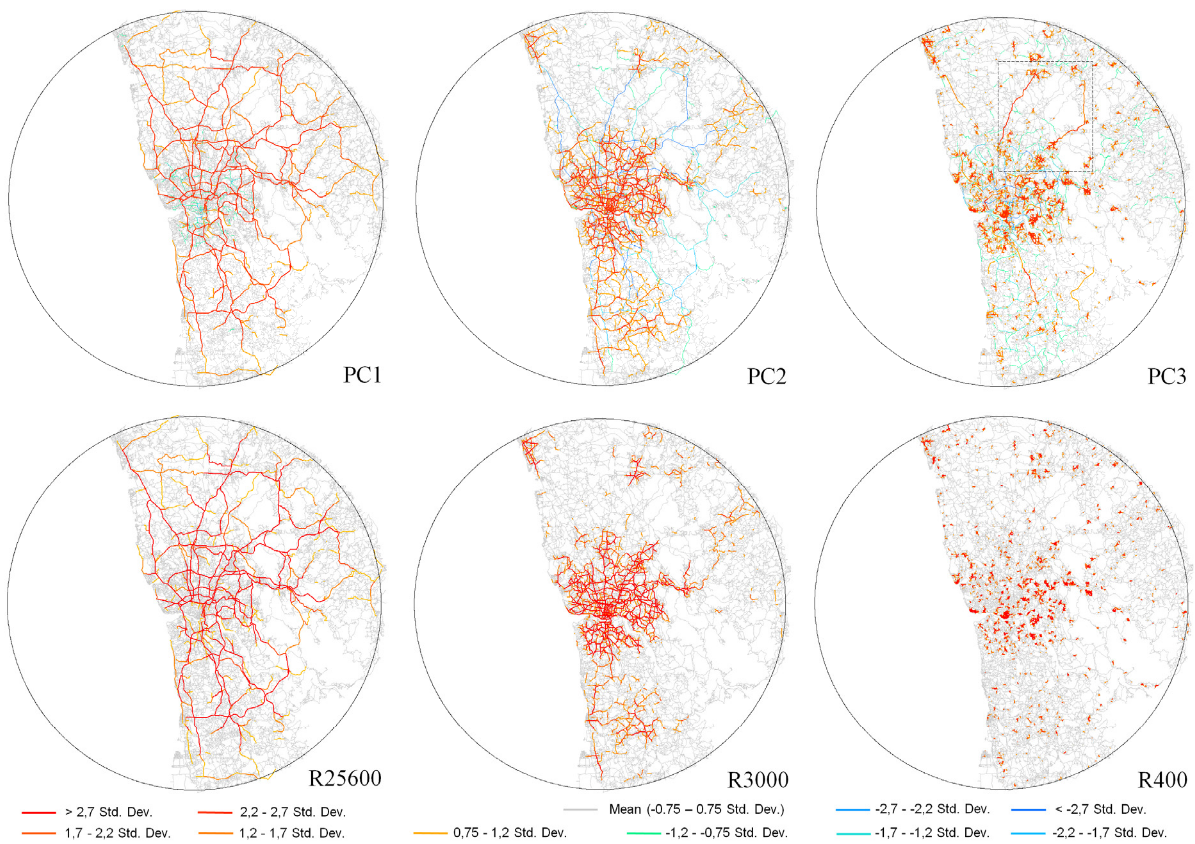

Fig. 86 – Choice, *t*=4: principal components (above) and the radii corresponding to the highest loading (below). The rectangle on the PC3 pattern indicates the location of Figure 88.

Regarding integration (Figure 85), the map of radius 25600 meters denotes the typical pattern that this measure produces at large scales. High values are strongly concentrated at the centre of the map, decaying fast towards the periphery. This is caused by the edge-effect discussed in Chapter 2, to which integration is particularly prone at large radii. Because of the much higher values occurring near the centre of the map, potential structures near the periphery may become overshadowed, even if possessing relatively higher values regarding their surroundings. However, the maps corresponding to the first and second principal components of integration show something different (Figure 85, PC1 and PC2). In PC1 the decay towards the periphery is less accentuated, because several radii below 25600 meters are now being taken into account; also, and most notably, the pattern is more heterogeneous, with higher values concentrated on the motorway network and clear lower values in its interstices. This is not noticeable on the map of radius 25600 meters. Likewise, PC2 highlights several important towns near the periphery of the study area, which are not so clearly represented in the lower map of radius 3000 meters. Such marked differences are not present at the local scale (PC3 and radius 400 meters), but a smaller number of local centres are visible in the first case (PC3), and these being also more contrasted and generally larger (this is more noticeable at the central part of the maps). Regarding choice patterns (Figure 86), there are also few relevant differences between the scores of principal components and those of the radii with highest loading, except for one detail in the map of PC3: certain radial roads show significatively high scores, but are not at all visible on the lower map (i.e. at radius 400 meters).

These differences arise from regularities in the variability of the centrality values of those spaces that PCA scores seem to capture. Because several radii are being considered in each component, structures having a constant positive variability in those radii seem to be ‘amplified’ in the component’s scores, while others with non-constant variability (i.e. with high values in some radii and not on others) seem to be ‘attenuated’, when translated to principal component scores. In the case of the pattern produced by PC1, this is noticeable in the lesser edge-effect but especially in the highlighting of the motorway network. In the original variables, motorways are also among the most integrated spaces at regional scales, but varying a lot between radii, while many other spaces have also high integration values at several radii. We illustrate this effect on Figure 87, showing the pattern created by the integration scores above 1 standard deviation, at radii 10400 and 30000 meters; and also an overlay of the patterns created by all radii above 10400 meters, for the same cut-off.

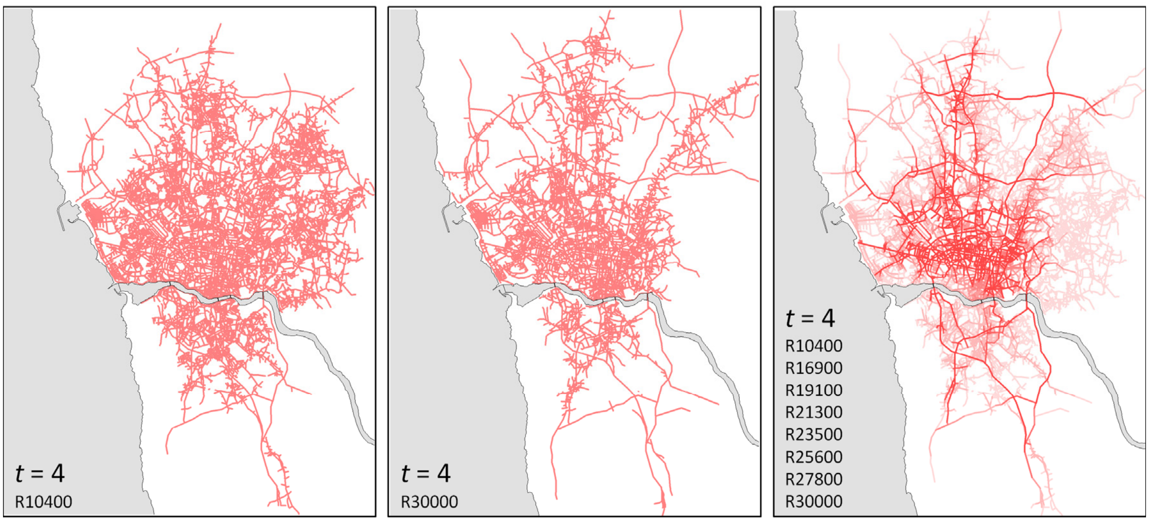

Fig. 87 – Integration values (std.dev. ≥ 1), at radii 10400 and 30000 meters (left and middle, respectively); an overlay of these and of all the other intermediate radii (right).

The overlay is made by giving the same degree of transparency to the several layers, therefore highlighting the elements they have in common (namely the motorway network)[119]. The same technique is adopted in Figure 88 and in other of the subsequent Figures of this chapter. In all those images, the colour scales are calibrated for the maps represented therein; PCA scores have normalized distributions and the classification is always based on similar standard deviation cut-offs, so their visual comparison is reliable.

The same ‘amplification’ effect happens in the PC2 pattern, where the peripheral urban centres become highlighted because they are consistently present in the original variables composing that component (albeit with lower values than those occurring near the centre of the map). In contrast, the ‘attenuation’ of some small centres in PC3 happens because several local radii are being taken into account (and not solely 400 meters) and only the areas that are consistently central across the local variables loading on PC3 end up with high scores. As stated in Chapter 2, variability is higher at local radii; radius 400 meters shows a cloud of very small centres that quickly vanishes in subsequent radii (i.e. 1200, 2100, 3000[120]) giving place to more widely spaced and larger local centres. Thus, in the PC3 map, only the local centres consistently represented in the original variables are highlighted and some of the very small centres present at radius 400 meters fade away.

In the first case (PC2), it is as if the ‘signal’ of the peripheral towns was ‘amplified’, because it is constant through the meso-scales in spite of being relatively weak; in the second case (PC3), it is as if the ‘signal’ of the small centres was ‘attenuated’, because it is not constant in spite of being strong at 400 meters. This is also the reason why the old radial roads become highlighted in choice’s PC3 map, while they seem undifferentiated in the map of radius 400 meters (Figure 88). These roads are in fact absent at radius 400 meters, but they begin to appear from radius 1200 on. At radius 3000 meters these roads are almost entirely highlighted. In fact, the road becomes the high-street of the small centres that punctuate its length, and which are visible at radius 400 meters. Therefore, these ancient radial roads, besides being admittedly central at long-range scales, are actually a kind of linear local centres. We illustrate this in Figure 88 (the exact location is indicated by a rectangle on the PC3 map of Figure 86).

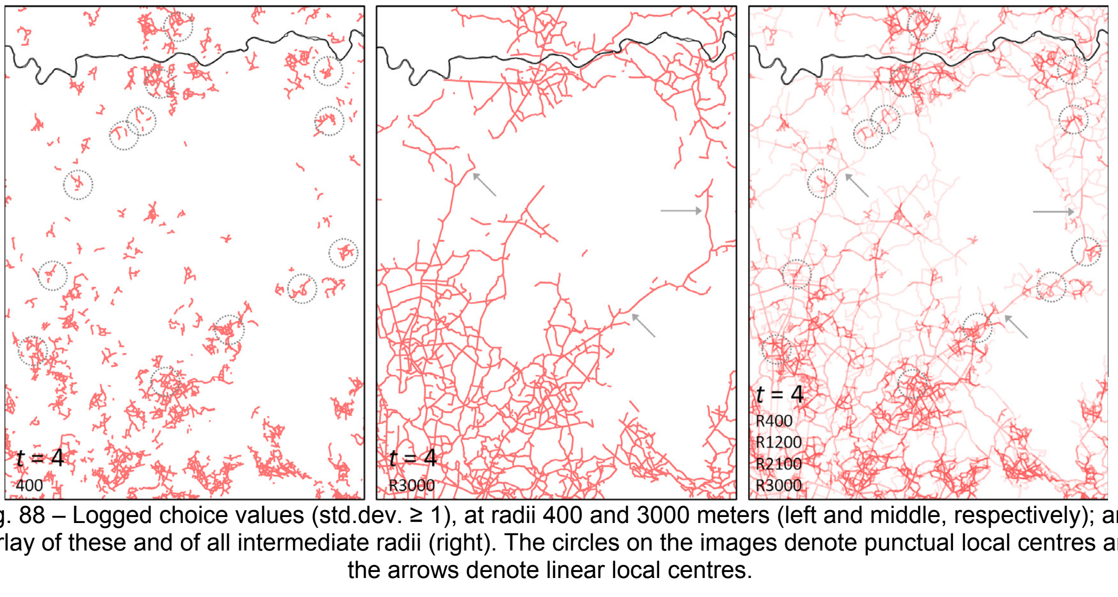

Fig. 88 – Logged choice values (std.dev. ≥ 1), at radii 400 and 3000 meters (left and middle, respectively); an overlay of these and of all intermediate radii (right). The circles on the images denote punctual local centres and the arrows denote linear local centres.

[119] This provides a demonstration of the above mentioned ‘amplification’ effect that PCA creates over structures that have consistently high values on the original variables. But also it is a literal instance of the metaphor of “overlapped movie frames seen by transparency”.

[120] Note that we said before that PC3 was defined from radius 400 to1200 meters. But we also said that that division was slightly artificial: in fact, radius 3000 meters still has a non-negligible loading on PC3 (r ≈ 0,35).

It seems then, that the noticeable differences between the patterns produced by the PCA scores and by the individual radii correspond in fact to latent variability trends of certain spatial structures, which are not at all evident when visualizing the maps of the original variables. But even if a careful analysis could eventually detect those trends in the values of individual radii, still that would have to be done through the joint analysis of many integration patterns and not only one, which is a much more difficult exercise. This makes PCA scores a useful way of visualizing the structure of the metropolitan centrality palimpsest, or at least of a part of it. We may now inspect the behaviour of its individual spaces along only three spatial scales (instead of 17), that we have identified as the *region's*, the *city's* and the *neighbourhood's* scales. And we know that these scales are also the fundamental modes under which centrality varies within the metropolitan spatial network, and that the centrality patterns they produce can effectively be seen as meaningful concatenations of the many patterns produced by the individual radii. In other words, that we can look at them without fearing that we may be looking at something that is just a section of a larger reality.

Therefore, we will now proceed with a more detailed visualization of the centrality patterns produced by integration and choice throughout time, at the three centrality scales discussed before. These patterns are depicted in Figures 88 and 14 (pages 19 and 24). The purpose of the following exercise is to provide a general reading of the temporal evolution of the structures occurring under the three centrality regimes, looking for general variability trends over time, and for particular areas where such trends might be most evident. But in order to make clear the following visual pattern interpretation, we need first to recall the fundamental relationships established within space syntax's theoretical framework between spatial centrality measures, on one hand, and urban form and functioning, on the other.

5.4. VISUALIZING NATURAL CENTRALITY SCALES ACROSS TIME

Within the context of what we might call the 'syntactic theory of the city' - a significative corpus of literature produced in the last 20 years, notably by Hillier and its colleagues at UCL (Hillier and Hanson 1984, Hillier 1996, Penn 1998, Hillier and Vaughan 2007) but also with important contributions of others (Peponis 1998, Read 2005, Turner 2005) - movement, the most basic and common use of urban space, plays the central role. The distribution of movement flows within an urban grid is seen as the basic functional correlate of its form (or layout); and the shaping of movement by the form of the grid as the basic causal explanation for the spatial distribution of urban functions.

This dialectic relationship between the form of the urban street network and the movement flows occurring therein is constructed around the concept of spatial centrality. The basic hypothesis is that a space's propensity for concentrating movement flows to - or through - itself, may be taken as a function of its centrality within the overall spatial network; in particular as defined by the two centrality measures of integration (or closeness centrality) and choice (or betweenness centrality).

These two centrality measures capture different properties of each space in the network, namely its proximity to all other spaces (integration) and its presence on the paths between all other spaces (choice). Therefore, integration is equated with the propensity of a certain space to induce movement to itself (thus, to act as a destination) and choice is equated with the propensity of a space to be part of movement routes (thus, to act as a channel for movement flows). These two properties are not mutually exclusive and both are present in varying degrees at every space of an urban spatial network. But they measure rather different properties and the centrality patterns that their values produce, when translated into colour scales on axial and segment maps, are also considerably different.

Generally speaking, integration tends to produce patchy patterns of areas with higher values (i.e. cohesive and continuous regions of well integrated segments or axial lines), that stand out from the rest of grid. Depending on the scale (or radius) at which integration is evaluated for each space in the network, these patches of higher values vary considerably: from many small centres at local scales, evolving to larger areas at higher scales, and usually ending in one single global centre, when the entire network is being taken into account[121]. This type of behaviour is directly related to the type of centrality that integration measures, namely global proximity or accessibility: spaces that are directly connected to integrated spaces are, in general, integrated as well because they are at similar average distances to all the other spaces[122] - hence the formation of patchy patterns.

Choice produces quite different centrality patterns, which are characterized by web-like structures, made by linear sequences of segments with high values. The distributions of choice values are highly heterogeneous, usually log-normal, as opposed to the typical normal distributions of integration values (Blanchard and Volchenkov, 2009).This happens because choice is not measuring the distance from a given space to all the others, but the number of times such a space lies on the shortest paths between all the others. And this type of characteristic tends to be highly specific in urban spatial networks, with the large majority of spaces showing very low or null values, and a just a few having significative higher values - hence the log-normal distributions of choice values. Furthermore, being part of the shortest paths between all the other spaces is not a characteristic obviously shared by contiguous spaces, unless those spaces are part of the same actual urban pathway. In other words, even if a given sequence of spaces with high choice values actually corresponds to an important urban route, the streets intersecting that route may well have low choice values, because in spite of intersecting it they are not part of the route itself. Unlike integration, whose values commonly spread evenly around the most central spaces at each scale, choice highlights sharply defined linear structures in an urban grid, forming web-like patterns which may be seen as corresponding to the most used routes at each spatial scale.

One may see the patchy patterns produced by high integration values as corresponding to the common idea of central *urban places*, whatever the scale at which the concept is invoked: from the small, named neighbourhood made up of a few streets, to the main centre of an entire city. And the web-like patterns produced by high choice values as corresponding to the common idea of main *urban paths*, again at whatever the scale we may define such concept: from the short trip to the neighbourhood's high street, to the long trip through the metropolitan network of highways and main thoroughfares. It is important to note, however, that both these structures of places and paths are *nested structures*: depending on the radius at which both measures are calculated, we may find that centres at the macro scales are actually composed by smaller centres at the meso scales and even smaller at the micro scales, without any mutual exclusion among different-scaled centrality structures.

These are the basic differences between the integration and choice measures, the patterns they produce and the structures they convey. We now return to Figures 89 (next page) and 15 (page 24); these will be read vertically, from top to bottom, inspecting the patterns of each of the three centrality regimes identified before at each t={1,2,3,4}, first for integration and then for choice. We will thus be looking at the temporal evolution of the structures of central *urban places* and of main *urban paths*, at the scales of the region, of the city and of the neighbourhood.

[121] This is not a description of a universal behavior, of course, but corresponds to the general patterns that integration may reveal in a typical urban spatial network (the same applies for the description of the typical choice pattern). Our intention here is just to provide explanations to make clearer the visual analysis of the patterns produced by the principal components of integration and choice, which we will describe next; not of making solidly defined theoretical statements.

[122] In network terms, this property is known as assortativity, or the propensity for nodes with a certain characteristic to be linked to nodes sharing the same characteristic.

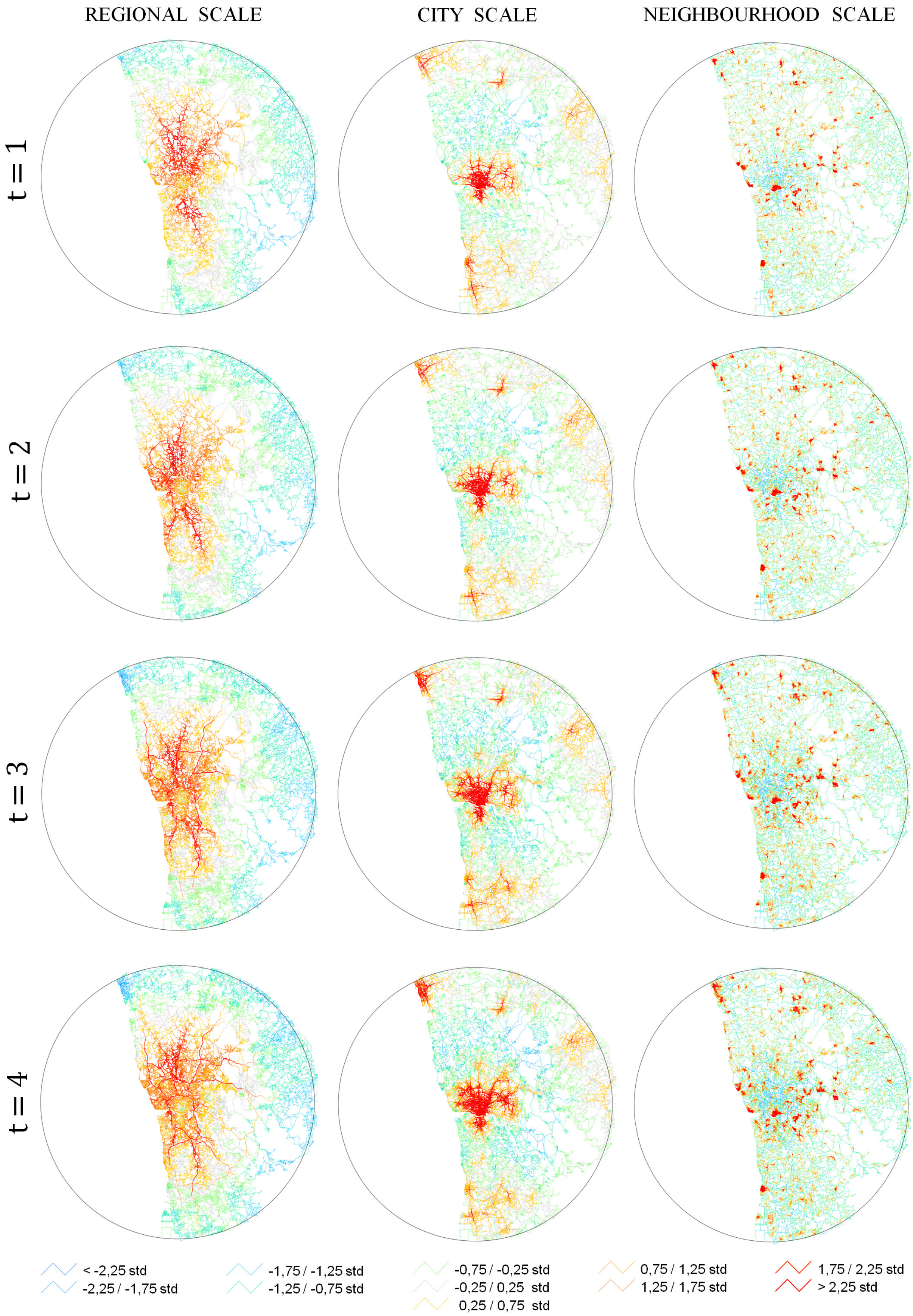

Fig. 89 – Integration patterns for each t = {1,2,3,4}, at the region, city and neighbourhood scales.

The centrality pattern produced by integration at the scale of the region is initially quite uniform, without sharp local variations (Figure 89, previous page). The area with highest scores at this scale is not the geographic centre of the study area, but the region that immediately surrounds it, extending significatively towards north and south, far beyond the administrative limits of the central city. The spaces scoring higher at the regional scale occur outside these limits and correspond to the ancient regional roads, emanating radially from Oporto towards the north and south. But high scores spread evenly from these roads, decreasing with distance from them, in a rather uniform manner. However, from $t = 2$ on, this pattern begins to change.

During the time interval $t_{[1,2]}$ a second road bridge over the Douro river is built (the Arrábida Bridge[123], concluded in 1963), west of the old bridge D. Luís I[124] located at the geographical centre of the study area (until then the only road crossing over the Douro river in the region). Several motorway stretches of some importance (related with the new bridge) are also constructed during this period, the first exemplars of this type of infrastructure on the territory. These interventions, especially the new bridge, expand the initial area with high regional centrality towards the coast, i.e. westward (Figure 89, $t = 2$). But a different qualitative change is also noticeable. The general pattern of highest scores at the regional scale, previously uniform at t=1, starts becoming heterogeneous and concentrated in the new motorway infrastructures; these appear sharply more integrated (in red) than the immediately surrounding areas (in orange). This transformation is increasingly clear in the subsequent observation periods, as the motorway network is being built. At t = 4 the integration pattern at the regional scale shows a mesh of red lines (the completed motorway network and several other important regional paths), in whose interstices integration values are clearly lower. This pattern transformation is a direct consequence of the new and very different type of connectivity that motorways establish with the existing network. Throughout time, motorways assume the previous role of the ancient radial roads as the most integrated spaces at the scale of the region. But their much more parsimonious connectivity also redistributes the former centrality pattern: concentrating the highest integration values and no longer spreading them uniformly over the remaining grid (as the ancient roads did). In order to make this explicit, we show in Figure 90 (next page) the patterns created by the highest integration scores at the regional scale, for t=1 and t=4. The differences are striking.

The large majority of today's main concentrations of logistic, tertiary and industrial functions in the central area of Oporto's metropolitan region[125], are discoverable in the t=4 map of Figure 90 (marked with numbered dashed circles), where are also displayed the larger polygons of industrial, logistic or tertiary functions (area ≥ 10.000 m^2), taken from a recent official dataset[126]. The location of these functional concentrations, catering for the entire metropolitan region and beyond (see footnote 18), is clearly related to the current structure of the most integrated spaces at the regional scale. As can be

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[123] The Arrábida Bridge is a master-piece of bridge engineering. Its delicate, single concrete arch had the world's longest span at the time of construction (615 meters). It was designed by the great Portuguese civil engineer Edgar Cardoso.

[124] The D. Luís I Bridge, also a magnificent example of XIX century iron construction, was concluded in 1888. At the time of completion, the span of its metallic arch (172 meters) was also the longest of its type in the world. It was designed Téophile Seyrig.

[125] Because the list is long, exhaustive and not so relevant, we provide the legend of the functional agglomerations on Figure 10 in this footnote, as follows: **1** - [Oporto International Airport, Industrial Area (I.A., henceforward) *Minhoteiras*, Oporto's Regional Logistic Platform I], **2** - [I.A. *Terronhas/Recarei*, "Lionesa" Buisiness Centre (advanced services)], **3** - [I.A. Maia I], **4** - Petrogal (oil refinery), I.A. *Frexeiro*, international TIR terminal (logistics), "Mar Shopping" (regional shopping mall), "IKEA" (global store)], **5** - [International Port (and logistic platform), I.A. *Matosinhos*, "Norte Shopping" (regional mall)], **6** - [I.A. Oporto (advanced services and commerce)], **7** - [Oporto University Campus 3, Central Public Hospital, advanced services], **8** - [Metropolitan Grocery Market (regional retail), "Parque Poente" (regional mall), industry], **9** - ["Arrábida Shopping" and "Continente" (regional malls), "Hospital da Arábida" (private hospital), advanced services], **10** -["Gaia Shopping" (regional mall), logistics and commerce (Mercecedes/Benz, Opel, and BMW regional centres)], **11**- [I.A. *São Caetano/Lages/Urtigueiro*], **12** - [I.A. Freiteira, Grijó Business Centre (advanced services)], **13** - [I.A. Avintes], **14** - [I.A. Alfena], **15** - [I.A. Maia II], **16** - [I.A. *Vermoin/Milheirós*], **17** - [I.A. *Maia Sul/Baixia*, logistics], **18** - [I.A. *Baguim*].

[126] The source is the COS2007 dataset (Carta de Ocupação do Solo 2007), the official Portuguese land-use map, made available by the Portuguese Geographic Institute (IGEO) at http://www.igeo.pt/produtos/CEGIG/Cos2007.htm.

seen in the left image of Figure 90, some of these regional centres simply did not exist as such at t=1 (ns. 4, 5, 9 and 13) while others are situated in previously accessible areas, but whose centrality patterns were significatively transformed (all the other cases). In any case, not a single of these current concentrations of regional-scaled functions is located without relation to, or 'decentred' from, the contemporary pattern of most regionally-integrated spaces. It is also important to note that most of these functional concentrations (except ns. 3, 5 and 6) were not deliberately planned as such (particularly ns. 9, 10, 11 and 14-18). Some are the product of nearby transportation facilities (n. 1, close to the airport and n. 5, close to the port) while others of nearby large industrial facilities (n. 4, close to the oil refinery), but even so they are all fairly spontaneous functional concentrations.

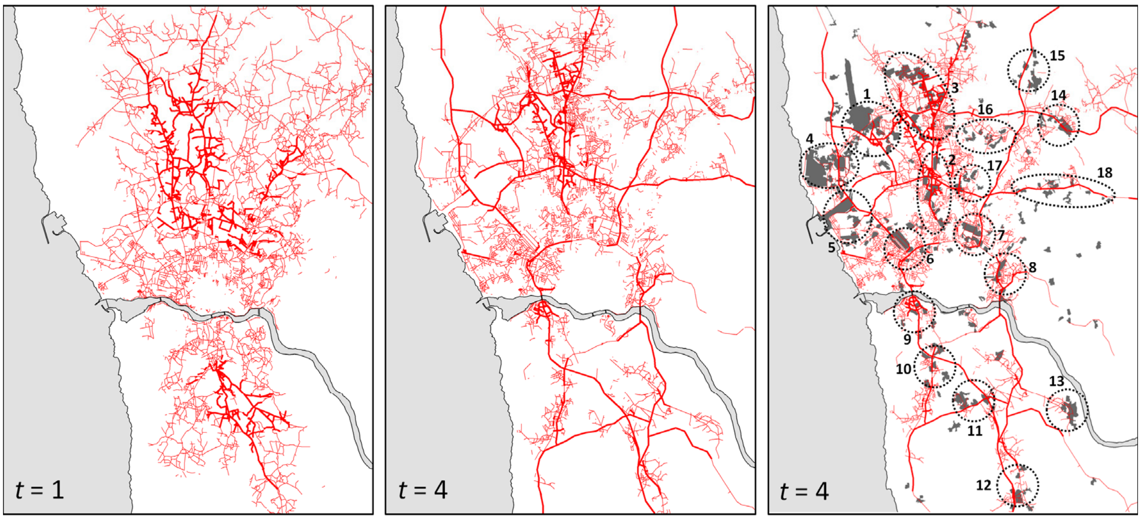


Fig. 90 – Integration at the scale of the region (thin red: std.dev. ≥ 1; thick red: std.dev. ≥ 2), for t=1 and t=4 (left and middle, respectively). The t=4 pattern, overlaid with industrial (ns. 3, 2, 4, 11-18), logistic (ns. 1, 4, 5, 8 and 11) and commercial/services (ns. 4, 6, 7, 9, 10, 12) polygons of the COS2007 dataset (area ≥ 10.000 m^2).

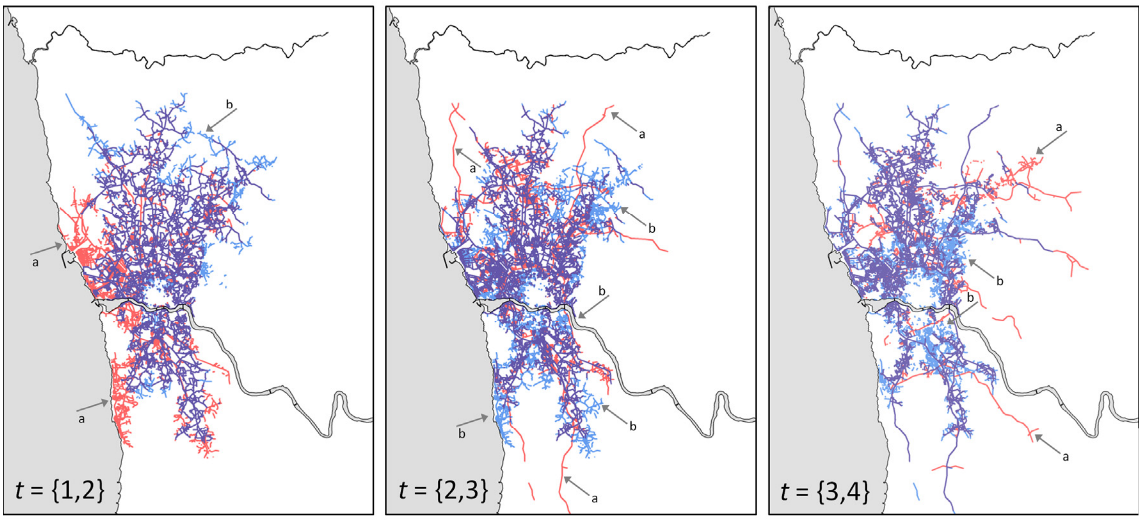


Fig. 91 – The evolution of integration at the scale of the region (std. dev. ≥ 1): overlays of each two consecutive periods of observation (the features belonging only to the former period are blue, those belonging only to the latter are red and those present on both periods are purple). The arrows and letters denote: a) expansion and b) contraction.

Two significative trends in the evolution of integration at the regional scale are therefore identifiable. One of general *expansion* of the area with values above the mean, first towards the coast but then also towards north, south and west, which corresponds to a general increase of accessibility at the regional level in these areas, clearly driven by the motorway system (see Figure 91). But also another trend, perhaps less expectable, of progressive concentration of highest integration values in the evolving motorway system and a concomitant *contraction* of values in the interstices of the lattice that it forms. This is visible on Figures 90 and 91, where large areas of previously well regionally-integrated spaces at t=1 have lost centrality and are simply absent in the t=4 maps. This deep transformation of the centrality pattern entailed the transformation of the initially homogeneous centrality pattern, into a final heterogeneous and lattice-like pattern, in whose intersections the main current concentrations of regional-scaled functions may be found (Figures 90 and 91).

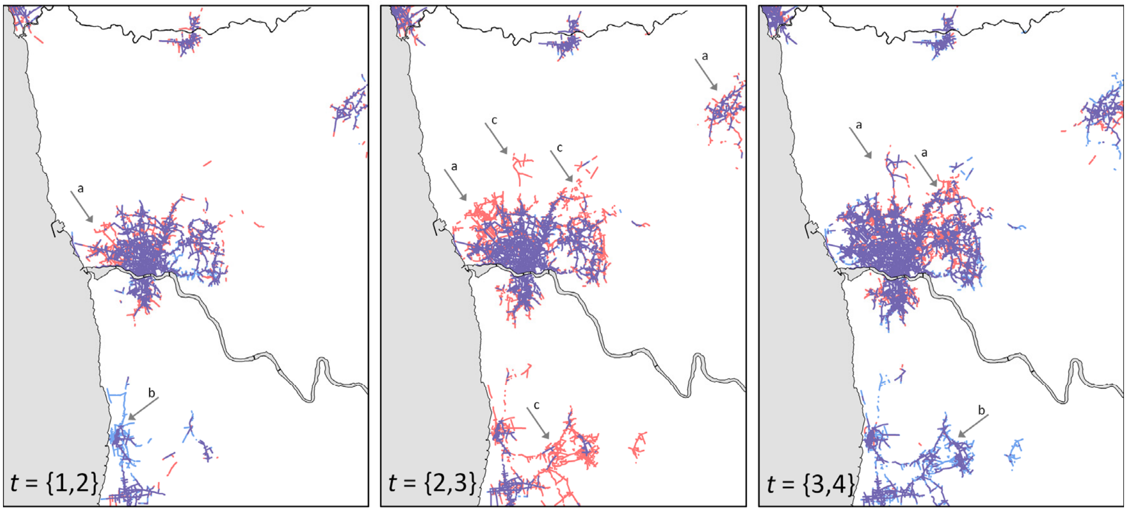


Fig. 92 – The evolution of integration at the scale of the city (std.dev. ≥ 1): overlays of each two consecutive periods of observation. The arrows and letters denote: a) expansion, b) contraction and c) emergence.

At the city scale, the initial pattern produced by integration depicts many of the historic urban agglomerations[127] in the study area as zones of particularly high scores (Figure 89, t=1). Over time, the generality of these zones are enlarged, but a few decay and still others appear. Nonetheless, their general spatial distribution remains stable and the observed transformations are not comparable with the drastic changes occurring at the regional scale.

Three main trends for the evolution of integration at the city-scale are identifiable: expansion, contraction and emergence. By expansion, we mean the increase in the number of segments with scores above the average, within and immediately around each of the previously mentioned areas; by contraction, we mean the decrease in the number of segments with scores above the average, in the same geographical circumstances; and by emergence, we mean the appearance of new cohesive areas with high scores, either because existing segments have their scores augmented, because new segments scoring high have appeared along time, or both. In Figure 92, expansion is most noticeable around Oporto and Vila do Conde (the city further north, at the limit of the study area), particularly from t=2 to t=3; but the generality of the other well integrated areas at the city-scale also expand. The contraction of previously well integrated areas is rarer, but it happens clearly twice and with greater intensity during t[1,2], near the southern limit of the study area (see Figure 92). The emergence of new nuclei of high values happens around Oporto, where two new satellite towns (Maia and Ermesinde) appear during t[2,3], and also in the most southern part of the study area, where a region of diffuse

[127] These are the city of Oporto (strongly highlighted at the centre of the study area) and the peripheral cities of (clockwise in the central column of Figure 89, from 11 to 6 o'clock) Vila do Conde, Trofa, Paços de Ferreira, Penafiel, Esmoriz and Espinho.

high values can be seen emerging from t=1 until t=3, when it attains its maximum. These three trends are clarified in Figure 92 (previous page).

At the neighbourhood scale, the centrality pattern is composed of a cloud of many small centres, whose spatial distribution is not immediately relatable to the well integrated areas identified at the city-scale (Figure 93). Nonetheless, some of them do occur within those areas, corresponding in these cases to smaller sub-centres. Also, some of these local integration centres are actually small towns of ancient foundation, which were not identified at the city-scale because they do not have that range of influence in spatial centrality terms. A clearly higher density of local centres is noticeable at the northern part of the study area (i.e. north of the Douro River).

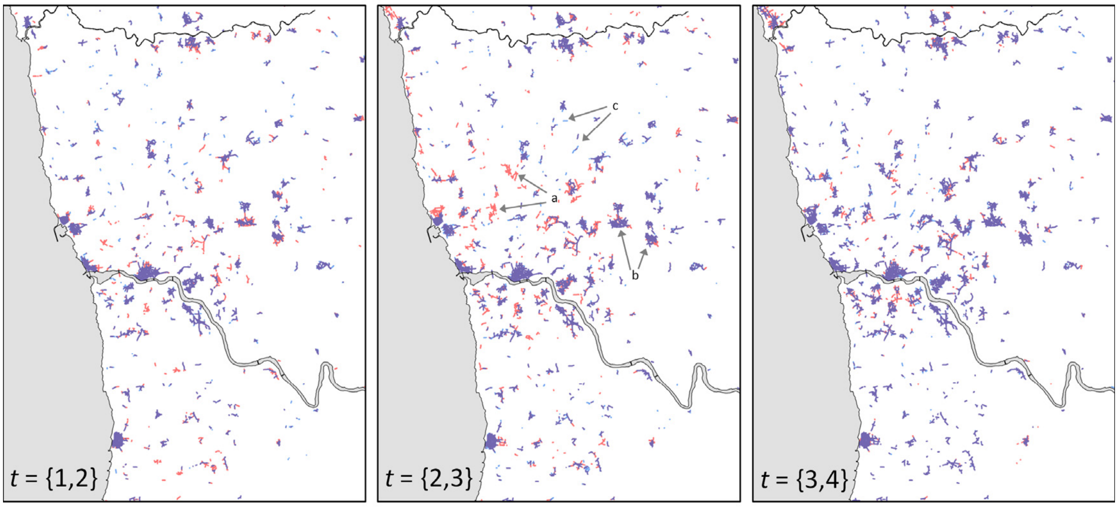


Fig. 93 – The evolution of integration at the scale of the neighbourhood (std.dev. ≥ 1): overlays of each two consecutive periods of observation. The arrows and letters denote: a) emergence, b) expansion and c) contraction.

The previous three transformation trends - expansion, contraction and emergence - are also observable. Emergence, however, is much more common at this scale: many new local centres arise during the study's time span, particularly during $t_{[2,3]}$. But these transformations occur mainly in the northern part of the study area. The southern part shows almost no transformations at this scale. The large majority of these new centres correspond to the coalescence of small, market-led interventions, as the ones described in chapter 1. They occur in a pulverized pattern, over the entire study area.

The expansion of existing centres is also frequent, occurring mostly on those lying within larger urban areas, as the ones identified at the city-scale; but also around the small towns referred to above. Contraction is rarer. It happens mainly at the smallest centres (i.e. composed by just a few street segments), but sometimes to the point of falling off the visualization threshold (i.e. below 1 std.dev. above the mean). These tend also to occur far from the main urban centres, in areas which remained fairly untouched by urban development. They correspond to small condensations of the rural grids (typically at the intersection of several roads), which loose importance along time because new, larger and more locally integrated centres emerge elsewhere, skewing the distribution positively.

We now look at the patterns produced by the choice measure through time, shown in Figure 94 (next page). As stated before, choice highlights important routes in the spatial network, corresponding to the nodes falling more frequently on the shortest paths between all the others nodes (or between all those within a certain radius). At the scale of the region, the initial pattern (t=1) is markedly radial. The structures with higher scores are again the ancient radial roads, but now clearly highlighted.

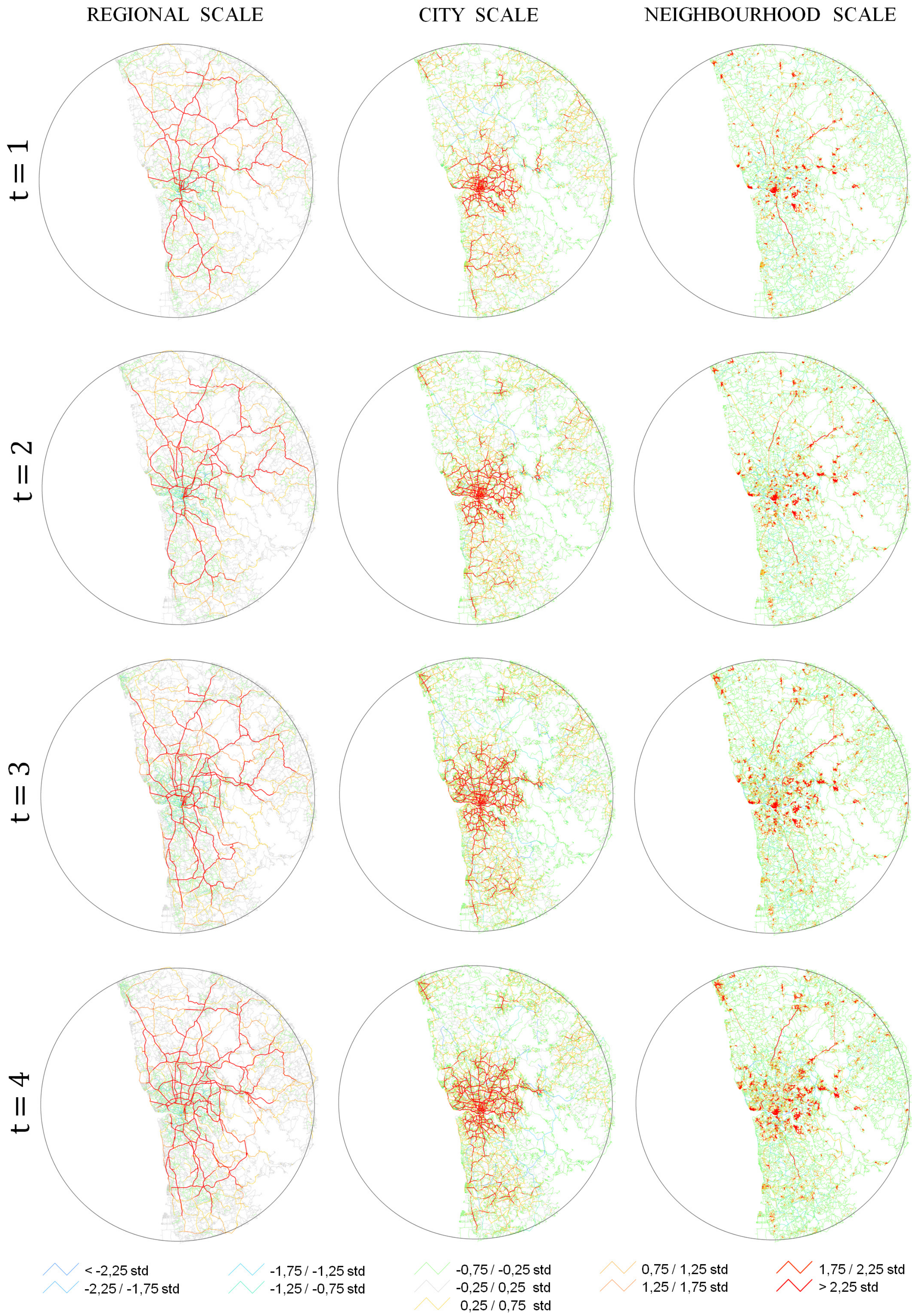


Fig. 94 – Choice patterns for each t = {1,2,3,4}, at the region, city and neighbourhood scales.

These radial roads are the oldest paths in the territory, indeed the very seeds of its urbanity. Oporto was born at the spot where the Roman road linking *Olissipo* (Lisbon) to *Bracara Augusta* (Braga) crossed the Douro River. This road still exists today (it is now known as EN1 and EN14) and is quite visible in Figure 94, as one of paths with highest regional choice at t=1. Also of Roman origin, the ancient roads from *Cale* (Oporto's Roman name[128]) to *Vimaranes* (Guimarães, today EN105) and to *Limia portus* (Vila do Conde, today EN13) are equally highlighted. Other radial roads are also visible, being likewise very old (at least of medieval foundation, but presumably earlier) linking Oporto to Aveiro (southwards, by the coast) and to Vila Real (eastwards). All these paths with high regional choice converge at Oporto's centre, and are traceable down to the oldest core of the city (today in the form of several well-known streets). Their perpetuity as main regional routes is indeed notable, and a clear sign of the impact that road infrastructures may have on territorial structuring: the areas identified before as the initial strong structures at the city-scale, fall perfectly over this old radial system. In fact, the superimposition of those two centrality layers summarizes quite eloquently the basic territorial structure of the study area at t=1 (Figure 95).

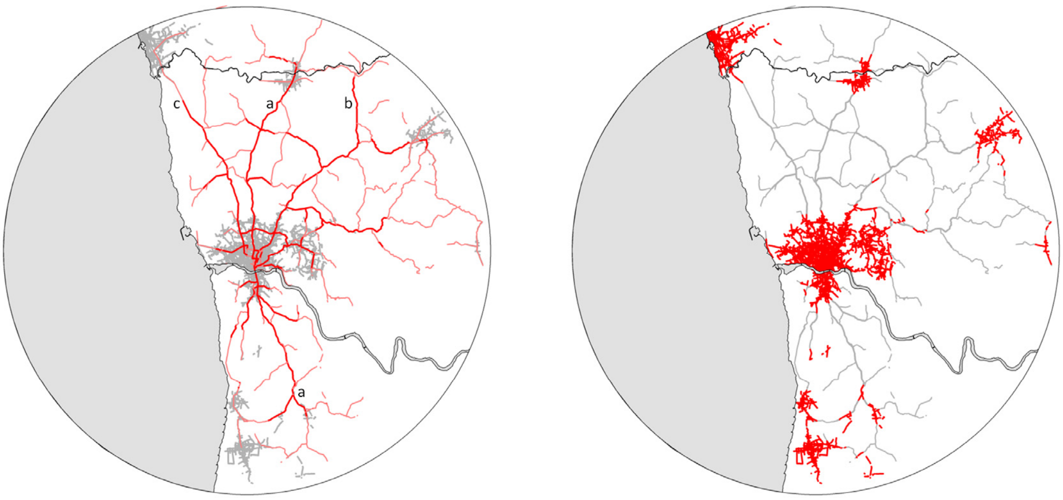


Fig. 95 – Overlay of the 'main paths' (pink: std.dev. ≥ 0,5; red: std.dev. ≥ 1) at the regional scale, with the 'central places' (std.dev. ≥ 0,5) at the city scale, at t=1. On the left image the letters denote the ancient Roman roads: a) from *Olissipo* to *Bracara* (current EN1 and EN14), b) from *Cale* to *Vimaranes* (current EN105), c) from *Cale* to *Limia portus* (current EN13).

This initial radial system is complemented by several concentric roads with also high scores, establishing transversal connections within it. Besides those, some streets of Oporto's inner urban grid are also part of the routes with highest choice values at t=1. As for integration, the most significative transformations revealed by the choice measure happen at the regional scale. These can be observed in Figure 94, but also in more detail in Figure 96 (next page).

The main transformation trend can be characterized by the progressive densification of the initial radial system, towards a final and much more complex radio-concentric system of main regional paths. Many of these correspond to the growing metropolitan motorway system; but not all, as several existent and new inter-municipal roads acquire also high choice values through time. But unlike what we saw with integration, the progressive densification of the system of main regional paths do not typically leads to the decay of previous central structures. As can be seen in Figure 96, many new strong structures appear at each period (in red), but the previous structures are kept (in purple) and just a few loose centrality (in blue).

[128] Oporto was called *Cale* in Roman times and it had a port - *portus Cale* (the port of *Cale*). The name "Portugal" has its origin in that toponym: *portus Cale* → *Portucale* → Portugal.

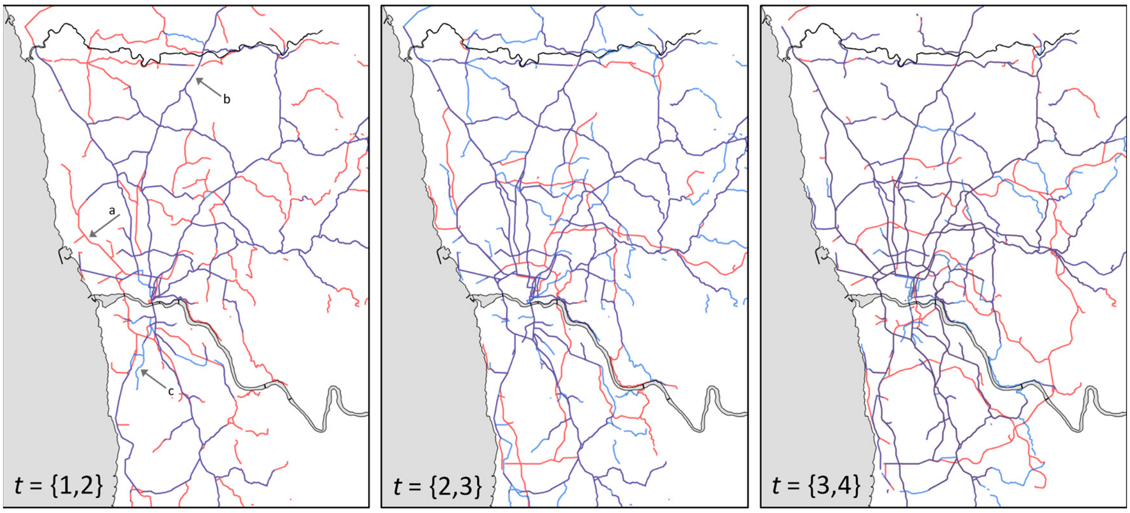


Fig. 96 - The evolution of choice at the scale of the region (std.dev. ≥ 1): overlays of each two consecutive periods of observation. The arrows and letters denote: a) expansion, b) maintenance and c) contraction.

Even if the evolving motorway network ends up with the highest choice values at the regional scale, previous paths have their values only marginally reduced, rarely falling off the visualization threshold of Figure 96 (std. dev. ≥ 1). The most significative losses happen at the roads providing the previous transversal connections between radials, as these are progressively replaced by motorways fulfilling the same function (Figure 96, t={2,3}). Also, the introduction of new road bridges across the Douro River129 causes some significative decays in previously important paths, while giving rise to new strong structures (Figure 96, t={1,2} and t={3,4}). But, in general, the resilience of paths is remarkable, with transformations happening much more by densification and expansion, than by the downgrade of previous structures.

At the city scale, the pattern produced by the spaces with highest choice scores is quite different (Figure 94, t=1). It depicts a finer-grained, middle-scaled grid, of which some of the previously discussed structures are part (namely the old radial roads), but also made up of a much greater number of streets and roads. This is the system of main thoroughfares used for intra or inter-urban trips of medium distance. Initially, it shows a heterogeneous distribution: highly dense and grid-like at Oporto's core and more large-grained towards the edge of the central-city. The peripheral towns identified by integration at the city-scale, show only a few dispersed segments with high scores (in red on Figure 94), which do not form cohesive grids. A significative difference between the northern and southern parts of the study area is noticeable (i.e. at north and south of the Douro River). The southern part shows a diffuse and considerably large grid-like structure, with not so high scores and more fragmented than that in and around Oporto, but still covering the generality of the area south of the river; whilst the northern part, beyond the central-city and outside the small peripheral towns, shows much lower scores (even tendentiously negative), with almost any visible structural differentiation.

This middle-scaled grid expands throughout time, but still in an inhomogeneous way. The area around and within Oporto suffers the most significative expansion, followed by the diffuse area at south (Figure 97, next page). But in or around the northern peripheral towns, hardly any change is visible (in spite of an actual increase, albeit very marginal, in the scores of those areas). Moreover, in the region between those towns and the central city, scores actually decrease steadily along time, reaching t=4 without any structural differentiation at all.

[129] We refer to the previously mentioned Arrábida Bridge (constructed during $t_{[1,2]}$), to Freixo Bridge (constructed during $t_{[2,3]}$) and to Infante Bridge (constructed $t_{[3,4]}$).

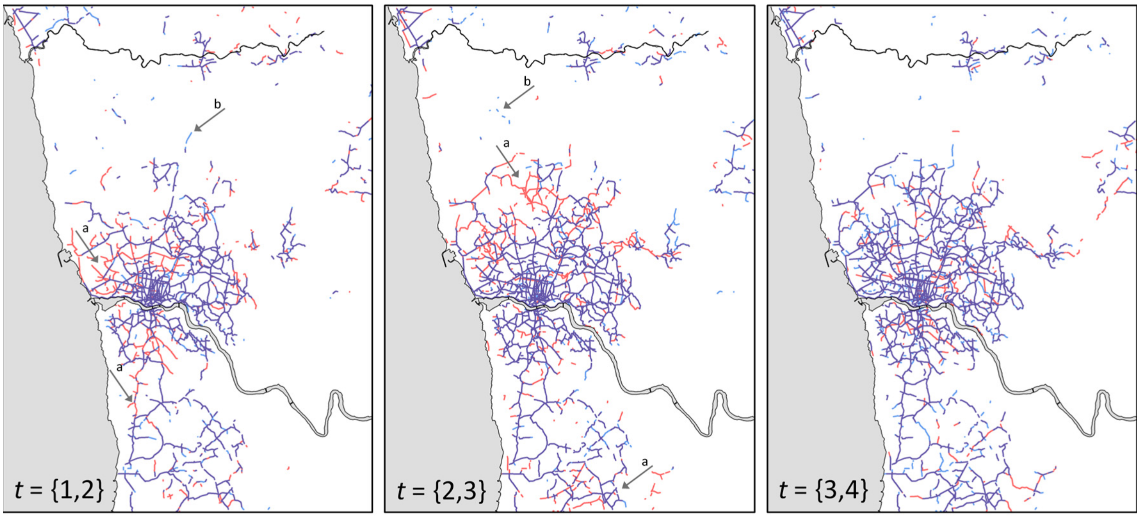


Fig. 97 – The evolution of choice at the scale of the city (std.dev. ≥ 1): overlays of each two consecutive periods of observation. The arrows and letters denote: a) expansion, b) contraction.

The dominant transformation trend of the pattern created by high choice scores at the city scale is expansion, albeit spatially heterogeneous. Decay (or contraction) seems rarer and quite erratic (i.e. without clear pattern across time or space), except in the area mentioned above where it happens consistently. However, the intensity of the observed expansion is rather variable: strong in and around the central city, visible but less intense on the southern part of the study area, and even lesser on its northern part. The final pattern is as heterogeneous as the initial: it shows a large and cohesive zone at the centre of the study area (corresponding to Oporto and to its immediate surroundings) which extends towards south, becoming sparser and less continuous; at north, the peripheral towns show undeveloped and fragmented middle-scaled grids, which do not merge or connect with each other.

At the scale of the neighbourhood, the pattern produced by choice's scores resembles that of integration at the same scale. But under a closer inspection several differences become apparent. The large majority of local centres identified by integration are also local choice centres. However, choice highlights a significative lesser number of spaces in those centres, namely only those with high degree of *path-overlap*. In other words, choice specifies - within the locally accessible areas identified by integration - the particular streets that are more often used for short-range trips. Moreover, choice identifies also other types of local centres, namely linear ones. A significative number of dispersed segments are highlighted, as places of high overlap of short distance paths. Some of these may be caused by artificial fluctuations of the model, i.e. they can be mere noise. But when they coincide with centres identified also by integration, we may in principle reject such hypothesis. Moreover, on certain structures, as it is the case of the old radial roads, these small choice centres are so frequent that entire stretches of the road become highlighted at the neighbourhood scale.

Like for integration, the main transformation trend for choice at the neighbourhood scale is emergence. Many small centres appear through time, especially during t[2,3]. But some spaces also decay: several stretches of the old radial roads loose centrality at this scale, during t[1,2]. These decreases seem directly related to the introduction of the first motorway infrastructures during that period. But the inverse trend also happens during t[2,3] and t[3,4]: some motorway stretches, built in the dense urban context of central Oporto, appear highlighted, just like the ancient radial roads. This shows that such type of infrastructure, when within dense grids and fulfilling a role more of arterial streets than of regional inter-connectors, may also be used (or at least are central for) short-range dislocations. In fact, in those contexts their connectivity is higher, and market-led urban development operations use it as a valuable externality, locating the closest possible to the points where these infrastructures connect to the local grids, boosting their role as local connectors. A last general trend is also identifiable at this scale, as it was already for integration: the emergence of local choice centres is much more prolific at the northern part of the study area (around Oporto and the northern peripheral towns) and much rarer at the southern part. These trends are clarified on Figure 98.

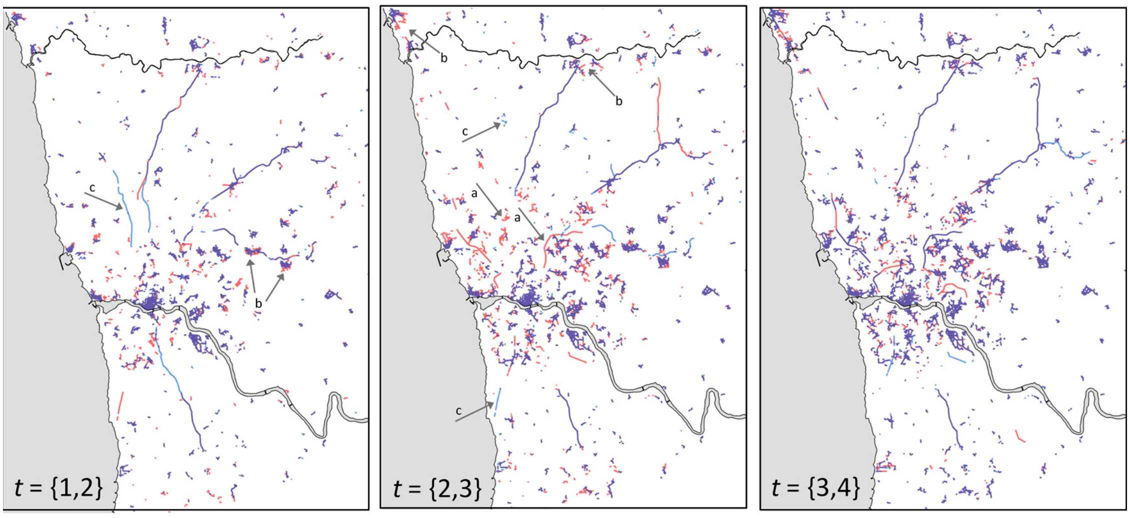


Fig. 98 – The evolution of choice at the scale of the neighbourhood (std.dev. ≥ 1): overlays of each two consecutive periods of observation. The arrows and letters denote: a) emergence, b) expansion, c) contraction.

Along the current section, we have shown that PCA can be an effective method for reducing the large-dimensionality that the centrality analysis of metropolitan spatial networks entails. Through its application to our specific case study, we have also shown that the variability of centrality values in the metropolitan region can be characterized by only three main *centrality regimes* or scales: those of the region, of the city and of the neighbourhood. These three fundamental scales are constant through time: in spite of the intense growth and transformation of the spatial network that we have witnessed in Chapter 1, all the identified spatial structures (existent or emergent) are relatable to just these three centrality regimes. They can, therefore, be seen as the fundamental spatial scopes for which street and road infrastructures are built and bound to function, within the metropolitan region.

Such statement would seem a triviality, if we were to forget that the overwhelming majority of such infrastructures are by no means planned to fulfil their functions within such a definite spatial hierarchy. Especially below the scale of the region, and particularly at the scale of the neighbourhood, the growth of the spatial network is driven by market-led interventions, whose concerns with the overall emerging spatial structure are little more than negligent. Municipalities, for their part, carry out several planned interventions at the scale of the city, but still little concerned with any structural impacts or synergies taking place outside its administrative limits, and even less in regard to the larger metropolitan context into which such interventions fit. At the scale of the region, interventions are centrally planned, but still they concur and co-operate with existing time-enduring structures pertaining to the same centrality scale, albeit with different capacities and structural specificities. Thus, the existence of the three fundamental centrality scales discovered, is not the obvious consequence of a simple and well implemented planning idea. On the contrary, it is an outcome of the self-organized development of the metropolitan spatial network, constructed incrementally by many agents driven by different intentions and acting at different levels, in a largely uncoordinated process. It is also important to stress that the identification of those three main centrality regimes was made through an objective and reproducible quantitative method (PCA) and not through some serendipitous analytical 'hunch'. They were defined merely through the centrality values occurring in the metropolitan spatial network, which are induced solely by its structure. Their identification is a pure *empirical result*, because the spatial network is a physical reality, built on the ground and measurable as any other material object. As such, the tripartite centrality regime indentified may inform physical planning decisions and strategies on the territory under study, based on its intrinsic and most basic structural segmentations.

The subsequent visualization exercise conducted in this section provided also several findings regarding the temporal evolution of centrality structures on Oporto's metropolitan region, as defined by the PCA scores of the integration and choice principal components. These will be recalled and summarized later, in the conclusions of the current chapter. We will now turn to another analytical problem, enunciated at the beginning: that of trying to understand if the objects in each table (i.e. its rows, on average 120.000 per table) may also be transformed into simpler aggregated structures, according to potential similar centrality behaviours, which they may have over the three centrality regimes identified.

5.5. Discovering centrality typologies in the metropolitan centrality palimpsest

In the previous section we have shown that it is possible to reduce significatively the number of dimensions in the metropolitan centrality palimpsest. In doing so, we also found that just three fundamental *centrality regimes* were enough to describe pretty much everything that happens within it, regarding the variability of centrality values. But that only tells us that the centrality of each space may be described by just three variables instead of seventeen (both for integration and choice). It does not tell us anything about potential regularities among the centrality behaviour of individual spaces in the metropolitan spatial network.

However, it seems plausible (and even probable) that such regularities may exist. Indeed, that is exactly what Figure 80 (page 125) is suggesting: that some spaces are central only at the regional scale, while others only at the neighbourhood or at the city scales, but still others may possess any possible combination of states at each of the previously defined centrality regimes. Of course, this may happen in a more-or-less random manner, without any particular similitude between the centrality behaviours of the individual spaces in the network. Only this seems much less probable. Urban spatial networks are characterized by strong structural regularities (some of which have been highlighted in the current and in the previous chapters), arising not only from their evident geographic constrains, but also from common fundamental functional purposes and even from processes of auto-organization, which have been claimed as having a high degree of universality (Hillier 1999, 2002; Carvalho and Penn 2004). Along with all these characteristics, network structural regularities may also be induced by planning actions, even if we might expect (with some hindsight) the outcomes of urban planning to be less effective on that regard. But it seems rather plausible, at least to anyone who reflects about cities, that there may exist something as 'families' of urban places or of urban paths, sharing traces of similarity regarding their roles in the spatial network, however difficult these may be to define. We do not refer to obvious physical similarities (as the architectonic style of buildings, or even just their volumes or heights); we mean something more intangible, as the type of urban experience such places and paths provide: e.g. in terms of urban flows and speeds; in terms of functional vocation, diversity and density; or in terms of the co-presence of a large spectrum of the metropolitan society or just of a segment of it. This may seem rather difficult to obtain. However, there is a handy shortcut: these characteristics are, at least in part, reducible to the degree and type of spatial centrality (if we take the concept broadly) that a certain urban area or path has within the overall urban spatial network. That is, indeed, the central hypothesis of the space syntax research programme. And because what we are studying is the complete, multidimensional spatial centrality structure of the metropolitan region, perhaps we could find a sign of such typologies of places and paths, through the use of systematic classification methods - namely cluster analysis - over the varying centrality values of all the spaces in the metropolitan spatial network. That is the hypothesis[130] from which we depart in the current section.

Specifically, what we will be looking for are regularities in the occurrence of each space's centrality values, as represented by the scores of three principal components of integration and choice. The aim is to find classes (or clusters) of spaces sharing the same behaviour at the three centrality regimes. As stated before, such behaviour can be any, as long as it is recurrent. Figure 99 shows two tri-dimensional scatter plots for t=4, depicting the position of each segment in the spaces of variables (i.e. the three principal components of integration and choice). As it is possible to see, both clouds of points are rather heterogeneous, which is a sign that indeed they may possess intrinsic sub-structures. The task of cluster analysis will be to define rigorously how many of such sub-structures each cloud may contain, and to make explicit their internal similarities and external differences.

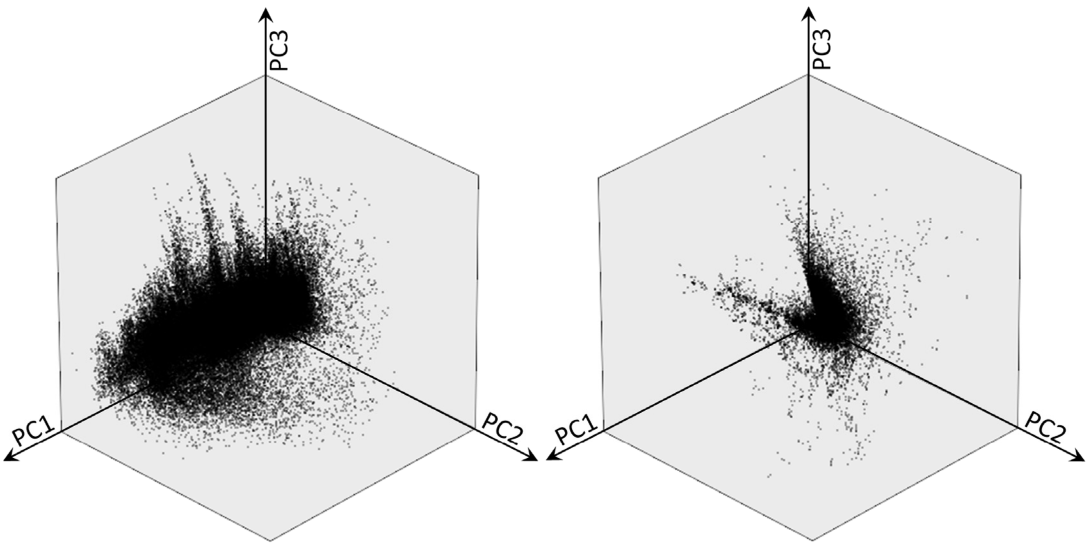


Fig. 99 – Tri-dimensional scatter plots showing the scores of the three principal components of integration (left) and choice (right).

As introduced in section 3.2, cluster analysis is a family of unsupervised classifications methods, aimed at dividing data into homogeneous classes (or clusters), so that the objects in a class are more similar among themselves than to the objects in the other classes. It differs from supervised classification techniques (i.e. classification with a previous model or division label), because the resulting classes are derived only from the data itself; i.e. they are the result of intrinsic cleavages and associations between the data points and not of pre-defined classification criteria. There are many clustering methods, usually divided into hierarchical and non-hierarchical methods (see section 3.2), which are used for different purposes. Hierarchical methods have several advantages, but are computationally expensive and are therefore restricted to small datasets (e.g. below 10.000 objects). Because of the large size of the dataset we will explore (over 120.000 objects per table t={1,2,3,4}), here we will use the K-means clustering algorithm (discussed below), which belongs to the non-hierarchical type and is capable of dealing with large amounts of data (Tan et al. 2005). Nevertheless, we will also use hierarchical clustering as a pre-processing procedure, but not for obtaining the final clustering solutions.

130 Such hypothesis, as well as the way to test it, was suggested to me by my dear friend and colleague Jorge Gil, who is a wellspring of inspired insights on everything that concerns urban phenomena.

The 'K' in K-means, indicates that the algorithm is able to find any number of clusters, but that such number (K) must be defined *a priori*. This is the major difficulty posed by this method, which we will discuss in a moment. The term 'means', indicates that the algorithm is based on average distances between the data points and a pre-selected number (K) of centroids, which will end up being also the mean points of the final clusters. These centroids are also called the 'prototypes' of each cluster, in the sense that the set of objects in each cluster are closer to their prototype (i.e. centroid), than to the prototype of any other cluster (Tan et al. 2005).

The algorithm starts by randomly[131] choosing K points from the dataset, as the initial centroids. Then, each point is assigned to the closest centroid and each set of points thus defined becomes a cluster. The mean point of each cluster is then calculated, and those mean points become the new centroids. Next, the distances from the points to the new centroids are re-calculated, the centroids are moved to those mean points, and the data points are re-assigned to the new clusters thus defined. This is important, because it means that points are allowed to change clusters until total convergence is achieved (something which is not possible with other clustering methods). The process is repeated iteratively, until the centroids remain fixed (or until no point changes clusters, which is the same), meaning that total convergence was attained and that the data points are assigned to the local optimal division for that number (K) of clusters. This process is illustrated in Figure 100, for a schematic dataset with three natural grouping of points.

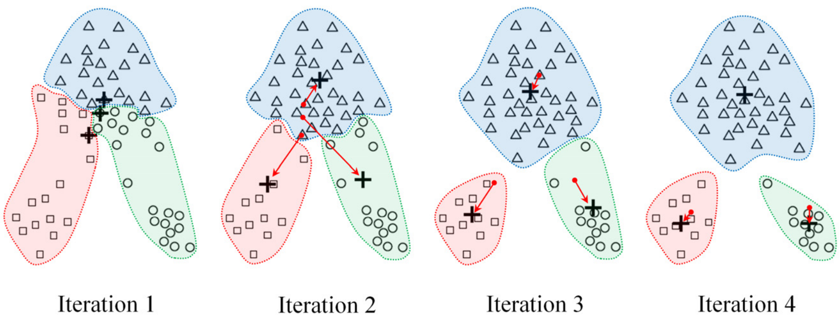


Fig.100 – The K-means algorithm at work: finding three clusters in a data sample. Adapted from (Tan et al. 2005).

There are several previous requirements for a conducting K-means clustering in a given dataset. First, because the similarity between data points is measured in terms of their Euclidean distances to the centroids, the several variables should have similar scales. If the scales of variables are very different the clustering results may be distorted, simply because variables with large scales will distribute the data points further apart than variables with small scales in the n-dimensional space they define, leading to spurious point distributions on which distances cannot be compared. Thus, the variables should be previously standardized, in order to guarantee similar scales. Secondly, collinear variables should not be used, but only variables without evident correlations (i.e. clearly describing different things). Collinear variables will 'drag' the clustering solution towards one preferential direction, because the algorithm will detect proximities between points that are only caused by the presence of several variables describing 'the same thing'. Thus, all variables should have null or negligible correlations between themselves (Tsiptsis and Chorianopoulos 2009). These two requirements make PCA scores particularly indicated as clustering variables. As stated before, principal components define orthogonal axes; therefore the correlation between their scores is zero: they are by definition uncorrelated. Moreover, they are also standardized variables (with mean zero and standard deviation one), which grants them similar scales.

[131] Actually, the choosing of the initial centroids needs not to be random neither to correspond to points from the actual dataset. In fact, we will not use such method. But that is the original and simplest formulation of the algorithm, to which we will restrict for now.

One last requirement, but particularly relevant, is that the data to be clustered should not have outliers (i.e. objects deviating strongly from the rest of the sample). Outliers can bias the results of k-means clustering in several deleterious ways. First, if an outlier is chosen as an initial centroid, odds are that such centroid will not move anymore, because it is by definition away from all the others points, producing a cluster with only one or just a few objects (i.e. the outliers themselves); second, even if not selected as centroids, outliers tend to create abnormally dispersed clusters, because in any case they will lay very far from their respective centroid; thirdly, if a centroid is 'caught' between a real cluster and one or several outliers, its movement towards the real cluster will be restrained by the nearby outlying points, leading to the non-identification or to the artificially sub-division of the real cluster by the remaining centroids; and fourthly, they may have a negative impact when the objective of clustering is identifying typical behaviours among objects (as it is our intention), because the difference between 'outlier' and 'normal' data patterns is so large that it may mask existing differences between the majority of 'normal' cases (resulting in degenerated solutions merely separating outliers from the rest of the data). Thus, in general cases[132], outliers should always be identified first, removed from the dataset before the clustering procedure and studied separately.

There are still two more important aspects to discuss regarding the K-means algorithm, before proceeding with the analysis of our data. The first is the way to choose the right number of clusters to obtain, i.e. to define K. The second is the fact that the choice of the initial position of the centroids may have great influence in the clustering result. We will delve into these two issues, because they are interrelated and entail several methodological choices.

When performing K-means clustering, choosing the optimal K is the main analytical problem. If the real number of clusters within a given dataset is not known *a priori* (which is usually the case), the only way to discover it is iteratively. This is because the K-means algorithm does not provide any answer on that regard; it simply tries to divide a given dataset into a number K of internally similar clusters. Thus, for a given dataset, it will produce solutions with any number of clusters, up to a limit equal to the number of objects in that dataset. But what one expects, if the number of clusters is not previously known, is to discover the optimal clustering solution; i.e. a partition of the dataset into its 'natural' internal sub-divisions, considering that they exist.

The way of ascertaining this, is by calculating the total sum of squared errors (SSE) for each K (or number of clusters), i.e. the sum of the squares of the distances between all points and the centroids to which they belong. SSE is inversely proportional to the variance of the dataset explained by the cluster solution. It decreases with the number of clusters, but in a dataset with intrinsic sub-divisions it does not decrease monotonously. There is a value of K from which SSE starts to decrease slower, because solutions with more clusters produce increasingly similar SSE (instead of increasingly lower). This means that more clusters will not explain any more significative variance, and that an optimal number of clusters was attained. Thus, several runs of the algorithm are performed for increasing K and the corresponding SSE values are calculated and recorded. Then, just like what is done for deciding the number of principal components to retain in PCA (see page 8), SSE and K values may be organized on a scree plot. Such plot helps to make clear the value of K from which SSE starts to decrease slower and thus the optimal number of clusters to attain.

However, when the initial centroids are randomly chosen at the beginning, different runs of the algorithm for the same K typically produce solutions with different SSE; which means that the clusters defined in each run are not exactly equal. This happens because K-means is not guaranteed to converge towards a global minimum of SSE (i.e. the SSE of all points to all respective centroids), but only to local minima of SSE (i.e. the SSE of a set of points to its respective centroid). And, depending

[132] In some applications, K-means clustering is used specifically to detect outliers. In those cases, they should obviously be kept.

on the value of K, there may be many of those local minima. Thus, the randomly chosen centroids, after wandering for a while in the space of variables, may not end in the positions corresponding to the desired global minimum of SSE, but in positions corresponding only to local minima (i.e. representing sub-optimal clustering solutions for a given K). This has to do with the initial random positions of the centroids being too eccentric, or in particularly unfavourable positions, in relation to the actual positions and shapes of the potential clusters. But because the method of choosing K passes through successive runs of the algorithm (for increasing K), and also through a rigorous definition of the value of SSE for each K solution, the simple random choosing of initial centroids constitutes a problem.

The way to tackle this drawback is not to choose the initial centroids randomly, but rather judiciously, and provide them to the algorithm. The more obvious way to do this is to perform multiple runs of the algorithm for the same number of K, each with a different set of randomly chosen centroids, and then to select the solution with the minimum SSE. But this is laborious for many values of K, which are usually necessary to ascertain the optimal number of clusters in a given dataset. Another solution recommended by (Tan et al. 2005), which we have adopted, is to take a reduced random sample of the original points (in our case 10%) and cluster them using a hierarchical clustering technique. Because hierarchical clustering produces unique solutions, and because from each unique solution one may extract a wide number of clusters - ranging from one to a number of clusters equal to the number of objects - one may extract K solutions and use those clusters to define the centroids to be given initially to the K-means algorithm[133]. This guarantees that the initial centroids will not fall very far from the centres of the possible partition of the dataset for that number of K, maximizing the probability of convergence towards the global minimum and the stability of SSE values.

We will illustrate the method we have employed with examples from just one observation period (t=4), because the procedure is repetitive. In the next section we will study the results for all periods and examine their evolution through time. Because our variables are PCA scores, the problems posed by different scales or collinearity do not arise. However, the same is not true for outliers. PCA scores are standardized and similar to Z-scores (i.e. their standard deviation is one and their mean is zero) so we use the common definition of outlier as an observation with a score higher than +/-3.5 standard deviations (Tsiptsis and Chorianopoulos 2009). The scores of integration at the three scales of the region, of the city and the neighbourhood, have some positive outliers; but the scores of choice have many more. However, for the average number of objects in each table (122.521) the average number of positive outliers for all the variables (5936) still represents a small percentage (4.8%). We thus first label these values as outliers for each variable, extract them for posterior analysis, but will not consider them in the clustering procedure.

After this first step, random samples composed of 10% of the remaining values of each table t={1,2,3,4} are generated. Even if they represent just a small part of the original objects, the size of these samples (12.252 objects, on average) is still considerable and they are definitely representative of the original variables (all their basic descriptive statistics are almost equal to the original ones; see Figure 102). On each random sample, a common hierarchical clustering method[134] is conducted and a range of clustering solutions (2 to 20) is extracted. As stated before, the only objective of this 'pre-clustering' operation, is the definition of the centroids (from 2 to 20 clusters, for integration and choice variables) to be used in the subsequent K-means clustering. But because the samples are

[133] After the hierarchical clustering of the reduced sample, and for each solution of (2, 3, ..., n) clusters, the means of the variable's values of the objects in each cluster are calculated. The vectors defined by those mean values are the centroids of each hierarchical cluster, which are then given to the K-means algorithm.

[134] We used Ward's linkage, with squared Euclidian distance as measure definition.

representative, the resulting dendograms[135] already provide some information on the divisibility of the complete datasets. Figure 101 shows the dendograms for integration and choice variables, at t=4; it is possible to see that the data are clearly divisible at least into four clusters and probably more.

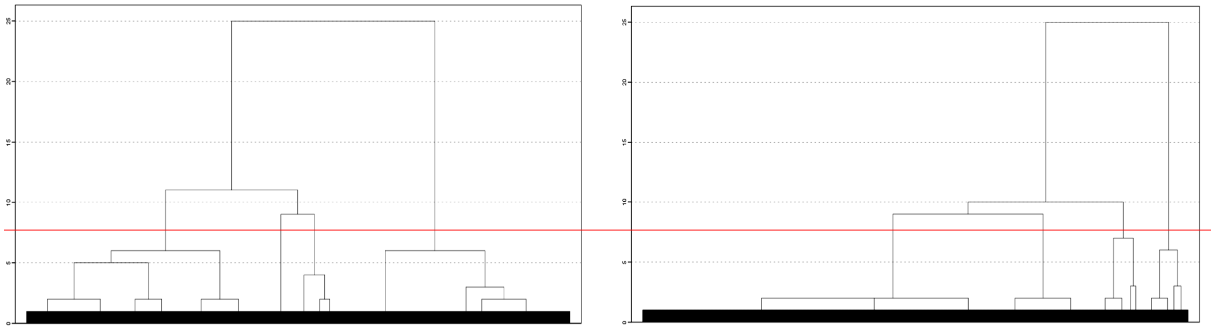


Fig. 101 –Hierarchical clustering dendograms of a random sample of the t=4 dataset, for the values of integration variables (left) and choice variables (right).

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
	141561	-2,76534	3,79351	0E-7	1,00000000	1,000
C2_int	141561	-3,23160	7,28747	0E-7	1,00000000	1,000
C3_int	141561	-3,83294	7,79032	0E-7	1,00000000	1,000
C1_ch	141561	-4,48687	26,83676	0E-7	1,00000000	1,000
C2_ch	141561	-9,63320	20,49825	0E-7	1,00000000	1,000
C3_ch	141561	-8,14471	19,50941	0E-7	1,00000000	1,000
Valid N (listwise)	141561					

	N	Minimum	Maximum	Mean	Std. Deviation	Variance
	14179	-2,65748	3,79351	-,0077974	1,00410824	1,008
C2_int	14179	-2,54024	6,87438	-,0047661	,98621257	,973
C3_int	14179	-2,59875	7,47669	,0040881	1,01267024	1,026
C1_ch	14179	-2,66003	26,62462	-,0075835	,94553263	,894
C2_ch	14179	-7,35037	15,35824	-,0054603	,96801503	,937
C3_ch	14179	-4,35366	17,26475	-,0014531	,99481402	,990
Valid N (listwise)	14179					

Fig. 102 – Descriptive statistics of integration and choice variables for the entire t=4 dataset (left) and for a random sample of 10% of its objects (right).

We then proceed with K-means clustering on the whole tables t={1,2,3,4} (without outliers), producing 18 cluster solutions for the integration and choice variables (2 to 20 clusters), using as initial centroids the means of the values of the clusters created on the random samples. As expected, convergence is quick even for the largest solutions (e.g. 20 clusters) and always total (i.e. the centroids find a fixed position at the end of the algorithm). We then compute the global SSE of each cluster solution for each table t={1,2,3,4}, and display these values on scree plots (Figure 103, next page; left plots), with the global SSE values on the yy axis and the corresponding number of clusters on the xx axis.

Several things become apparent. First, it is noticeable how the curves representing each table (i.e. each observation moment) are quite parallel, meaning that the internal structure of the clouds of points represented in the 3d-scatters of Figure 99 remains stable over time; or, in other words, that the number of clusters into which the street segments composing the network at each observation moment may be divided, does not change over time. Another immediate conclusion is that the values of SSE suffer a clear increase from t={1,2} (blue and yellow curves) to t={3,4} (green and red curves). This is consentaneous with the intense network growth observed during t[2,3] and reported in Chapter 1. But because the curves are parallel, what this means is that the potential number of clusters at each t={1,2,3,4} remains the same, they only become larger with time (i.e. with more data points, hence the increase of SSE).

As stated before, the purpose of these plots is to try to make clear sudden slower decreases in the value of SSE from one cluster solution to the other, meaning that subsequent solutions with more clusters are redundant. One needs therefore to find points on the curves lying after a strong decrease of SSE

[135] A dendogram is a tree diagram used for representing the results of hierarchical clustering. The base of the diagram represents the initial individual objects, which are grouped in pairs successively, accordingly to their similarities. The 'branches' visible in Figure 22, represent clusters of many objects. These are progressively grouped until a single cluster is attained (i.e. the entire dataset: the top level of the dendogram). One may 'cut' the dendogram at any level, obtaining a number of clusters equal to the number of vertical lines 'cut' at that level.

and before a clear weaker decrease; this translates as an ‘elbow’ on the curve; i.e. a segment with strong slope, followed by a segment with a smaller slope. However, such effect may be difficult to ascertain if the curves have rather regular shapes, as it is the case. Therefore, we introduce also another type of plot on Figure 103 (right), depicting the variation of SEE (δSSE) from one cluster solution to the other[136]; for example: δSSE(4,5) = SSE(4 clusters) - SSE(5 clusters). These plots make explicit the slope variations of the traditional scree plots. Moreover, they also show that from a certain point on (i.e. 12 clusters, both for integration and choice) the relative parallelism of the curves gives place to a much noisier pattern, where the values of δSSE for all t={1,2,3,4} start oscillating randomly. This clearly means that any solution beyond twelve clusters is artificial and does not correspond to real patterns in our data. But before that point the curves have regular patterns and reveal several potential cluster solutions.

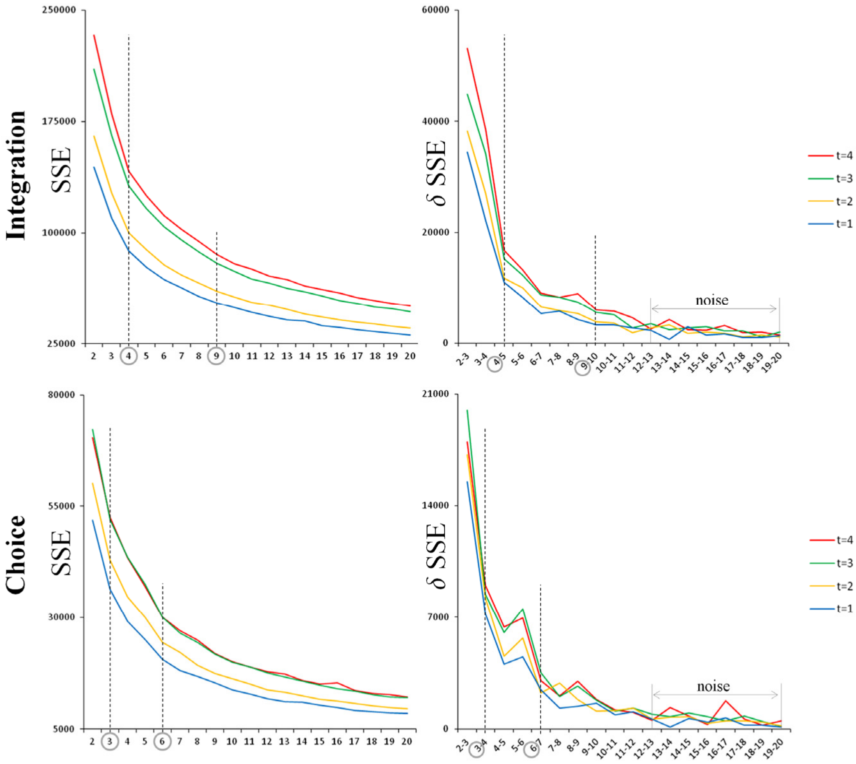


Fig. 103 – Scree plots of SSE and δSSE for the K-means cluster solutions of integration and choice.

Regarding integration, a first solution of four clusters is quite evident, both on the left and right charts of Figure 103 (on all charts, potential solutions are marked with dashed lines). On the scree plot (left) the decrease in slope of the curves of all t={1,2,3,4} is obvious, after 4 clusters. This is translated in the plot of δSSE as a steep drop from (3,4) to (4,5), followed by a clear decrease of δSSE at (5,6). Therefore, 4 clusters is clearly an inflection point and seems a promising solution for the values of integration variables. After that point the curves of δSSE reveal other possible solutions (e.g. 6, 9 and 10 clusters). But 9 clusters is the last possible solution which is consistent for all periods (i.e., δSEE(8,9) > δSEE(9,10), for all t={1,2,3,4}). Therefore, we will extract two cluster solutions for the values of integration variables at all observation moments: one with 4 clusters (explaining 58% of the original variance) and another with 9 clusters (explaining 75% of the original variance).

[136] More specifically, the plots on the right of Figure 24 depict the derivative of the function $y = SSE(x)$, where x is the number of clusters of each solution. But because the derivative of a function is $f'(x) = \delta f(x)/\delta x$ and in this case $\delta x = 1, \forall x$ (the number of clusters are sequential integers), the derivative of $y = SSE(x)$ is simply $SSE'(x) = \delta SEE$(x), i.e. equal to the difference between the SSE value of consecutive clusters.

Regarding choice, the curves of all periods (even if also parallel) show some more variation. We will not repeat the detailed reading of the plots of Figure 103, as the explanations given above for integration also apply to choice and the information on Figure 103 complements them. But we have adopted the same strategy of choosing the first and most clear solution (3 clusters, in this case) and also the last possible solution consistent in all periods (which is 6). There are other interesting points beyond 6 clusters (e.g. 9 and 12), but they are not consistent in all periods. Therefore, we will also extract two cluster solutions for the values of choice variables at all observation moments: one with 3 clusters (explaining 53% of the original variance) and another with 6 clusters (explaining 73% of the original variance).

We may now start to visualize these clusters and trace their profiles, in order to understand to what they correspond in terms of potential typologies of places and paths in the metropolitan region; but before we need to inspect the outliers that we have isolated at the beginning. In fact, by itself, the isolation of these spaces with extreme values is also a type of classification (albeit not unsupervised); and we may find later that such classes of spaces with extreme values may complement (or even be merged with) the clusters defined by K-means. Again, t=4 will be used as example of the adopted methodology, until the end of the current section. Both for integration and choice variables, occurrences of negative outliers (i.e. spaces with scores lower than -3.5) are very rare: the average number of negative outliers for all periods is just 0.2% of the total average number of spaces (while of positive outliers is 4.8%, 24 times more). The minimum value for all temporal periods and all variables is -9.6 (while the maximum value is +26.9). Furthermore, only choice has negative outliers and these tend to occur without clear spatial pattern, when visualized on the segment map. We will focus therefore on positive outliers, which represent clearly identifiable spatial structures.

Figures 104 and 105 (next page) depict the spatial distributions of outlier spaces for the three variables of integration and choice, as well as their centrality ‘profiles’ (represented on charts, below the maps). Each of these profiles depicts the mean of the values of the original variables of integration and choice (normalized within [0,1]) for the spaces in each class; the ranges of the three centrality scales (regional, city and neighbourhood) are also represented as dashed lines on the profiles. This type of graphical representation allows for the quick reading of the average centrality behaviour represented by each class, and will be used also for characterizing the clusters obtained with K-means. We will describe very briefly Figures 104 and 105, in order to help their reading and the identification of relations between the patterns they depict and those of the clusters discussed further ahead.

Regarding integration (Figure 104), at the scale of the region there are only 17 segments with outlying values (≥3.5), corresponding to a few motorway stretches. These are not of course particularly relevant as individual structures. Moreover, they are also outliers of choice at the regional scale (which displays a much more relevant structure) and will therefore be handled there. But at the city scale, integration shows many more outliers (1438). The entire area corresponding to Oporto’s current CBD (i.e. the northward and westward XVIII and XIX centuries’ expansions, beyond the medieval core), appears highlighted. Outside the centre of Oporto, just a few dispersed segments are outliers, but some correspond to the spinal spaces of peripheral urban centres (namely of Vila do Conde, at north, near the limit of the study area), which are actually parts of ancient roads converted into streets. These spaces have also very high values at the regional scale, as can be seen by their centrality profile (they have almost the same level of values than the spaces that are effectively outliers at that scale). At the neighbourhood scale, there are also a considerable number of spaces with extreme integration values (1200). These tend to correspond to inner centres of dense urban areas, particularly old city cores, with small blocks and high road density. That is particularly the case of Oporto’s medieval core (at the centre of the study area), but also of other highlighted ancient centres[137]. Many other dispersed segments (or small groups of segments) show also extreme values, which correspond in general to the main streets of peripheral agglomerations. These are of course the spaces with highest values at the neighbourhood scale, but their profile shows that they have also high values at the city scale and even higher at the scale of the region.

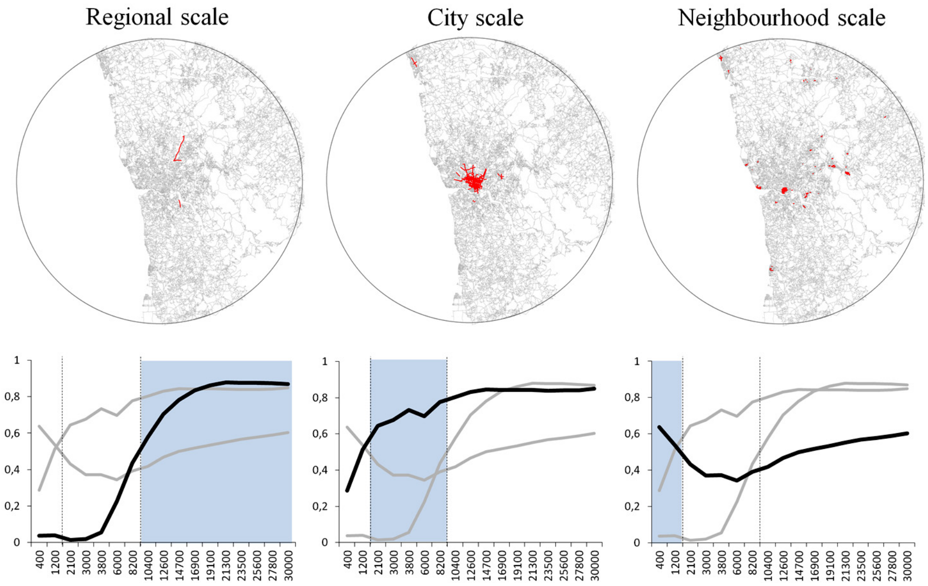


Fig. 104 – Spaces with outlier values (≥ 3.5) on integration variables, at the regional (left), city (middle) and neighbourhood (right) scales.

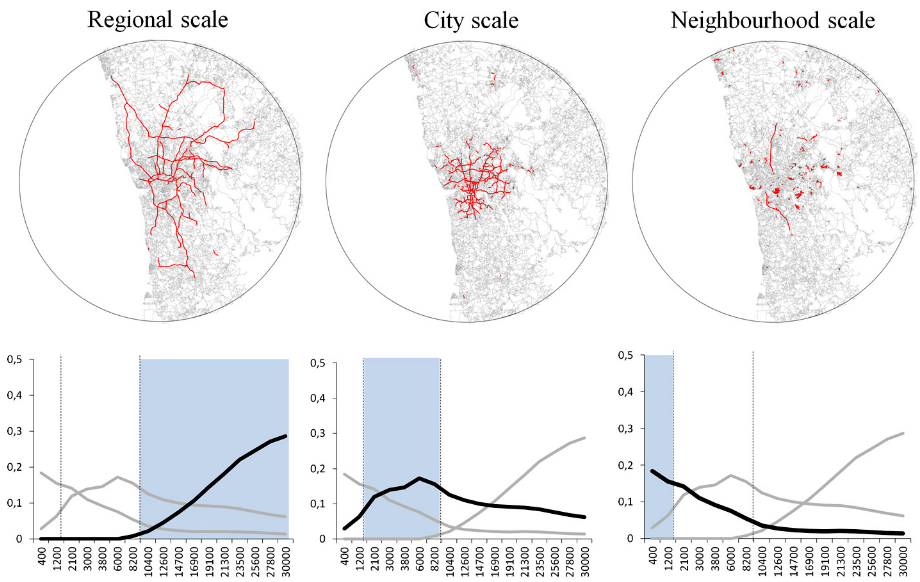


Fig. 105 – Spaces with outlier values (≥ 3.5) on choice variables, at the regional (left), city (middle) and neighbourhood (right) scales.

The spaces with outlier values of choice show different patterns (Figure 105). At the regional scale, they comprise all the main metropolitan motorways (or at least large parts of all of them), but also all the ancient radials roads, as well as some important streets within Oporto, forming a rather continuous,

[137] Namelly, “Foz Velha” (at the mouth of Douro River), “Leça da Palmeira” (further north, near the port) and the historical core of “Póvoa do Varzim” (top north, near the limit of the study area).

large-spaced grid (totalizing 1613 segments). Looking at their profile, it possible to verify that these spaces have indeed very high choice values at the regional scale, but also extremely low values both at the scales of the city and of the neighbourhood. Thus, even if some urban streets are contained in this set, it is mostly composed by spaces that are primarily regional paths. At the city scale, the spaces with highest choice values (2282) highlight the central part of the middle-scaled grid (i.e. at Oporto and immediate surroundings) which was described in section 3.3. However, the pattern is significatively truncated, as only the spaces with extreme values are considered here. Outside that area, only a few dispersed segments (occasionally corresponding to main streets of peripheral centres). Besides the obvious peak at the city scale, the centrality profile of these spaces shows that their influence extends also significatively into the regional scale. Finally, the spaces with outlying values of choice at the scale of the neighbourhood (1888), produce a pattern similar to integration's at the same scale, but more dispersed and fragmented. Also, several long linear structures (already discussed in section 3.3, for choice at the neighbourhood's scale) are present. The centrality profile shows that all these spaces have also high values at the city scale.

We now look at the first two cluster solutions of integration and choice (Figures 106 and 107, respectively; next page). We recall that the solution of 4 integration clusters explains 58 % of the original variance (i.e. of the joint variance of the three principal components of integration), and the solution of 3 choice clusters explains 53% of the original variance. Thus, broadly speaking, both solutions encapsulate just over half of the information contained in the three variables of integration and choice, which is not a very satisfactory result. In both Figures 106 and 107 we represent (on the segment map) the respective clusters in red and the outliers discussed before in black, so that their patterns may be compared. We should also recall that these classes are all mutually exclusive, i.e. the spaces belonging to each cluster are not present in any other cluster.

Looking at both Figures 106 and 107 (next page), it is possible to see that the clusters formed by the first two solutions do not add much to what we have seen when analyzing the patterns produced by the scores of the principal components of integration and choice. However, together with these clusters, we must also consider the sets of outlier spaces, both of integration and choice at the three spatial scales, which add other six centrality classes (represented in black on the segment maps). But even so, the results are not very eloquent.

Regarding integration, the first cluster (Figure 106, 1) gathers the entire city of Oporto, several of its immediate surrounding towns and still two small areas near the south limit of the study area (in a total of 12% of the network's spaces). The cluster profile tells us that these areas have extremely high and constant values at the regional scale. At the city scale, their values are also the highest on average, but they quickly decrease towards the neighbourhood scale, at which they are not so high. Thus, this cluster represents places highly accessible at the entire regional scale and also important at the city scale; roughly speaking, we could say it represents metropolitan centralities. But it is unlikely for regional-scaled centres to be so scarce and amalgamated in the region under study; and this is even truer for city-scaled centres, which are not explicitly indentified in this cluster solution.

The second cluster (Figure 106, 2) gathers the spaces with the highest integration values at the neighbourhood scale, but also with significatively high values at the regional scale (15% of the network's spaces). However, at the city scale, these spaces have relatively low values. The spatial pattern shows a myriad of these small, local centres; some of which are larger and occur together with outlier spaces at the same scale. These could, therefore, be seen as differentiated or more important local centres. In the same way, others occur together with outliers at the city-scale, and could therefore be thought as being also related with that scale. But the gap between the centrality behaviour represented by the first cluster (i.e. metropolitan or regional centres) and the one described by the second cluster (i.e. sub-city or neighbourhood centres), is as evident as unlikely.

The third integration cluster (Figure 106, 3) is interesting though. It represents a very large circular area, ranging from the central city to about two-thirds of the distance to the study area's limit (representing 31% of the network's spaces). Spatially, it is completely undifferentiated: a wide, ring-like area, without apparent inner structure. However, its centrality profile reveals very high values at the regional scale and also relatively high at the city-scale. This area represents therefore a highly accessible territory of diffuse centrality, where many of the main metropolitan productive and tertiary functions are actually located (see Figure 90, page 143). The spatial distribution of the last integration cluster is similar (Figure 106, 4), also ring-like, but extending over the last third of the distance to the study area's limit. It is even larger, representing 42% of the entire network. However, it is composed of spaces with very low values at all spatial scales. Both this and the previous clusters, because of their centrality behaviour and also because of their concentric shapes, may also simply represent the trivial decrease in integration values from the centre to the periphery of the map, related with artificial effects induced by the definition of the model's boundary, already discussed at length under the designation of 'edge-effect'.

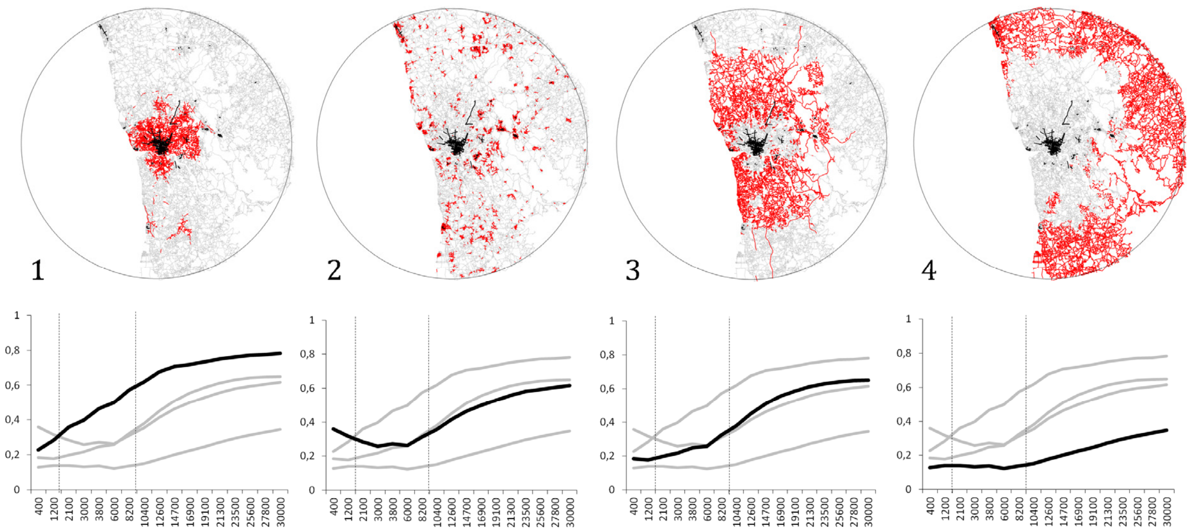


Fig. 106 – First solution with four integration clusters.

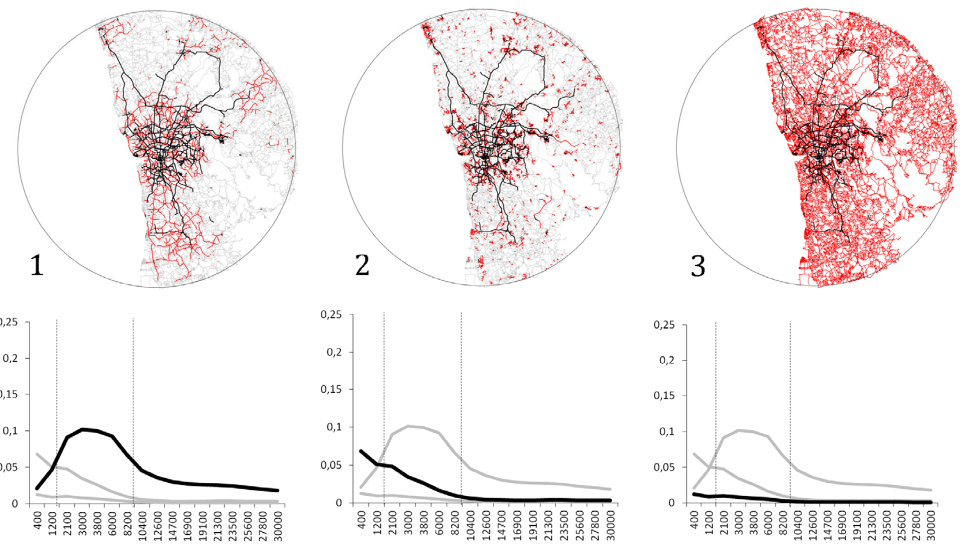


Fig. 107 – First solution with three choice clusters.

The solution of three choice clusters is also little significative (Figure 107). The first cluster (consisting of 7% of the network) catches the entire middle-scaled grid, discussed in section 3.3, which may be naturally combined with the outliers of choice at the city scale. As expected, this cluster's centrality profile shows a peak of high values at that scale. The second choice cluster (12% of the network's spaces) corresponds to the micro-scaled grid discussed also in the same section, forming small patches similar to the second cluster of integration. Some of these small centres occur together with choice outliers at the same scale, and may therefore be also combined with them. The centrality profile shows the corresponding peak of values at the neighbourhood scale. The third choice cluster is trivial and has no structural meaning, albeit gathering 81% of the network's spaces. As mentioned before, choice detects the spaces with higher path-overlap at every scale, and such property is highly selective; therefore, the overwhelming majority of the network's spaces have very low, or even null choice values. This third last choice cluster corresponds simply to those spaces. Accordingly, its centrality profile shows an almost flat line at the bottom of the plot. Not only both these two cluster solutions account for just over half (58% and 53%) of the initial variables' information, as they also add very little to what was already made clear by the exploration of the centrality patters created by the variables themselves (see section 3.3). We thus turn to the second selected pair of solutions, 9 clusters of integration and 6 of choice. These are depicted in Figure 108 (next page) and in Figure 109 (page 164), respectively. The results are much richer.

The solution of nine clusters of integration (Figure 108), displays all the previous four clusters, but also several new interesting structures. These can be, in a first general approach, divided into *continuous* and *discontinuous* structures. Clusters 3, 7 and 9, are examples of the first type; i.e. large and continuous circular areas without apparent inner differentiation, characterized by a certain centrality profile, which shows very low values both at the neighbourhood and the city scales, but varying values at the regional scale. Clusters 1, 2, 4, 5, 6 and 8, are examples of the second type; i.e. patchworks of smaller areas, more-or-less localized or dispersed over the study area, characterized by varied centrality profiles, but in general showing strong values at the neighbourhood and at the city scales. These discontinuous structures seem to correspond to a significative variety of urban environments; from large, global centres, to the smallest neighbourhood centres. Also, they display varying spatial distributions, corresponding to clearly distinct metropolitan *places*.

The second solution of six choice clusters (Figure 109, page 164) also shows more interesting results than the first solution. Again, we may divide these clusters into continuous (clusters 1 and 2) and discontinuous structures (clusters 3, 4 and 5; cluster 6 is irrelevant). All the three previous clusters are present, but three new meaningful structures appear. Firstly, a new network of highly central paths at the regional scale (cluster 1) is identified. These are clearly related with the spaces identified as choice outliers at the regional scale, complementing and knitting them together, forming a regional-scaled global network. Secondly, a new cluster of spaces with very high values at the city scale appears (cluster 3). This cluster represents special points (small stretches, usually with intersections) of the middle-scaled grid (represented, as before, by cluster 2) with particularly high centrality values. Thirdly, a new cluster of spaces with medium choice values both at the neighbourhood scale and at the first half of the city scale is also newly identified (cluster 5). These spaces seem to belong also to the middle-scale grid, as they unite and complement it, but they are also commonly connected to those belonging to cluster 4 (also present in the first solution), which are the spaces with the highest values at the neighbourhood scale. This new fifth cluster seems therefore to represent interface spaces, between the city-scaled grid (cluster 2) and the neighbourhood grid (cluster 4). The last choice cluster (6) is again the unavoidable trivial set of spaces with very low choice values, constituting the generality of the spatial network.

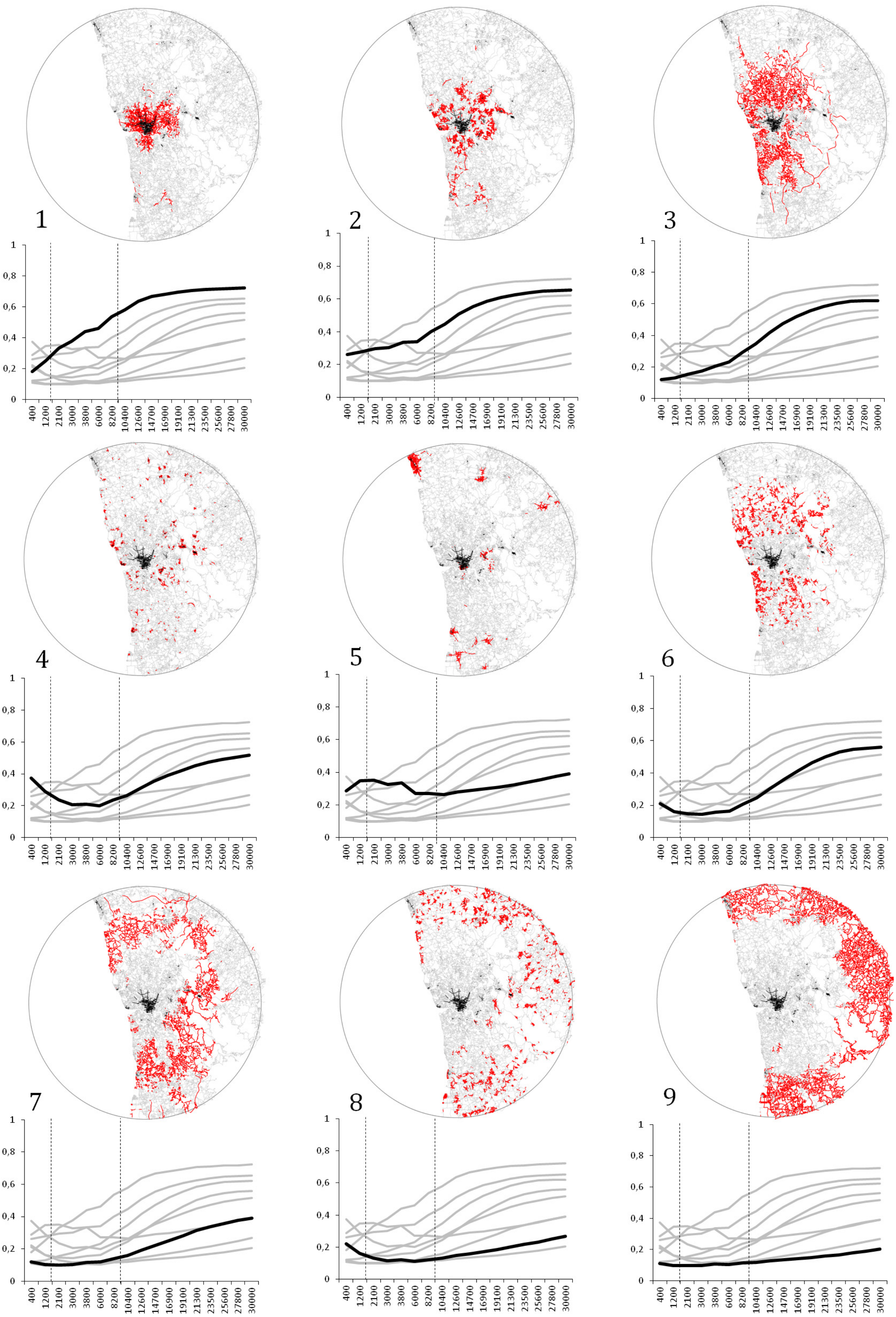


Fig. 108 – Second solution with nine integration clusters.

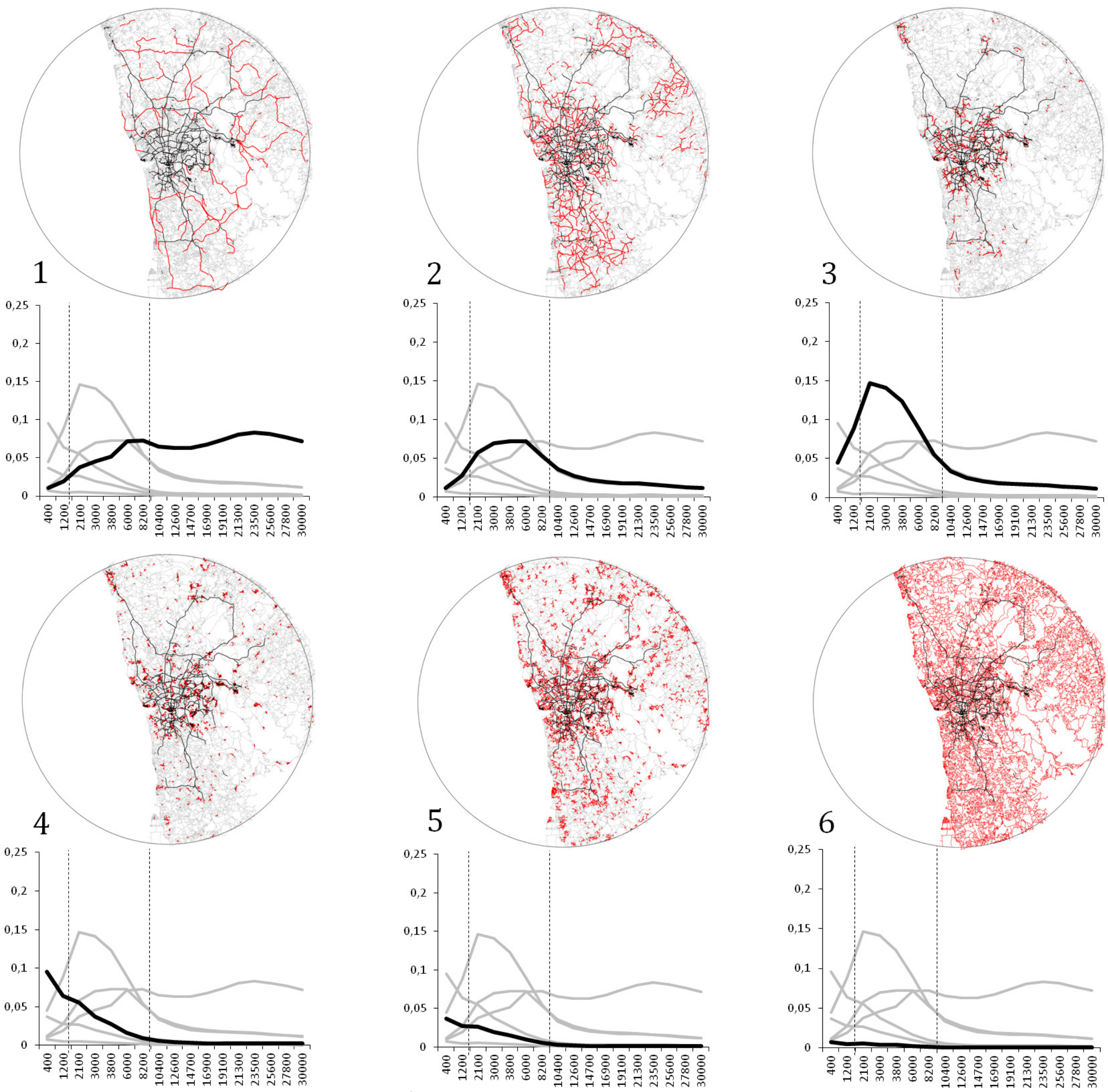
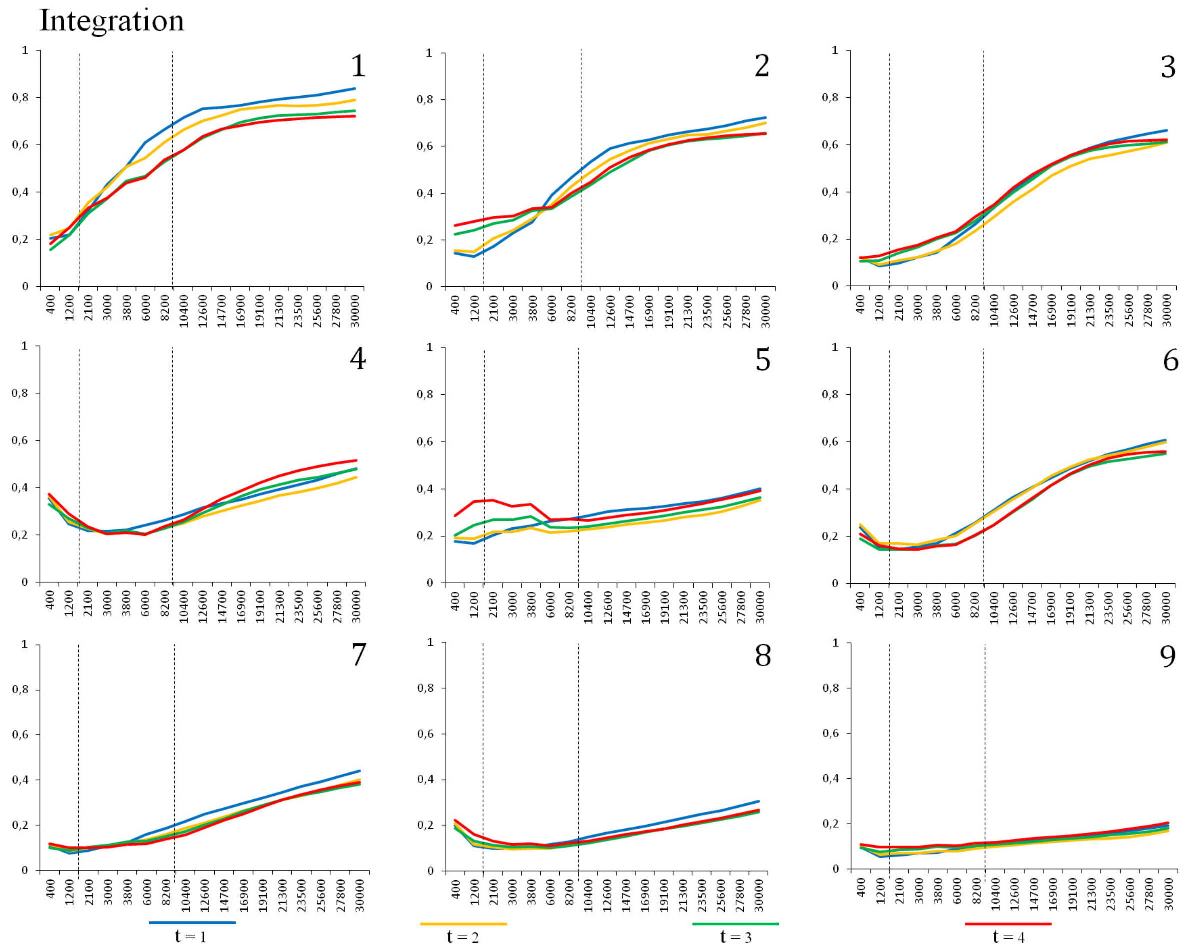


Fig. 109 – Second solution with six choice clusters.

All these clusters of spaces, defined through the spaces' centrality behaviours as measured by integration and choice, seem at first sight to represent meaningful classes of metropolitan *places* and *paths*. But what is more remarkable, and indeed a very strong empirical sign of their substantiality, is their stability and persistence through time. Figure 110 (next page) shows the centrality profiles of the 9 integration clusters and 6 choice clusters, for all t={1,2,3,4}. As can be seen by the plots, all clusters represent the same structures at each moment of observation and the values of the original centrality variables are remarkably stable. The centrality value of each individual radius may change over time, but the general shapes of the profiles (characterizing the intrinsic nature of each cluster) remain largely the same. The majority of the classes are truly stable (i.e. the curves of each period overlap), but some show more variation (namely integration clusters 1, 2 and 5; and choice clusters 1, 2 and 3). The cases of integration cluster 1 and of choice clusters 2 and 3, are simply attenuations (integration) or intensifications (choice) of the same centrality behaviours. But the other cases (integration 2 and 5, and choice 1) are different. They seem to represent different centrality behaviours through time, thus to correspond to different spatial structures. However, as we shall see, this is true only for one of these cases; the others cases are in fact changes of centrality behaviours, but of the same spatial structures.



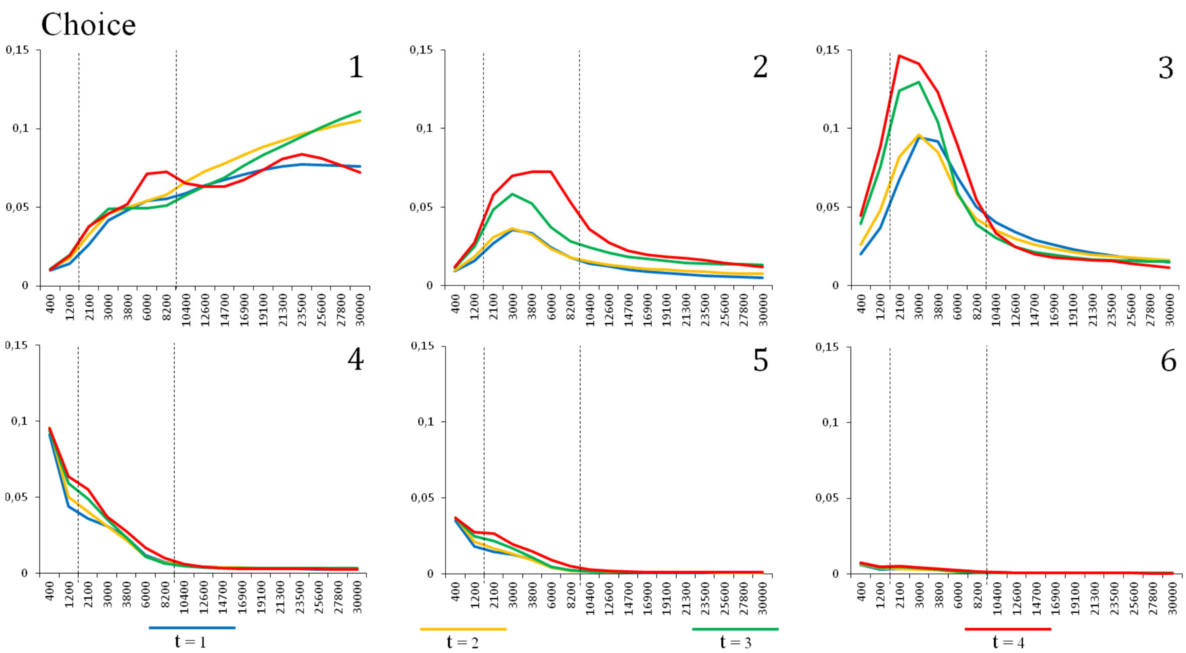


Fig. 110 – Centrality profiles of the final 9 integration clusters and 6 choice clusters, at each t={1,2,3,4}..

In this section we have showed that it is indeed possible to typify the spaces composing the metropolitan network, according to their centrality behaviour along the *continuum* of spatial scales. We found several meaningful classes, both of integration and choice, apparently corresponding to identifiable urban spatial structures. Furthermore, we have found that such centrality classes of spaces are stable through time, which is an unequivocal sign of their substantiality. Therefore, these centrality classes are liable of representing *types of metropolitan places and paths*, which may be relevant both as research subjects and as operational planning information. In the next section we will interpret and semantically designate each of these classes, in order to better define such types.

5.6. DEFINING A TAXONOMY OF METROPOLITAN PLACES AND PATHS

The clusters discovered in the previous section represent regularities in the centrality behaviour of the spaces composing the metropolitan network, across many spatial scales. As we have seen, such numeric regularities are not simply statistical by-products: they correspond to well-defined spatial structures. Moreover, these classes of spaces are stable across time, which proves that they are not a fortuitous discovery, but time-enduring centrality types.

As a first attempt to understand the clusters discovered, they were characterized as representing *continuous* or *discontinuous* structures. Such characterization, based only on their immediate appearance, is not intended to be definitive but rather to make the following description of those structures easier; moreover, it is clearly more appropriate for integration clusters, than for those of choice. Nevertheless, we will keep this basic division for now. We will start by studying the clusters describing particular types of places (i.e. those of integration) and next we will look at those describing particular types of paths (i.e. of choice). Figure 111 (next page) shows the continuous clusters of integration. For each cluster of integration and choice, Figures 111 (next page), 112 (page 169) and 113 (page 171), show a snapshot of the spaces gathered under each class, together with their centrality profile and a small icon, summarizing the cluster general shape and spatial distribution on the study area. The numbers referencing each cluster are the same of Figures 108 and 109 (pages 163 and 164), which complement the following description.

The first integration cluster (Figure 111, 1), already present in the first solution with four classes, represents the inner core of the metropolitan region, encompassing the entire city of Oporto, some parts of the immediately surrounding municipalities, and still some small patches to the south and north of these areas. We shall call to these places *metropolitan kernels*: dense, highly accessible and central urban areas, both at the city and at the regional scales. Together with the spaces with outlier values of integration at the city scale, with whom they may be naturally concatenated, the metropolitan kernels constitute the places where the experience of urbanity - with its characteristic functional and social highly dense mixture - is maximized. Somewhat unexpectedly, this cluster is not restricted to the actual geographical centre of the metropolitan region (i.e. to the central-city and its immediate surroundings), but shows fragments of spaces with the same super-centrality characteristics significatively away from it (notably at south).

The second integration cluster (Figure 111, 2) represents the first ring of cities around the main metropolitan kernel. These places have almost the same integration values of the previous cluster at the regional and city scales, only slightly lower; but at the neighbourhood scale they have higher values, revealing a strong local importance. Some of them are, however, much more recent and have only appeared during the time span considered in this study. In fact, as we shall see later, this cluster is not present as such at t={1,2}, emerging suddenly at t=3 out of the fragmentation and local differentiation of a previous, less heterogeneous class of spaces.

Fig. 111 – Example snapshots and semantic designation of 6 clusters of metropolitan places.

We shall call to the places represented by cluster 2, *inner satellite cities*: urban agglomerations with strong functional relations with the central-city and close to it, albeit not functional-dependent of it. The term ‘satellite’, here as well as in cluster five, is not intended to mean functional dependency, but simply the spatial position of such places regarding the metropolitan kernel (i.e. on its ‘orbit’). These urban areas possess both the demographic mass and the functional diversity to be considered cities under the Portuguese legal definition of the concept[138], and several are actually the seats of their municipalities. They are places of clear urban character and ambiance, but not with the intensity and density typical of the metropolitan kernels, or super-centralities, described by the previous cluster.

Cluster number four (Figure 111, 4) represents a large number of small patches, with very high integration values at the neighbourhood scale, less at the city scale, but again considerably high at the regional scale. Some of these places are urban neighbourhoods of the metropolitan kernel, others the cores of the inner (and outer, as described below) satellite cities, and still others are small towns scattered all over the study area. We call the set of these small urban intensifications the metropolitan *constellation of local centres*, with which the spaces with outlier values at the neighbourhood scale may be naturally joined, for they show similar centrality profiles. Some of these places have ancient origins; others are the product of recent metropolitan development and have emerged along the study’s time span. In all cases, these places have very high accessibility levels at the neighbourhood scale, and are therefore expected to concentrate urban functions and services of proximity. But their regional accessibility is also considerable, and thus they should not be regarded as mere local centres, but as places with strong local importance and at the same time with reasonable accessibility regarding the overall metropolitan region.

The fifth integration cluster (Figure 111, 5) gathers a number of peripheral urban areas, which are actually cities at the outer limit of the metropolitan region. The centrality profile is very similar to the one of the second cluster (i.e. with strong values both at the neighbourhood and city scales), but with lower values at the regional scale. However, this is only likely due to the peripheral position of these cities regarding the limits of the study area (making them prone to edge-effect and therefore bounded to having lower integration values at global scales). Also, they are more independent from the central-city and almost all are urban areas of historical foundation (unlike those described by cluster two). They also have slightly higher values at the neighbourhood and city scales. But because they show almost the same centrality behaviour (except at the regional scale) and represent similar-sized urban areas, we consider both clusters related. We shall call therefore these places *outer satellite cities*.

The last two ‘discontinuous’ integration clusters (Figure 111, 6 and 8), are differentiated by the degree of their regional centrality, having similar values at the neighbourhood and city scales (even if cluster 6 shows slightly higher values at the latter scale). They occupy two concentric ring-like areas, both showing a plethora of small patches, with a denser pattern than that revealed by cluster 4. However, their accessibility values at the neighbourhood and city scales are much lower. The spaces gathered by these two clusters represent places with some local significance, but on the very limit of differentiation. They should not be confused with the local centres gathered in cluster 4, which have significatively higher centrality values at all scales. They correspond to small network intensifications, to which a higher presence of buildings is usually associated and, expectably, also the presence of proximity functions. But their profusion is such that, in some cases, they may correspond to just slight centrality fluctuations in the network, without true empirical value. In any event, they represent local centrality potentials, which may be exploited (and expanded) or not by urban development. As the

[138] The Portuguese Law 11/82 of June 2th, defines the basic criteria for the granting of city-status to an urban area, by the Portuguese Parliament. It must have a minimum of 8000 inhabitants and possess, at least, half of the following urban facilities: hospital, pharmacies, fire department, cultural forum, museum, public library, hotels, educational facilities (preschool, primary and secondary) and public transportation services.

composition of both these clusters is quite similar, and their centralities profiles vary only trivially at the regional scale with their concentric positions in the study area, we have called the set of places defined by them, as the *inner* and *outer nebulas of micro-centres* (clusters 6 and 8, respectively). The term 'nebula' is also intended to convey their fuzzy centrality character, not so obviously marked as that of the places in cluster 4.

We now look at the 'continuous' integration structures, defined by clusters 3, 7 and 9 (Figure 112). These are very different from the ones described above. Firstly, they do not display patchy patterns but rather large and nearly-continuous expanses of the spatial network. Secondly, they are ring-like areas, clearly fitting concentrically into each other. Their centrality profiles vary only regarding this concentric disposition, with the inner-most cluster (i.e. number 3) having relatively high centrality values at the regional scale, and the outer-most cluster (i.e. number 9) very low centrality values at the same scale. In all cases, these three clusters have the lowest values at the neighbourhood scale, which mean a total lack of local structural differentiation. And thirdly, all three clusters show curvilinear and irregular grids, which are rather sparse, forming large cells of private space; this is in clear contrast with the denser and more regular grids (sometimes rectilinear) of the previously described clusters, which correspond always to areas with smaller cells of private space.

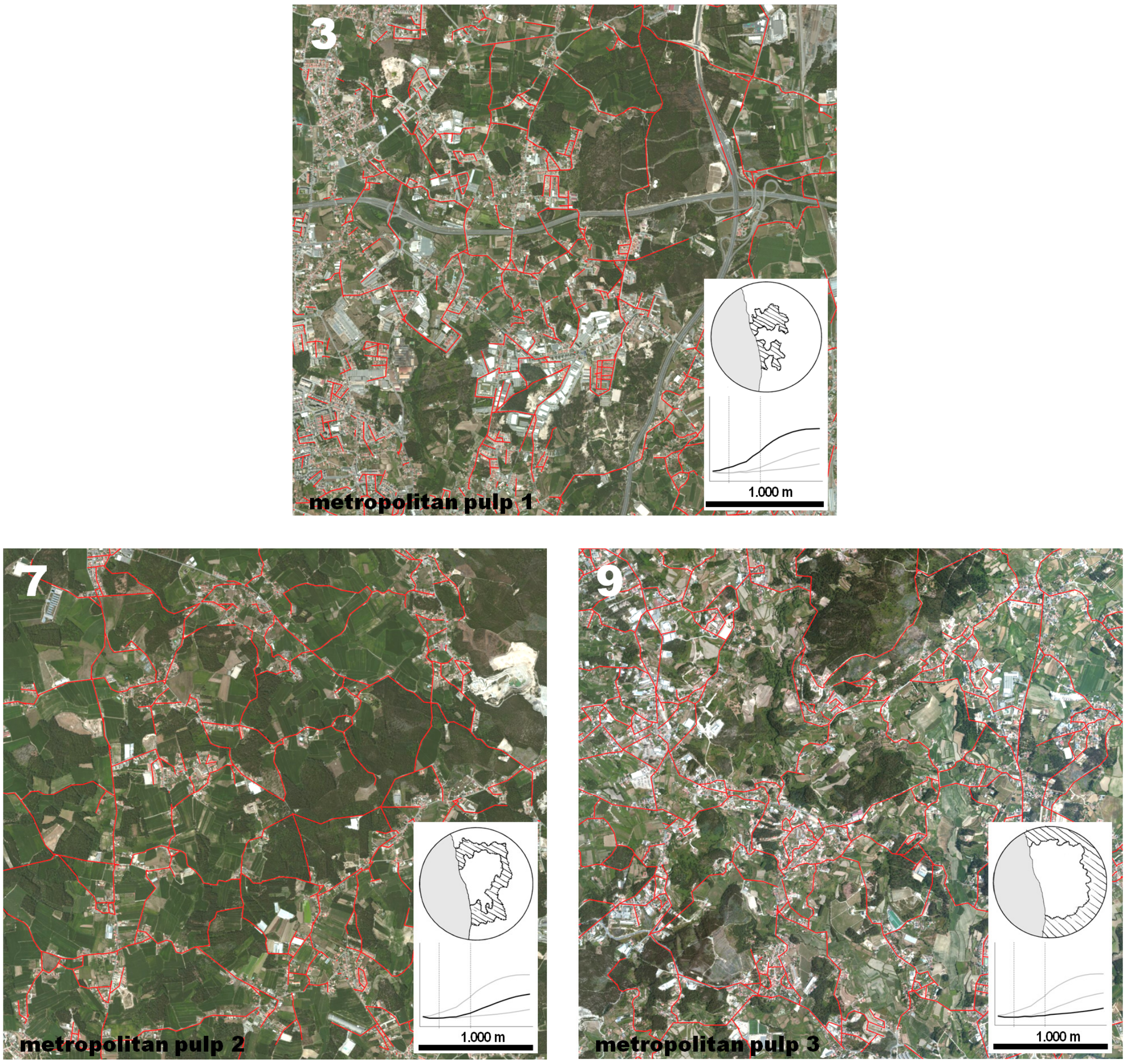


Fig. 112 – Example snapshots and semantic designation of 3 clusters of metropolitan places.

In fact, regarding the clusters described before, the cells of private space defined by the spatial network usually correspond to urban blocks; whilst the large cells defined by the network spaces of these three clusters correspond in large part to rural parcels, many still in activity and with little presence of built structures. Thus, these three clusters gather what is left (and which is plenty, in many places) of the original pre-metropolitan rural grid, made of sinuous and narrow paths and of unfathomably ancient genesis.

It is quite interesting to notice how such grid has been eroded and transformed by urban development in varying degrees in the three clusters (see Figure 112). In the inner-most cluster, such grid has been much altered and fragmented, mingled with many spaces of recent origin, corresponding to disperse and erratic urban developments. However, in clusters 7 and 9, which correspond to areas farther from the main urban centres and from foci of intensive urban growth (and also because of the presence of highly fertile and protected rural land in some areas), the pre-metropolitan rural grid is still much preserved. In these areas, new building construction simply colonizes the borders of the ancient rural roads, without making strong structural alterations to the spatial network (this is noticeable in Figure 112, 9). In any case, all three clusters show the same lack of local structuring, but also the same diffuse centrality at the regional scale, which only decreases with increasing distance from the centre of the study area. However (as already mentioned) such decrease is, at least in part, artificial and caused by the imposition of the study area’s boundary. Thus, what really characterizes these three clusters is the lack of local (and even of median) structural differentiation, a diffuse accessibility at the regional scale and the permanency of the pre-metropolitan rural grid. Over this locally undifferentiated sub-network, urban development seems to occur haphazardly and absolutely free from any planning directive, but with some intensity nonetheless (at least in cluster 3). Because of their structurally undifferentiated character, we have termed these three clusters *metropolitan pulp,* distinguishing them only by ordinal numbers regarding their decreasing regional accessibility. Thus, integration clusters 3, 7 and 9, will be called from now on simply *metropolitan pulp 1*, *2* and *3*.

We now look in more detail at the six choice clusters (Figure 113, next page), representing different types of paths in the metropolitan region. Cluster 1 displays the large-spaced grid of streets and roads with high choice values at the regional scale. As already stated, these spaces are complemented by the set of choice outliers at the same scale, together forming a rather continuous and cohesive regional network, largely made of metropolitan motorways, but also of the long-lasting radial and radio-concentric regional roads (described before), as well as of a few important urban streets. This is the uppermost movement system, the arterial network that knits together the metropolitan region and which confers it unity at the regional scale. We will therefore call this cluster the network of *regional paths*. But besides of being composed by more than motorways and highways, it also shows strong values at the city scale, revealing also functional importance at that level. Moreover, the set of spaces with outlier values at the regional scale grants it yet another centrality level. Therefore, its role in the overall metropolitan spatial network (as well as of the other clusters of choice, as we will see), seems to go beyond the reductionist idea of the top-tier in a rigid and straightforward road hierarchy, characterized by well separated speeds and scopes of travel, which ideally should not to mingle. The reality seems indeed more complex and richer - we could say also more organic and less mechanistic - with different-scaled networks performing several functional roles at the same time.

The second choice cluster (Figure 113, 2) displays a less spaced network, but still quite continuous. Its centrality profile shows high values at the city scale, extending also onto the regional scale. This cluster can naturally be joined with the set of spaces with outlier values at the same scale, together forming the system of main urban thoroughfares, to which we will call the network of *primary city paths*.

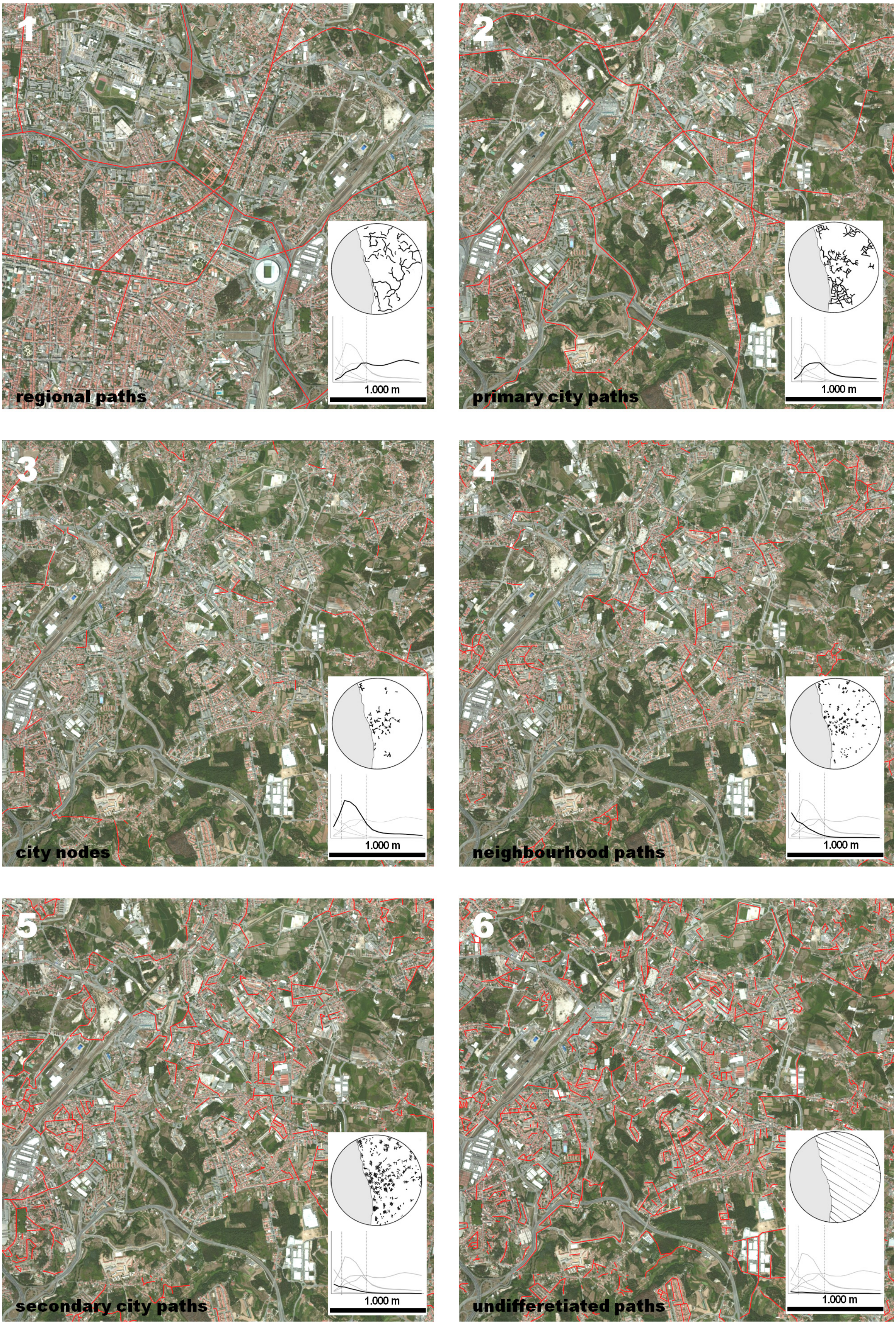


Fig. 113 – Example snapshots and semantic designation of 6 clusters of metropolitan paths.

But again, at the city scale, the structure of paths seems to be more complex than just one level in a simple hierarchy. In fact, both clusters 3 and 5 also belong to such city-scaled network, but they create interfaces between it and the upper and lower systems of paths (i.e. the networks of regional and neighbourhood paths). Cluster 3 displays a set of discontinuous spaces with very high choice values at the city and neighbourhood scales, which invariably connect the network of primary city paths (i.e. cluster 2) to outlier spaces at the same scale or to the network of regional paths (i.e. cluster 1, including outliers). Because the spaces in cluster 3 make the interface between two different-scaled path systems, while still having very high values at the city scale, we call them *city nodes*. For its part, cluster 5 shows a pattern made of grid fragments with medium values both at the neighbourhood and at the city scales. These fragments are in clear continuity with the network of primary city paths, but they almost invariably connect it to the spaces of cluster 4, which have the highest choice values at the neighbourhood scale. Therefore, they make the interface between those two path systems; but because they have median values at both scales, we call the spaces in cluster 5 the system of *secondary city paths*. These three classes of spaces - *primary city paths* (including outliers), *city node*s and *secondary city paths* - complete the network of paths at the scale of the city as complex system with three distinct centrality behaviours.

Returning to cluster 4 (Figure 113, 4) - the set of spaces with highest choice values at the neighbourhood scale - a new spatial distribution is noticeable: no longer more-or-less continuous networks of spaces, but rather a cloud of very small grid fragments. These are the spaces with highest path overlap at the local scale, which may be equated with neighbourhood's spinal streets. They may be also joined with the set of spaces with outlier values at the same scale, in order to complete the neighbourhood path system. We will designate the spaces in cluster four as *neighbourhood paths*. Finally, the sixth choice cluster displays the remaining network (which is, on average, more than 60% of the total network) with extremely low or even null choice values. As already stated, this cluster is rather trivial, its only interest being the way its share of network spaces evolve over time, which may reveal the increase or decrease of structurally relevant paths in the network. This cluster will be simply denominated *undifferentiated paths*.

Having succinctly described the discovered clusters of integration and choice, corresponding to structures of places and paths in the metropolitan region, we now turn to the inspection of their evolution through time. This will be done in two ways: by studying their quantitative variation (i.e. the evolution of the number of spaces in each cluster) and their qualitative variation (i.e. the evolution of their composition, in terms of the original centrality variables). The quantitative variation of the clusters will be accessed through the temporal evolution of their *shares*, i.e. the percentage of the total number of spaces in the network that each cluster gathers at each $t=\{1,2,3,4\}$.

The qualitative variation will be accessed by the studying the movement of each cluster's *centroid* in the space of variables. The centroid (or centre of mass) of a cluster defined by the K-means method, may be seen as its *archetype*: the point that best describes the cluster's general behaviour, in terms of the variables out of which it was defined. Our variables are, of course, the three principal components of integration and choice (defined in section 3.2), describing the centrality of each space at the scales of the region, of the city and of the neighbourhood. The centroid of a cluster is then defined by the mean of the values of each variable, for all the spaces gathered by that cluster. These three mean values constitute the coordinates of the cluster's centroid in the space of variables, i.e. its position regarding the three axes describing centrality at the three fundamental metropolitan scales. By studying the varying positions of these centroids at each $t=\{1,2,3,4\}$ one can evaluate the general qualitative evolution of each cluster through time (i.e. if its composition, in terms of the original variables describing its qualitative nature, remains stable or changes with time).

Figures 114 and 36 (next page) show the shares of the integration and choice clusters at each t={1,2,3,4} (upper images), as well as their variation at each time interval $t_{[1,2]}$, $t_{[2,3]}$ and $t_{[3,4]}$ (lower images). Again, the temporal stability of all clusters is notorious (the maximal share variation is 6%, in absolute value), in spite of the 31% increase (see Chapter 1) that the spatial network endured through the study's time-span. Thus, the network grows through time, but the relative sizes of the clusters remain almost the same. Obviously, the number of objects in each cluster also increases, but the general distribution of the shares at each t={1,2,3,4} remains stable.

As already mentioned, this temporal stability is quite relevant, at least in two senses. Firstly, it is a very strong sign that the found clusters have empirical validity, are not just numerical artefacts and are very little affected by noise effects. Secondly, and in strong contrast with the common idea of contemporary metropolitan development as an amorphous and rampaging new type of urban manifestation, they show that underneath the apparent turmoil there are stable spatial structures. The acknowledgment of such structures may be decisive to overcome the operational paralysis that seems to affect urban planning in the face of contemporary metropolitan formations.

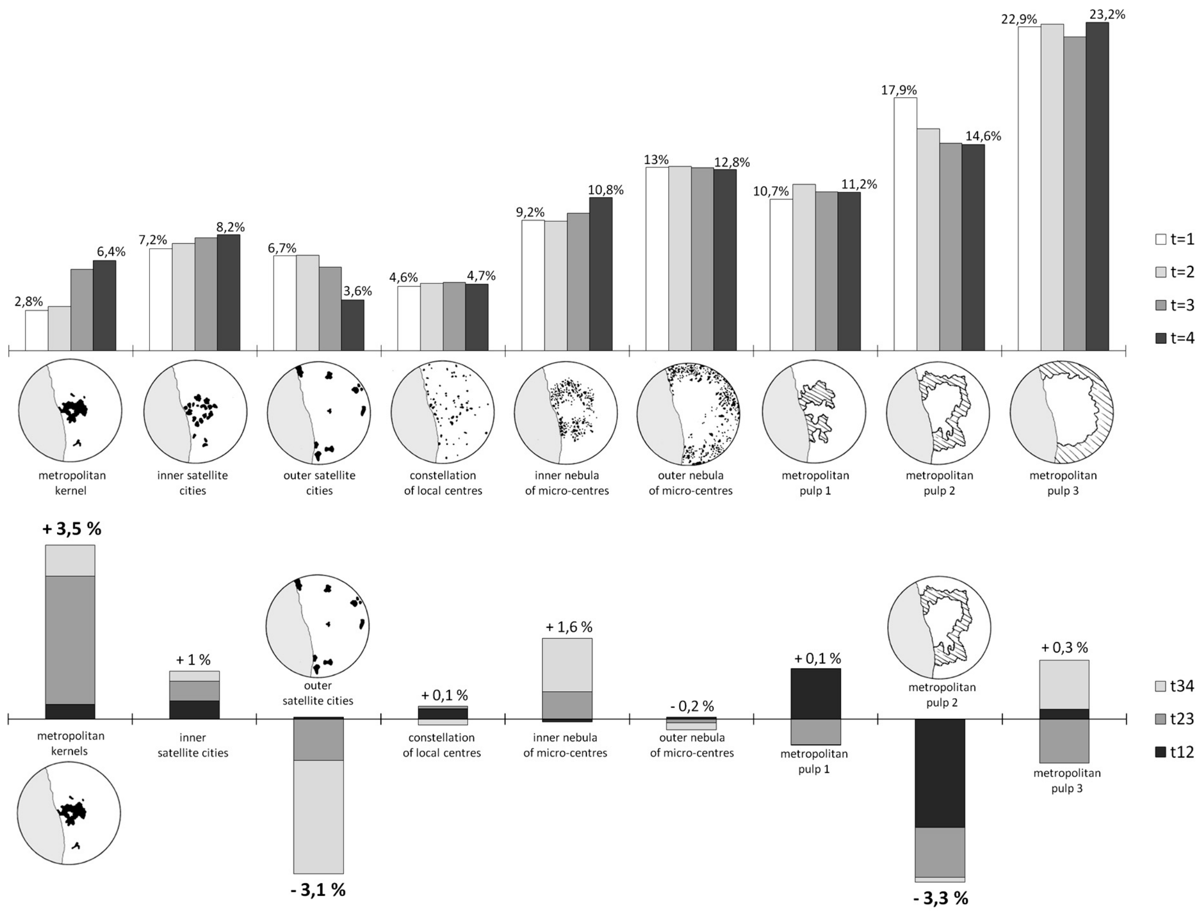


Fig. 114 – Shares of the clusters of metropolitan places (above) and respective absolute variations at each time interval $t_{[1,2]}$, $t_{[2,3]}$ and $t_{[3,4]}$ (below).

Another important remark is that the most significative centrality classes (i.e. those corresponding to the better defined and most meaningful spatial structures) represent only a small part of the entire metropolitan network. We refer to the first four integration clusters (i.e. the metropolitan kernel, the inner and outer satellite cities and the constellation of local centres) and to the first four choice clusters (i.e. metropolitan paths, primary and secondary city paths, city nodes and neighbourhood paths) which represent, respectively, only 23% and 34% of the entire spatial network (values of t=4). This does not mean that the other centrality classes (especially in the case of integration) are irrelevant. But it does mean that the fundamental spatial structures of the metropolitan region, defined in terms of places and paths, are not that fuzzy or polysemic and not so territorially ill-defined; and that, once acknowledged as parts of a whole, they may become manageable planning targets.

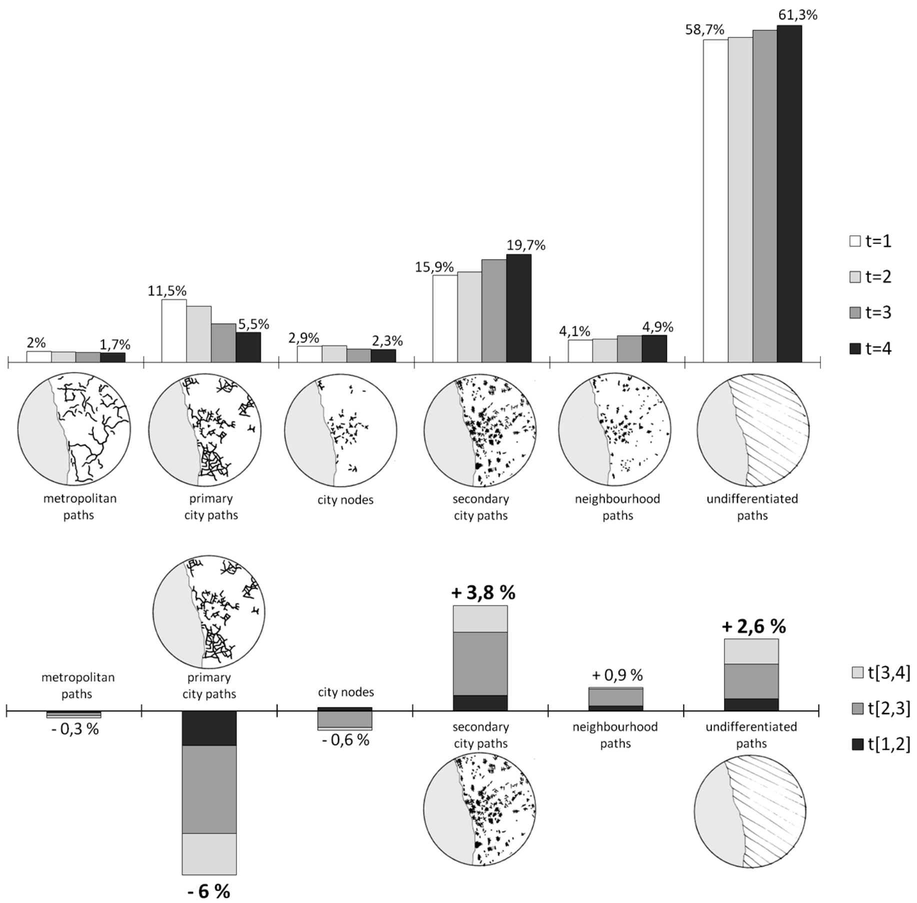


Fig. 115 – Shares of the clusters of metropolitan paths at each t={1,2,3,4} (above) and respective absolute variations at each time interval $t_{[1,2]}$, $t_{[2,3]}$ and $t_{[3,4]}$ (below).

Nevertheless, there are some clusters (both of integration and choice) that show some absolute variation through time, which are worth of a more thoroughly investigation. The distribution of all absolute share variations (i.e. the sum of all periods' variations, both of integration and choice clusters) is normal[139], without outliers and with standard deviation = 2,6. We thus consider absolute variations equal or higher than 2,6% in absolute value (i.e. equal or higher to one standard deviation) as relevantly deviating from the mean and indicating significative quantitative changes.

The integration clusters with absolute share variations equal or larger than one standard deviation are: the metropolitan kernel (+3,5% of total variation), the outer satellite cities (-3,1% of total variation) and the metropolitan pulp 2 (-3,3% of total variation). The choice clusters in the same conditions are: the primary city paths (-6% of total variation), the secondary city paths (+3,8% of total variation) and the undifferentiated paths (+2,6% of total variation). We flag these clusters now, in order to visualize the evolution of their spatial distributions later.

Regarding their qualitative evolution, the majority of the clusters reveal the same temporal stability. Figures 116 and 117 (next pages) show the position of the clusters' centroids in the space of variables,

[139] Both Kolmogorov-Smirnov and Shapiro-Wilk tests of normality have non-significant p-values (0,106 and 0,287, respectively), thus not rejecting the null hypothesis that the distribution is normal.

at each t={1,2,3,4}. The centroids are represented in three-axial polar plots, where each axis corresponds to one of the three fundamental centrality scales. Such plots make apparent the qualitative nature of the clusters' centroids (i.e. their particular centrality mixes, regarding the three variables) through the different triangular shapes that their linked coordinates on each axis form, and also their evolution across time, through the transformation (or conservation) of such triangular shapes, for each t={1,2,3,4}.

Some of the observed quantitative changes are reflected at the qualitative level, others are not, and still others only now become apparent. Regarding integration (Figure 116), the centroids suffering greater movements through time are those of the inner and outer satellite cities; the latter cluster had also significative quantitative losses. The inner satellite cities show a drastic push towards high centrality levels at the neighbourhood scale, from t=2 to t=3 (the other coordinates remain stable). The outer satellite cities show changes on all dimensions, albeit less suddenly: they lose centrality at the regional scale, while gaining at the city and neighbourhood scales (slightly more, at the latter). Other centroids show only very slight movements (as the constellation of local centres, the inner nebula of micro-centres and the metropolitan pulp 1), but they all happen between t=2 and t=3. The remaining centroids show none or irrelevant changes through time.

Qualitatively, the choice clusters are even more stable than those of integration (Figure 117, next page). Their centroids remain fixed through time, with only two exceptions. The cluster of primary city paths, which showed the greater quantitative loss, has only a slight centrality recess at the city scale. But the cluster of city nodes shows significative qualitative changes (even if quantitatively it showed none). It has a sudden increase at the city scale from t=1 to t=2, and a gradual increase at the neighbourhood scale from t=1 to t=4.

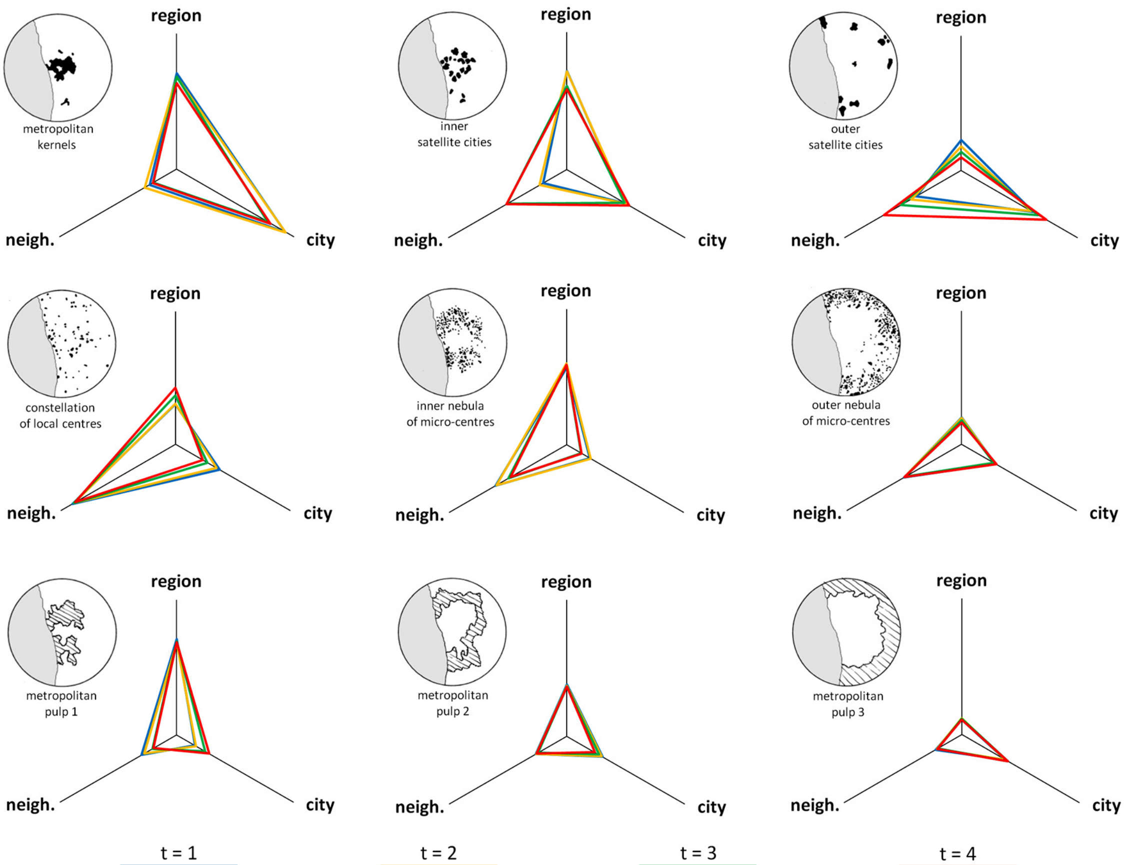


Fig. 116 – Temporal evolution of the centroids of metropolitan places' clusters.

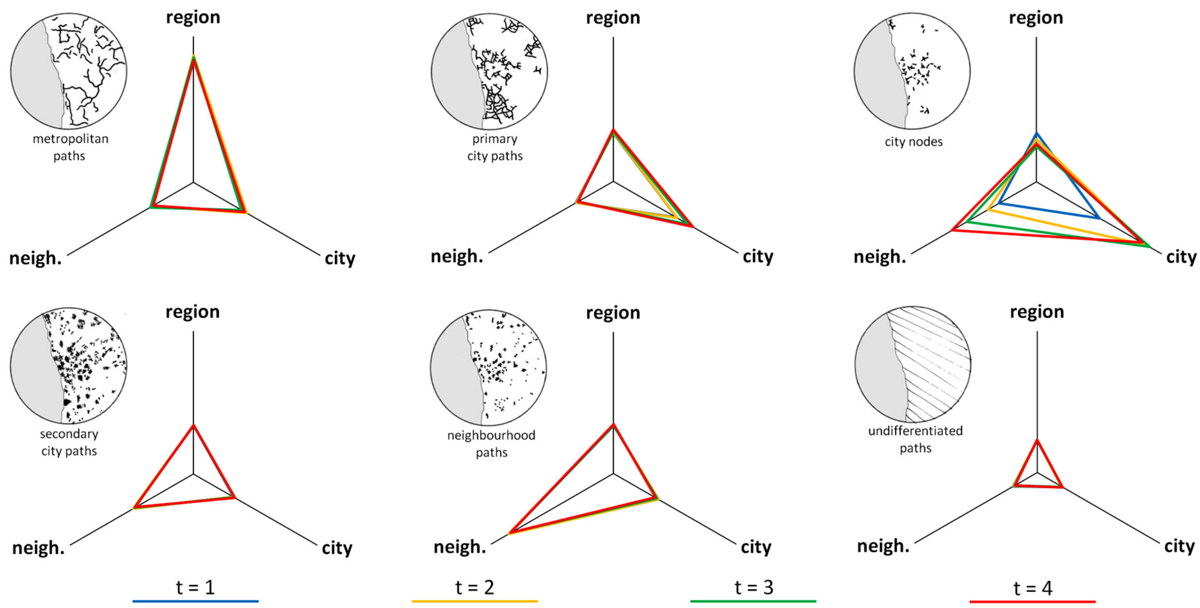


Fig. 117 – Temporal evolution of the centroids of metropolitan paths' clusters.

In summary, the clusters of metropolitan places showing significative quality changes are the inner and outer satellite cities; and regarding metropolitan paths, the cluster of city nodes shows the greatest qualitative transformations. We will now try to understand what these changes mean in spatial terms, through their visualization on the segment maps. The figures on the following pages show the spatial evolution of the clusters with significative transformations, at each time-interval $t_{[1,2]}$, $t_{[2,3]}$ and $t_{[3,4]}$. We use the same overlaying technique as before, in which the spaces of a former period are represented in blue, those of a latter period in red, and those common to both periods in purple. Thus, blue means spaces that the concerned cluster has lost; red, spaces it has gained; and purple, spaces that remained in the cluster during each time interval. Figure 118 (next page) shows this for the metropolitan kernel and for the metropolitan pulp 2 clusters.

The metropolitan kernel cluster shown an absolute variation of +3,5% (maximized during t[2,3]) and the metropolitan pulp 2 cluster a an absolute variation of -3,3% (maximized during t[1,2]). These effects are quite clear in the images. During t[2,3] the kernel almost doubles its share (3,1% to 5,8%) and geographic the area it occupies. At all time intervals its losses (blue spaces) are insignificant. This corresponds to a bustling urban development activity at this area during that period, which will also lead to the rise of the first ring of satellite cities (see below). Thus, the kernel grows not so much by transference of spaces from other clusters, but by the addition of newly built spaces. As it will become clear later, we witness here the emergence of a metropolitan core: the transformation of the city of Oporto (at t=1 still a self-contained urban agglomeration) into a larger composite system of highly central and diversified metropolitan places. This is done in just two decades, as Δt[2,3] = 21 years. The metropolitan pulp 2 cluster, suffers a very different process of continuous erosion (with a greater intensity during t[1,2]). However, such erosion occurs in localized areas and not in a spatially undifferentiated manner. These losses are transfers of spaces between clusters, namely to metropolitan pulp 1 (and to some extent also to 2); note on Figure 114 how their shares increase concomitantly at t=2. Such transfers correspond mainly to localized gains in regional centrality (the only dimension differentiating metropolitan pulp 1 and 2), which seem to be directly related with the introduction of new highway and motorway infrastructures (represented as black lines, on Figure 118).

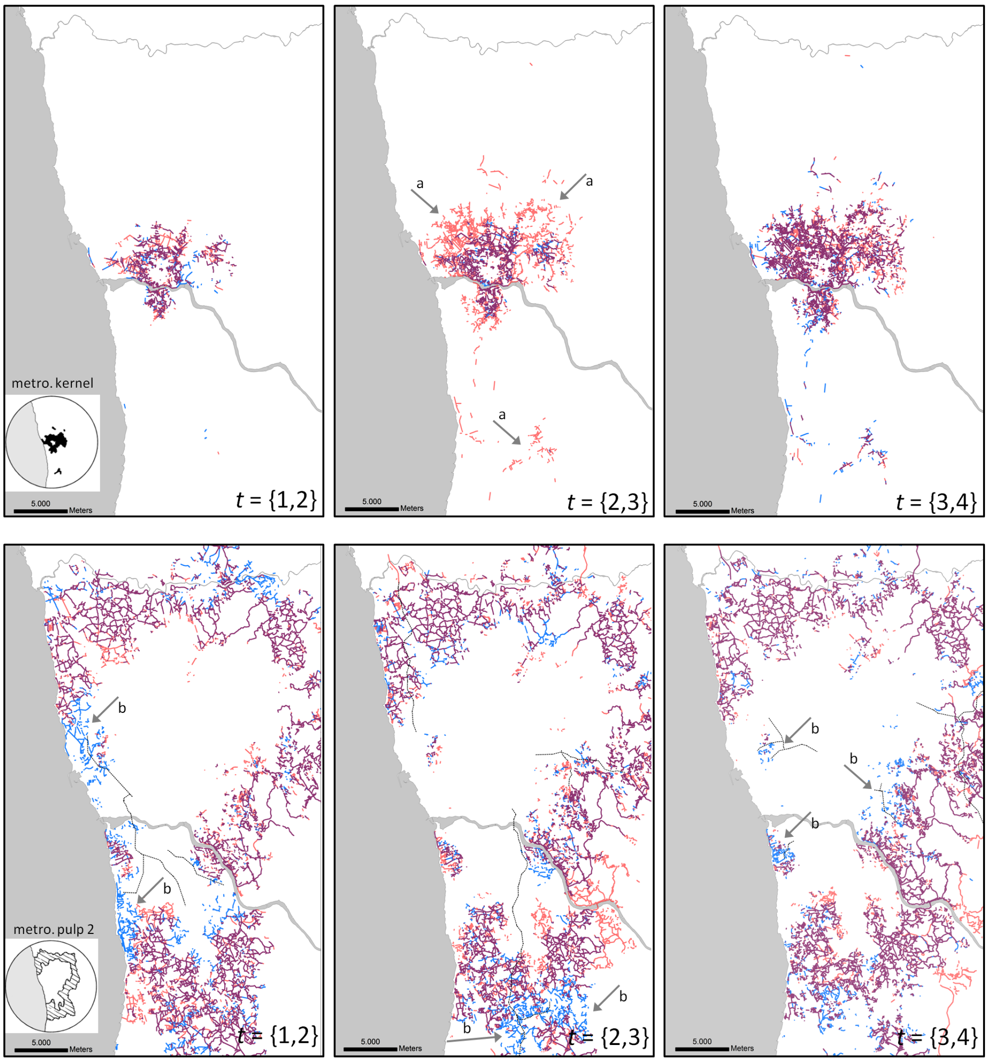


Fig. 118 – Spatial evolution of the metropolitan kernell and metropolitan pulp 2 clusters (above and below, respectively); expansion areas are marked as a) and contraction areas as b).

Figure 119 (next page) shows the evolution of the inner and outer satellite cities. The former cluster showed no quantitative variation, but a very significative change in quality (a sudden increase in neighbourhood centrality during t[2,3]). The latter, a strong decrease in its absolute share (-3,1%) as well as a significative change in quality (losing centrality at the regional scale, but gaining at the city and neighbourhood scales). Looking at the upper images of Figure 119 we realize that, at t={1,2}, the cluster of inner peripheral cities had a completely different nature than that it has assumed latter; in fact, we could say that it was something much more alike to what we have called metropolitan pulp, than to a group of urban agglomerations. As we have seen before, also the metropolitan kernel was much more restricted at that time. It is only during t[2,3], when a true burst of urban development occurs in and around the city of Oporto, that the previously undifferentiated spaces surrounding the metropolitan kernel, suddenly differentiate themselves as a crown of separated denser areas, with high centrality at the neighbourhood scale. Some of these are not actual cities in the administrative sense, but newly developed, large neighbourhoods of Oporto. Others are truly new, administratively independent urban agglomerations, almost entirely built during that period. Together with the suddenly expanded metropolitan kernel, these new inner satellites cities correspond to the emergence of a complex and multi-layered metropolitan core, made up of several types of places, with high centrality levels at several scales.

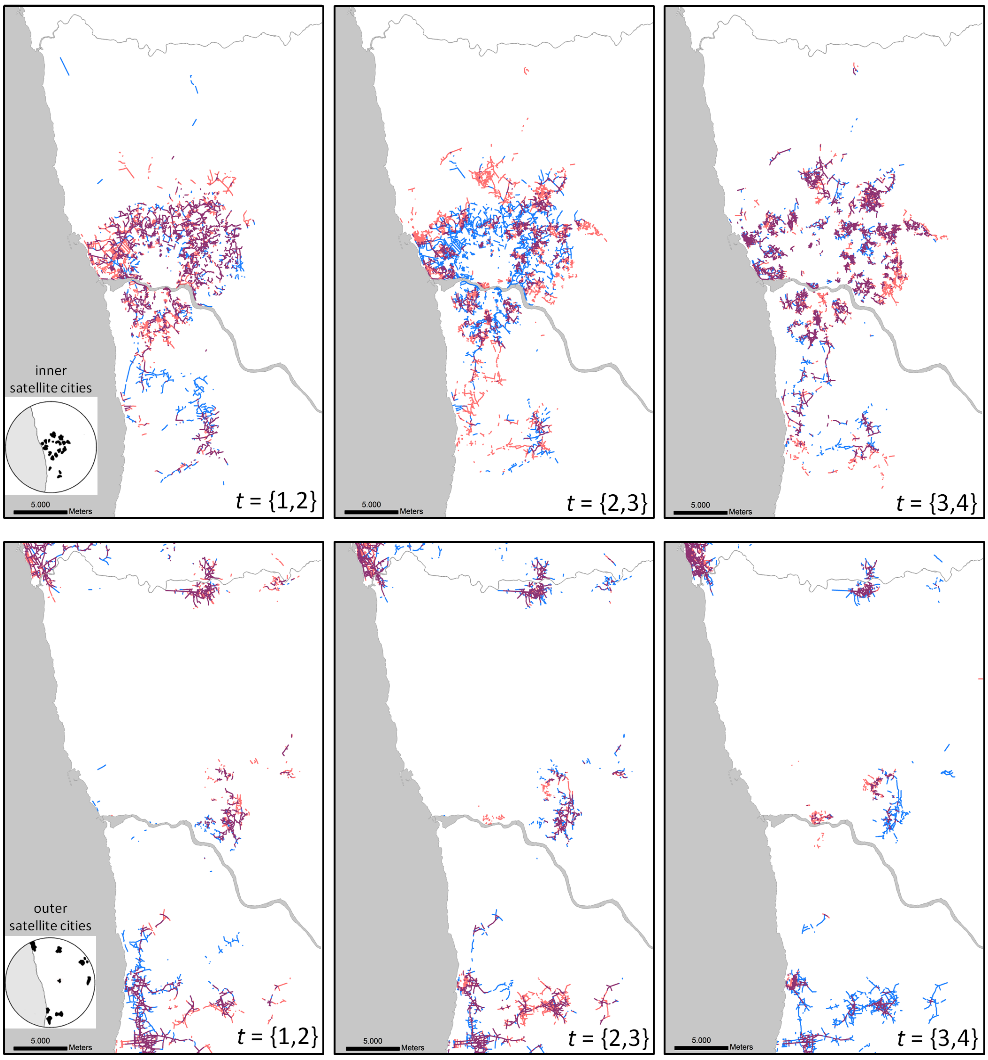


Fig. 119 – Spatial evolution of the inner and outer satellite cities clusters (above and below, respectively).

The bottom images of Figure 119 display the continuous erosion that the cluster of outer satellite cities endured through time, losing spaces at each observation period. This quantitative loss is accompanied by an increase of centrality at the neighbourhood and city scales and a decrease at the regional scale, as the cluster becomes more and more restricted to the urban centres of these peripheral agglomerations, i.e. more specifically urban. The losses correspond to transfers of spaces to other clusters, mainly to the outer nebula of micro-centres and to the metropolitan pulp 3 clusters. Thus, through time, these outer satellite cities lose their previous role as small regional centres (as the metropolitan core becomes ever more dominant at that scale), while their immediate surroundings differentiate as micro-centres or dilute themselves into the metropolitan pulp.

We now look at the clusters of paths showing the most significative changes through time. Figure 120 (next page) shows the spatial evolution of the primary city paths (upper images) and secondary city paths (lower images) clusters. Both had no qualitative changes, but the former revealed the strongest quantitative decrease (-6%) and the latter a significant increase (+3,8%). These changes are clearly reflected on their spatial evolution. It is notable how the cluster of principal city paths, representing the important middle-scaled grid of inter and intra-urban main thoroughfares, seems spatially unstable (with many spaces entering and leaving the cluster through time, in a seemingly erratic manner) while revealing a strong erosion and decline, especially on the northern part of the study area. This was already noticeable in the visualization exercise made in section 3.3, but now it becomes flagrant.

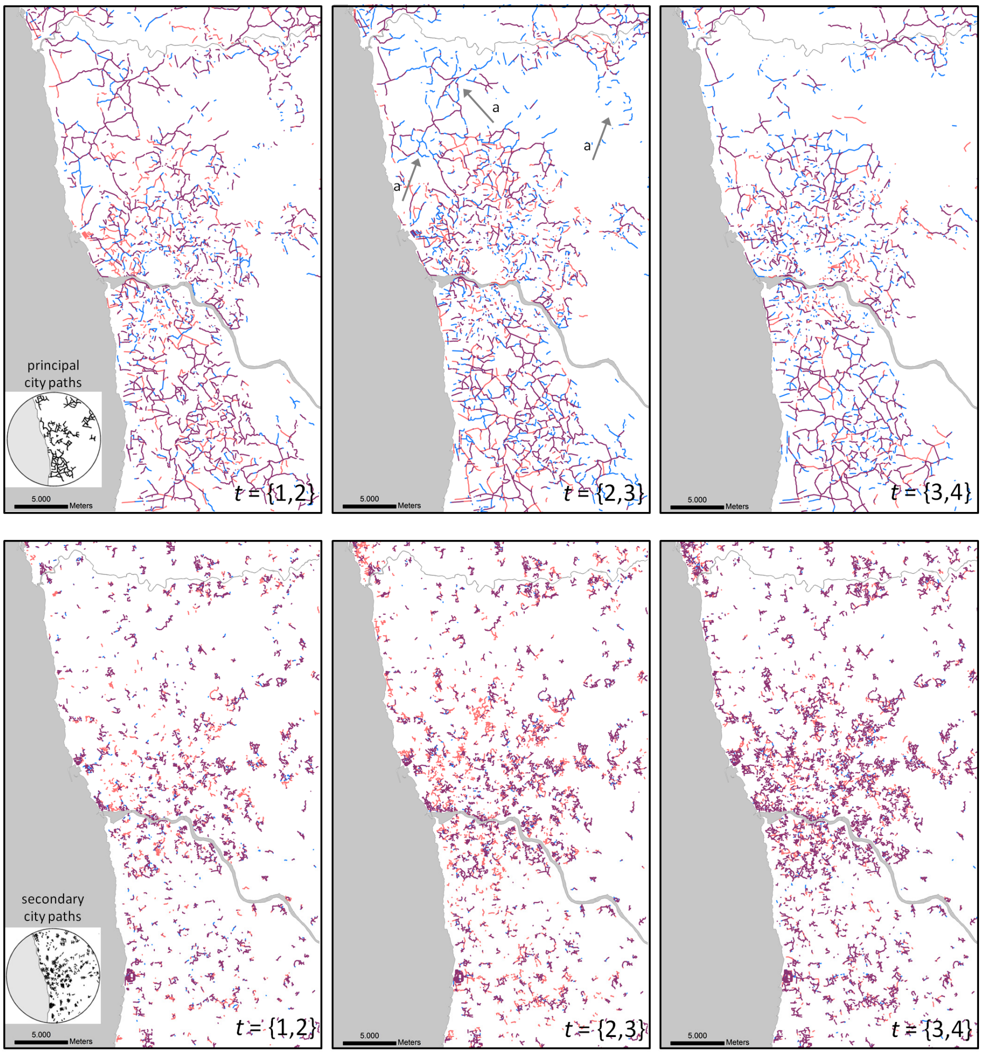


Fig. 120 – Spatial evolution of the principal and secondary city paths clusters (above and below, respectively). Contraction areas are marked as a).

In contrast, the cluster of secondary city paths, representing local grids with lesser structural importance and without clear continuity, grows steadily at all periods. It seems clear that the network of principal city paths, a potentially critical structure between the scales of the region and of the neighbourhood, which could convey unity and intelligibility to the metropolitan territory, has been degraded by the process of metropolitan development and seemingly forgotten as a planning target. In fact, the bulk of public investment made to the metropolitan network through time as been mainly devoted to the creation of new regional scaled infrastructures, i.e. to the system of metropolitan motorways and highways. As for private investment, it is naturally indifferent to these concerns, focusing exclusively on the much localized developments it promotes, of which the significative growth of the secondary city paths cluster is a direct consequence. But there seems to be no doubt that the network of primary city paths has not beneficiated from that, neither from the public investment in the network of regional paths. It is important to note that the decrease in this cluster's share is not the main issue; it could have become smaller while still showing a clear and continuous structure. But besides decreasing, the network of primary city paths has become highly fragmented and discontinuous. Moreover, its decrease is mainly due to transfers to the cluster of undifferentiated paths (which grows concomitantly), meaning that such network has indeed lost centrality and structural differentiation at the same time.

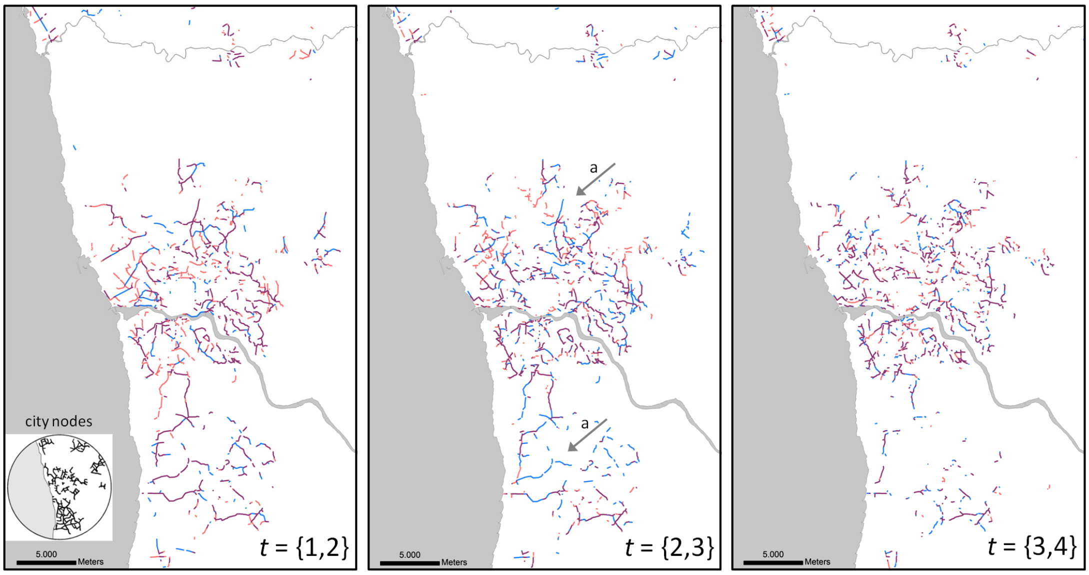


Fig. 121 – Spatial evolution of the city nodes cluster; contraction areas as a).

Two last clusters of paths have shown significative changes through time: the undifferentiated paths cluster (+2,6% increase in absolute share) and the city nodes cluster (with a stable share, but with strong increases in centrality at the city and neighbourhood scales). Of these, we only visualize the spatial evolution of the latter (Figure 121, above), because the former is rather meaningless in visual terms; it simply gathers all the spaces without structural differentiation, which are the overwhelming majority. As already stated, its interest is only quantitative, acting as a benchmark of the proportion of structurally irrelevant paths in the network. However, the steady increase of its share is revealing in that sense, because it shows that a number of existing and newly built spaces continuously feed that class through time. In other words, even if the metropolitan spatial network grows considerably during the time span considered in this study, its path structure also has become more ‘entropic’, as the share of undifferentiated paths is larger today than it was at t=1.

Although the decrease in the share of the city nodes cluster is only marginal (-0,6%), a clear transformation of its initial spatial distribution is noticeable. At t=1 it shows thready structures, which gradually break up at the following observation periods; at t=4 it shows a speckled pattern of small fragments, clearly concentrated at the more densely urbanized areas (compare the pattern of t={3,4} on Figure 121, with those of the same periods on Figure 119, p. 178).

Actually, the initial centroid of this cluster shows a mix of the three fundamental spatial dimensions which is quite similar to the one of the principal city paths cluster (see Figure 117, p. 176), suggesting initially akin structures. However, a significant number of new small network fragments are added to this cluster over time, while others are lost, but those lying on the specific areas mentioned above remain (resulting in an almost null absolute share variation). What happens here is a kind of progressive ‘speciation’[140] of the cluster: a gradual transformation towards a new and specific path type of the city-scaled network, whose role seems to be that of interfacing such network with the one of regional paths (as noted before). This results in a strong increase of centrality values at the city and neighbourhood scales in this cluster, because it progressively gathers only spaces deeply embedded in urban areas and in particularly strategic points of the city-scaled network. As with the cluster of inner satellite cities, the qualitative alteration of this cluster is therefore also understandable and spatially interpretable.

[140] Speciation is a biology term, designating the evolutionary process by which new biological species arise, namely through the gradual transformation of previously existing species.

We thus have a series of classes of metropolitan spatial structures, defined in terms of their centrality behaviour within the overall metropolitan spatial network over many spatial scales, and discovered only by objective and reproducible methods. These classes represent in fact *types* of metropolitan *places* and *paths*. Furthermore, they have a number of important properties, which make them liable of being translated into the elements of a true typology. They have shown to be:

1. *Stable* - the temporal stability of the discovered types was demonstrated several times and by several means. This is fundamental, because it proves that they are neither numerical epiphenomena nor subject to spurious noise effects. On the contrary, they are purely empirical findings, because they are derived only from objective measurements of a real-world physical object (i.e. the street network of Oporto's metropolitan region). Their temporal stability very strongly supports their consistency as descriptions of real urban phenomena.
2. *Substantial* - the sizes of the clusters corresponding to each type, both regarding the number of spaces concerned and the geographical areas they occupy, are large enough to serve both as objects of analysis and as operational planning targets.
3. *Differentiable* - the types are distinguishable both conceptually and spatially, corresponding to clearly distinct spatial structures.
4. *Parsimonious* - the number of types of places and paths is small and manageable, both for analytical or for operational purposes.
5. *Familiar* - the spatial structures described by each type are apprehensible, recognizable and easy to fit within current urban or planning knowledge.
6. *Relevant* - the spatial structures described by the types are relevant, in that they represent actual, recognizable and acknowledged metropolitan places and paths of different scope and importance: from the most local structures at the neighbourhood level, to the most global ones at the level of the entire metropolitan region.
7. *Novel* - even though the types are recognizable and familiar, they are not trivial nor do they simply state the obvious; some of them represent non-evident spatial structures (e.g. the metropolitan pulp types) or spatial structures otherwise very difficult to define (e.g. the city nodes type).

Therefore we may consider the classes of spatial structures defined by the methods used in this chapter, as the elements of a metropolitan typology of places and paths. But at this stage, such a typology is simply a list of types. We can go further and try to organize such types in a structured way, according to their eventual kinship relations or intrinsic differences. In other words, we can try to organize our types into a hierarchical typology: a *taxonomy* of metropolitan places and paths.

A taxonomy is a systematic hierarchical classification, in which each class is either independent from the others (because it is intrinsically different from them) or is a sub-type of a higher-order class (because it is has the same properties of that higher-order class, plus one or more); however, in a taxonomy all classes are also sub-types of a general super-class (i.e. the object of classification itself, in this case metropolitan places or metropolitan paths), to which all others classes are related and from which they are derived. Taxonomies produce always nested hierarchies that may be represented as tree structures (called dendrograms), in which the root-node is the super-class (which applies to all objects within the hierarchy) and the subsequent nodes are more specific classifications that apply to sub-sets of the total set of classified objects. Taxonomies are much used in biology (from where the term and the concept stem), but they apply to many classification subjects and are widely used in many disciplines, as diverse as genetics, linguistics, history (genealogy), information analysis or computer science. In particular, the sub-field of biology called numerical taxonomy (Sokal 1996) makes direct use of clustering algorithms, in order to achieve solid and non-subjective classifications of living organisms.

We will use a similar method to try to organize our types into a hierarchically structured typology, or taxonomy. In fact, hierarchical clustering methods are widely used for that purpose, because they always produce hierarchically nested classifications (in the form of dendrograms) which may be immediately taken as taxonomies, if the objects to be classified are all members of the same phenomenological class. This is of course the case of our types, belonging to the phenomenological classes of metropolitan places and of metropolitan paths.

The method we will use is straightforward. We will classify the centroids of our clusters, which are also their archetypes (i.e. the points that better describe the centrality behaviour that each cluster represents), using a hierarchical agglomerative clustering procedure. We will classify simultaneously all the centroids of the clusters of each t={1,2,3,4}, in order to obtain datasets with minimally acceptable sizes and variability, but this will also serve to test once more the consistency of our previous results. Such procedure will allow understanding if the clusters are all equally different from each other or if some of them have kinship relations; the same is to ask if some of them are more fundamental than the others. Furthermore, if any relationships of similarity are found, they may disclose higher-level classes of metropolitan places and paths: not perceptible in the individual types, yet revealed by their eventual grouping as members of a same hierarchically superior class.

The method of agglomerative hierarchical clustering starts with all objects separated, each one representing an individual cluster. These clusters are then sequentially merged according to their similarity. First, the two most similar clusters are merged to form a new cluster at the bottom of the hierarchy. In the next step, another pair of clusters is merged and linked to a higher level of the hierarchy, and so on until all clusters are merged into a single one. This allows a hierarchy of clusters to be established from the bottom up (Mooi, Sarstedt 2011). There are several methods of agglomerative hierarchical clustering, using different measures of similarity and criteria for merging the clusters. Here we will use the most common of these methods, namely Ward’s minimum variance criterion. This algorithm merges iteratively the clusters entailing the minimum increase in total within-cluster variance. Thus, Ward’s method leads to the definition of compact clusters of roughly the same size, where the similarity between the objects in each cluster is maximized (Mooi, Sarstedt 2011). These properties serve our purposes, because we want to understand if our metropolitan types have intrinsic similarities or not.

Our clustering objects are therefore all the centroids of the clusters of places and paths, of all observation periods (but obviously places and paths will be classified separately). However, for several reasons we will not use the centroids of the cluster of undifferentiated paths (i.e. choice cluster 6). Firstly, because we also know in advance that such is cluster is obviously different from all the others. Secondly, because we know that such cluster has no structural meaning whatsoever, so there is no point in trying to compare it with the other clusters (which do have structural meaning). And thirdly, because the extreme difference between that cluster and the others may preclude the algorithm of identifying less obvious differences between the remaining clusters. The two datasets with the centroids of the clusters of places and paths have no significative outliers and are described by standardized variables (i.e. PCA scores), two things to be taken into account when using Ward’s method, so we may proceed directly to the clustering process.

Figure 122 (next page) shows the dendrogram resulting from the classification of the centroids of metropolitan places. Each branch at the base of the dendrogram, represent the cluster’s centroids at each t={1,2,3,4}. Hierarchical clustering does not provide a single cluster solution. Instead, the dendrogram shows the history of the successive merging of the clusters, up to the moment of their merging into a single set, containing all the objects of the classification (the top-level of the dendrogram). Such diagram may be ‘cut’ at every level, producing a different number of clusters.

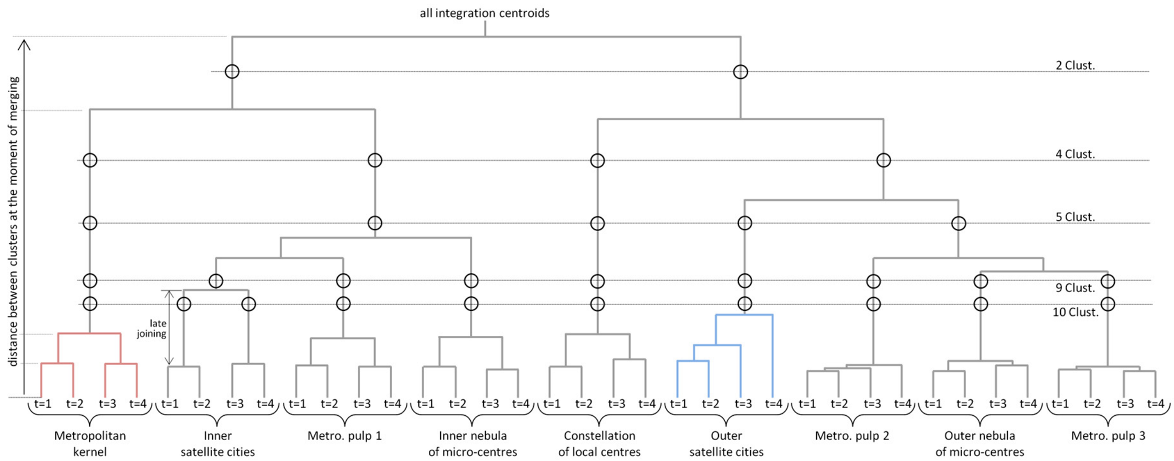


Fig. 122 – Dendrogram of Ward's clustering for the centroids of metropolitan places.

Moreover, it shows the relative dissimilarity between the clusters produced by each possible 'cut', represented by the length of the vertical lines joining each horizontal line (representing the moments of cluster merging). The longer these lines are, the more distant (i.e. the more different) are the clusters at the moment of their merging (which is represented by the horizontal lines). Thus, one can visually evaluate the dissimilarity between the clusters created by each possible cut and, at the same time, the optimal cutting moments (i.e. those crossing reasonably long vertical lines).

On Figure 122 we have represented several cutting options, namely those producing 10, 9 (the original number of clusters found by k-means), 5 and 4 clusters. We will discuss these solutions in a moment, but first there are other relevant information resulting from the dendrogram shape that we should note. In fact, the dendrogram shows several properties that confirm our previous findings while providing still some new information.

The first (i.e. the lower) three levels of the dendrogram represent the merging of the four centroids of each cluster (one for each t={1,2,3,4}), into the 9 types of metropolitan places identified before. As expected, the centroids quickly converge towards a single cluster, showing that indeed they correspond to very similar points and that the types of metropolitan places identified before are indeed quite time-stable structures, at least regarding this study's time-span. However, some converge faster than others, and not all in the same order. There are two types of merging sequences. The first one (and the more frequent) is represented in red on Figure 122; it corresponds to a merging scheme in which the centroids of t={1,2} and t={3,4} are first merged in pairs and only later into a single cluster. The second (less frequent) is represented in blue on Figure 122; it corresponds to a merging scheme in which the centroids of each period are merged sequentially, i.e. first t=1 with t=2, then these two with t=3 and finally with t=4. These two merging schemes imply quite different things. The latter corresponds to clusters which differentiate linearly with time, i.e. t=1 is more similar to t=2, which together become similar to t=3 and only then to t=4. In a scenario of linear urban transformation, one would expect this to be the rule; however, such situation is instead the exception. The former merging scheme is much more frequent, with t={1,2} merging later with t={3,4}. What this means is that there is a fundamental morphological divide between t=2 and t=3 or, in other words, that what is happening during the time-interval $t_{[2,3]}$ is profoundly different from what was happening before, making the centroids of t=2 and t=3 quite different. This corroborates some findings already suggested in Chapter 1 and further explored in this Chapter. The time-interval $t_{[2,3]}$ corresponds to the moment of strongest intensity of urban growth, a moment of profound transformation of the spatial network, not only in quantitative terms but also qualitatively, as these particular results show. Only the outer satellite cities and the metropolitan pulp 2 clusters seem to escape this situation, having a gradual transformation process over time.

We now look at the clusters formed *after* the merging of the four centroids, i.e. after the identification of our types of metropolitan places by the algorithm. This happens at the level of the dendogram marked in Figure 122 as “9 clust”. But still one can note that there is a previous solution which produces 10 clusters, by the sub-division of the inner satellite cities in two, one for t={1,2} and another for t={3,4}. The centroids of that cluster resist longer to the merging, than those of the others (this is flagged on Figure 122). This is a direct consequence of the previously observed fact that such cluster actually represents different things, before and after $t_{[2,3]}$. At t={1,2} it represents a structure similar to that conveyed by the metropolitan pulp clusters (to which we will henceforward call metropolitan pulp 0); at t={3,4}, such structure breaks up to properly become the cluster of inner satellite cities: hence the late joining of that cluster. But after that point, all of our previously defined types of metropolitan paths are identified. What is important now is to understand how these types merge successively into one, single general class of metropolitan paths. From this point we will read the dendrogram from the top-down, as it makes easier the understanding of the hierarchical relations among the types of metropolitan places.

The first division of the dendrogram (i.e. from the top, marked in Figure 122 as “2 clust”) separates the macro-class of all metropolitan places in two: one containing all places pertaining to the core of the metropolitan region (i.e. the metropolitan kernel, the inner satellite cities, the inner nebula of micro-centres, and metropolitan pulp 1); and another containing, at this stage, all other metropolitan places’ types. Therefore, we assist at first hierarchical differentiation of the types of metropolitan places into two large classes: those pertaining to the metropolitan core and all other metropolitan places.

The next division happens by the separation of these two large classes into four classes (marked in the figure as “4 clust”): one contains the metropolitan kernel, another all the other clusters from the core, another with just the constellation of local centres, and still another containing all the peripheral places. We can see here that the metropolitan core may be divided into the kernel and “outer core places”, that the constellation of local centres is an independent entity by itself, and that all other clusters may gathered into a general class of “peripheral spaces”.

Still a further division (marked in Figure 122 as “5 clust”) preserves the previous classes but divides the peripheral places in two: the outer satellites cities and still another aggregated class (containing the metropolitan pulp 2 and 3 clusters and the outer nebula of micro-centres) to which we may call the “metropolitan fringe”. We thus note how the outer satellite cities have also a rather differentiated character in the overall set of metropolitan places. Finally, the last division (marked as “9 clust”) individualizes all our types of metropolitan places. We could point still another intermediate division with 7 clusters (not marked on the figure) which would keep four types joined in two composite classes, but the distance between the creation of these two sub-classes and the next joining represented by the solution of 5 clusters is very small. This indicates a small degree of consistency or individuality of these two hypothetical sub-classes, which therefore we do not consider meaningful or liable of being taken into account in the hierarchical organization of the types.

It becomes clear that what we have now is a hierarchically organized collection of types of metropolitan places; indeed, a *taxonomy* of metropolitan places (Figure 123, next page). Such taxonomy may be sliced at several levels, each one representing a different degree of *resolution* of the set of all metropolitan places (resolution here being directly equated with the degree of structural individuality or intrinsic difference among the several types of metropolitan places). Such levels of resolution could, for example, correspond to different metropolitan policy agendas or targets. One may imagine urban policies having the “metropolitan core” as target, others aimed only at the constellation

of local centres, at the metropolitan kernel or at the outer satellite cities, and still others having the places of the “outer core” or of the “metropolitan fringe” as main targets.
This could be also useful in the definition of urban assessment targets regarding, for instance, their SWOT[141] analysis. Also, this taxonomy greatly elucidates the structure of places in the metropolitan region, and may also serve as a useful research map for more thoroughly investigations of each of components and levels of resolution. In any case, it seems quite clear that our types of metropolitan places have not all the same degree of individuality and external difference. Paraphrasing George Orwell, one could say that ‘all metropolitan places are different, but some are more different than the others’.

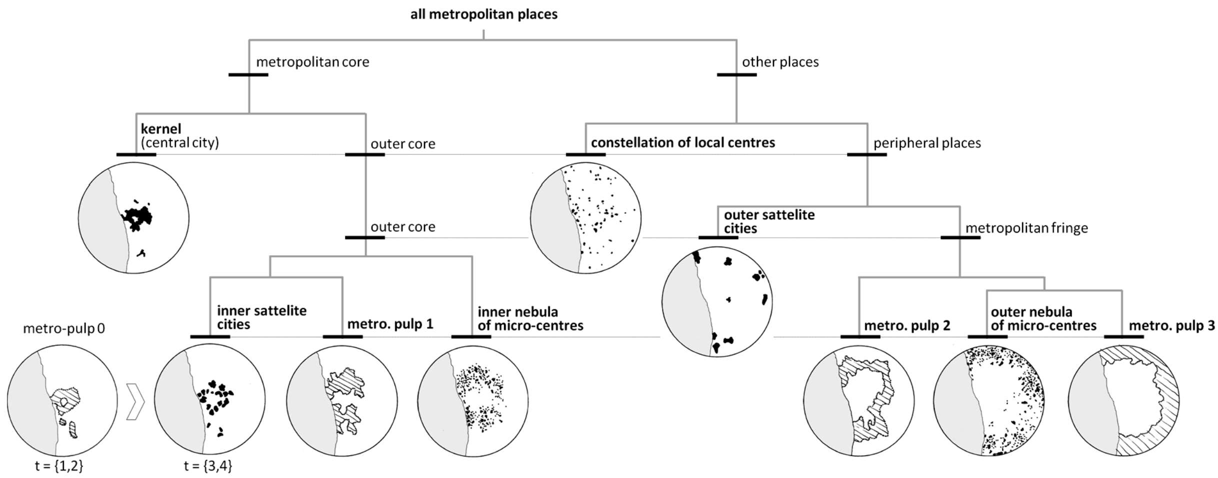


Fig. 123 – The final taxonomy of metropolitan places.

Exactly the same exercise may be done with the set of types of metropolitan paths (Figure 124, above). We will not make the detailed description as we did for metropolitan places, because the same considerations also apply here. The divide between the centroids of t={1,2} and t={3,4} is also apparent, but the regional and the neighbourhood paths clusters show a gradual agglomeration scheme. These structures are therefore more gradually transformed, even if the cluster of regional paths is greatly improved over time (namely through the gradual construction of the metropolitan motorway system). But it seems that such seemingly revolutionary transformation is not so overwhelming in spatio-structural terms. Also, it suggests that both regional and neighbourhood paths are structures with a greater ‘inertia’, not prone to sudden changes over time. One of the path clusters (city nodes) shows also a late joining between t={1,2} and t={3,4}. This corresponds to the deep transformation that such cluster suffers during t[2,3], also described before (see p. 57).

But the hierarchical differentiation is in this case much more marked and sequential than it was in the case of metropolitan places. Reading the dendrogram from the top-down, one can see that the set of all metropolitan paths begins by differentiating into regional paths and a general class of “all other paths” (the “2 clust” level, on Figure 124). Next, the cluster of neighbourhood paths stands out in its turn, leaving the clusters related to the city-scale together in a general class of “city paths”. This is followed by the differentiation of the city nodes cluster, recognizably different from the other city-scaled paths, leaving still a composite class to which we call the “city grid”. Finally, this city grid is broke up into primary and secondary city paths. The last cluster of undifferentiated paths, not included in the clustering classification, may be allocated as a lateral class, in the final taxonomic scheme, represented in Figure 125.

[141] Strengths, weaknesses, opportunities and threats (SWOT) analysis, is a well known and wide applied assessment methodology, used in many decision-making situations, namely in strategic planning (urban or not).

The greater differentiation of the structure of metropolitan paths is mainly explainable the smaller number of types, but also because the measure of choice is a much less prone to effects driven by boundary-conditions than integration. Some of the types of places (i.e. integration clusters) that we have found are related with that type of effect (e.g. the distinction between inner and outer nebulas or metropolitan pulps 1, 2 and3) and thus have natural kinship relations, regarding their relative positions on the study area. This creates less clearly defined types, leading to more nested taxonomies. But the same remarks made before for metropolitan places, about the utility of such a systematic type of classification, also apply for the taxonomy of metropolitan paths. These could be the tiers of a structurally-derived metropolitan road hierarchy, the individual subjects of further research or clearly defined targets of urban planning actions. In all, the discovered types of metropolitan places and paths, together with their taxonomies, or hierarchical typologies, may be seen as the fundamental pieces of a spatio-structural model of the metropolitan region. These pieces may be put together to form a new picture of the metropolitan region, one that depicts its spatial structure in terms of its intrinsic centrality variability.

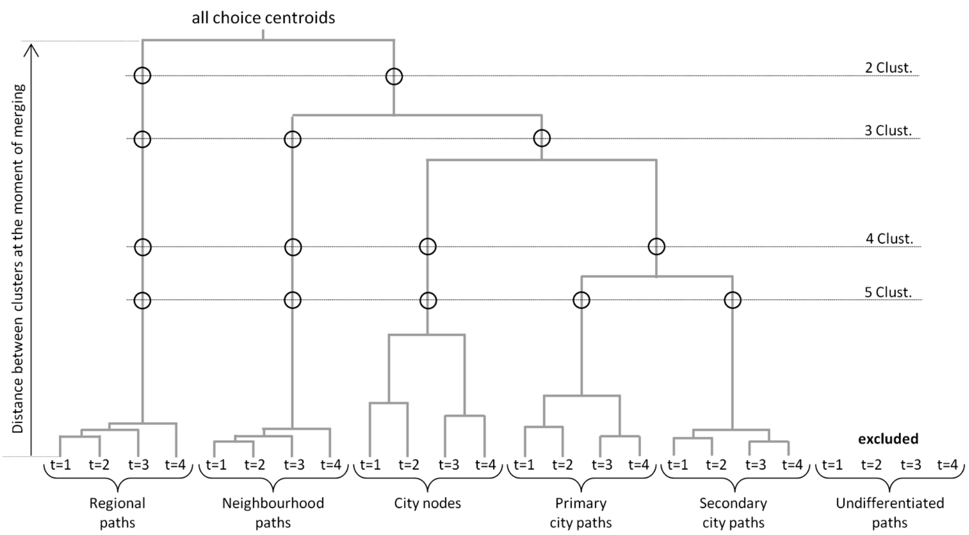


Fig. 124 – Dendrogram of Ward's clustering for the centroids of metropolitan paths.

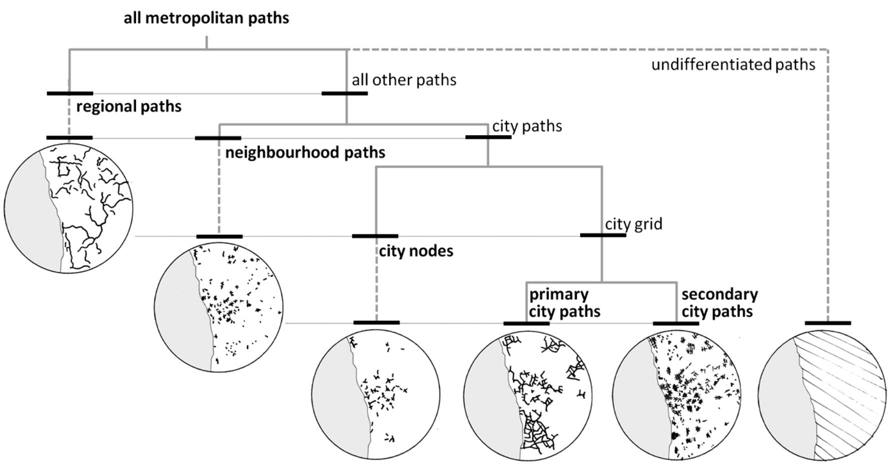


Fig. 125 – Final taxonomy of metropolitan paths.

6
MICRO-STRUCTURAL ANALYSIS

ABSTRACT

In this chapter we will address the problem of defining objective and empirical derived typomorphologies of metropolitan development operations. The material for such exercise will be provided by the sample of individual network interventions, collected during the diachronic axial modelling phase, described on Chapter 3.

The objective, non-dazzled, typomorphological study of the commonplace urban developments which incrementally construct today's metropolitan regions, may be of great interest to their necessary appropriation as manageable objects by urban planning. However, in order for such typomorphologies to have effective validity and to act as substantive examples of the range of spatial forms being produced on a certain geographical and cultural metropolitan context at a given moment in time - so that they can provide the basis for urban policies and planning strategies aimed at controlling urban form - their actual occurrence cannot be the object of doubt. In other words, to the extent of possibility, they must be unquestionably true.

The same empirical validity is also necessary, if we aim one day to understand the potential causal relationships between the variegated forms of incremental metropolitan growth and the emerging metropolitan global morphology. However, the current methodologies for defining urban typomorphologies, based on small (or non-explicit) samples and on the conviction of the analyst are not enough, especially in non-traditional metropolitan contexts. We need to be able to produce typomorphologies that are numerically described and objectively defined.

That is the aim of the current chapter. Using a large sample of 4208 urban development operations observed during a time-span of 60 years and described by their street layouts, we explore and propose a methodology based on descriptive statistics and unsupervised classification methods, to discover and characterize a number of typomorphologies occurring on the metropolitan region under study. We show that these typomorphologies have different frequencies in different time periods. Furthermore, their spatial distributions at each time period are analyzed using GIS spatial statistical techniques, showing also unexpected but clear temporal differences in that regard.

We conclude by suggesting that the proposed method is capable of finding clear typological regularities in an otherwise very complex and diverse morphological reality, that those regularities correspond to previously unknown types and that, therefore, the method is capable of serving both operational and research purposes.

6.1. THE MICRO-COMPONENTS OF METROPOLITAN SPATIAL GROWTH

On the previous chapter we studied the evolution of the metropolitan spatial network as an aggregated entity. The focus was on structural properties arising from the fact that such network is a continuous, connected and single physical object. However, as we have seen, such object is not immutable. Quite the contrary: it grows and changes through time, sometimes rather drastically. The elements responsible for such grow and change - that is, the 4208 additions or transformations made to the metropolitan spatial network over time, identified and isolated on Chapter 1 - will now be the main objects of analysis.

These 4208 interventions, to which we may formally call the *micro-components of metropolitan spatial growth*, constitute a rather different object of study, but of no lesser empirical value. They represent the spatial morphology of each operation of urban development realized along this study's time span, be it public or market-led (the latter type being overwhelming more frequent). Thus, they allow seeing what has changed in the metropolitan spatial network between each moment of observation; but they represent also the opportunity to study, characterize and quantify the morphological nature of the individual elements responsible for the network's growth and transformation.

Even if a greater understanding of metropolitan morphology is undoubtedly necessary, it also seems clear that any attempt to globally plan the physical development of such vast urban structures would be vain, or even childish. Any detailed metropolitan physical plan would be overridden a minute after its inception. Current planning approaches to metropolitan territories (Berg et al. 2006, Allin and Walsh 2010), other than being quite scarce, focus more on methods of governance and 'soft power' in order to streamline the cooperation between local administrations so as to achieve economic, social or environmental goals, than on theorizing possible or desirable morphological scenarios.

If we put aside purely aesthetic considerations, the morphological dimension seems to have been almost forgotten in metropolitan planning debates. The city-region is frequently seen as a formless agglomeration of activities and spaces, deemed ultimately non-describable in physical terms (Prosperi, Moudon, Claessens 2009). Yet, contemporary metropolitan regions are human artefacts - not extraneous realities imposed by some remote entity, acting against and in spite of our will. They are the collective built-product of human societies, as cities have always been. And, as it has also always been the case with cities (at least until very recently[142]), metropolitan regions are built incrementally: led either by collective or by individual volitions, but always growing according to an internal clock that ticks at the pace of each new physical addition or transformation made to the ever-changing urban object.

Throughout urban history, the incremental growth of cities has been fundamentally free from any kind of planning directive. Systematic urban regulations are a modern invention, whose earliest and manifestations are perhaps the plans for the reconstruction of London (after the 1666 Great Fire) and of Lisbon (after the 1755 earthquake). However, nowadays, urban development is subjected to planning regulations, at least in all western countries. In Portugal, every urban operation - from the construction of a single house to large urban development projects - must be subjected to the approval of municipal authorities, which base their decisions on stipulations of municipal master plans and on general laws, regulating building construction. Thus, the supposedly non-describable metropolitan landscape is, after all, the direct product of urban operations that have all passed through the sieve of planning instruments and of general law. This creates a truly paradoxical situation: on one hand, we

[142] Nowadays, this may seem almost an anachronism, when entire cities pop up like mushrooms in Asia, in Africa or in the middle-east. However, such rates of urban development are not those we are dealing with here, and surely will not be in any plausible mid-term scenario.

have metropolitan regions which are object of the worst academic criticisms, in what concerns their patterns of physical development; on the other hand, we have metropolitan regions whose physical development has been fully scrutinized by legal and planning instruments.

Obviously, any cursory explanation for such paradox - as, for instance, the incompetence (or even the corruptibility) of public agencies - is not only unfair but also completely misses the point. The point being the fact that we do not have the instruments for regulating the physical development of contemporary metropolitan regions, because we do not know the stuff of which contemporary metropolitan regions are made of, in the first place. In other words, we do not know what our regulations are regulating. In morphological terms, the real problem is that the objects of regulation themselves are strange to us, and before we understand what they truly are - how they are composed, which of those compositions are good or bad, the ones we want to avoid and those we want to foster - we cannot expect urban regulations to produce any substantial results in steering the morphology of the extended city.

There seems to be a strong mismatch between what planning instruments and planning regulations are saying (or aiming at controlling) at the morphological level, and the actual reality of contemporary urban form and development. The cohabitation of blatant criticisms on metropolitan morphologies, and of metropolitan areas fully covered by municipal master plans (as it is the case in Portugal and elsewhere), cannot mean anything else but the failure, or at least the strong inadequacy, of current planning knowledge and instruments in steering the morphology of the extended city. Moreover, the few operational proposals to address such issues, as the enthusiastic adoption of form-based codes in the U.S. and in the U.K. (Carmona et al. 2006) seem somewhat superficial. Samuels (2008), for instance, makes a stringent critique of the shallowness of those approaches (especially when taken by public agencies), which seem to emphasize only superficial and ephemeral architectural features and show little awareness of the importance of deeper and less visual aspects of urban form, as those we have studied in the precedent chapters.

It is true that we cannot fully control metropolitan physical development, nor is this a desirable goal. Because metropolitan development occurs on such vast territorial scales and under so great a variety of political and economical contingencies, it seems clear that any top-down, centrally devised physical plan, would be bond to irrelevance and failure. What we would need were ways of steering metropolitan form from the bottom-up; that is, to devise general morphological concepts and rules that, once systematically applied to the continuous production of small or large urban incremental developments, would somehow lead to the emergence of structured urban areas (Marshall 2005, 2009). We must not forget that every incremental addition made to the metropolitan city - every tick of the urban clock - is today scrutinized by planning officials, which decide on its viability at the light of existing planning instruments, policy directives and current disciplinary knowledge. Each of these administrative decisions, on each of those urban development initiatives, ought to be seen as an opportunity to foster urban order and not as a distasteful obligation to consecrate urban disorder.

The mind-set and the intentions of private urban developers are straightforward: they aim simply at maximizing the profitability of their investments, in one way or the other. They are, quite understandably, oblivious to collective goals. That is exactly why urban planning exists and is necessary. However, private developers do want their projects to be approved and supported by public agencies. It is the role of public agencies to know what to consider desirable or avoidable types of physical development. In fact, the current Portuguese general law on building-construction[143] regulates

[143] The *Regulamento Geral das Edificações Urbanas* (general regulations for urban edifications) - RGEU - is the Portuguese Law that establishes the general spatial, geometrical and functional requirements for civil buildings and for their aggregation in urban areas. These regulations have, of course, a strong morphological content, regarding the definition of minimal areas, heights and distances between buildings. However, the Law was published in 1952, albeit revised several times since then, so is rather anachronical in what concerns contemporary metropolitan morphologies.

many morphological aspects of urbanization, even if in a relatively elementary way. Also, municipal master plans - the core instrument of the Portuguese planning system - can (and sometimes do) include morphological guidelines and regulations for new urbanization operations. Only these are apparently ineffective; or, perhaps more precisely, they are aimed at aspects of urban form that are either irrelevant or non-sufficient conditions for guaranteeing the emergence of structured urban areas. But of course, unlike existing built structures current laws and planning instruments may be easily adapted, retrofitted or even discarded.

It seems clear, therefore, that a much more substantive knowledge about contemporary metropolitan typomorphologies - down to the level of the individual urban operations - is urgently needed, in order to provide planning agencies, practioners and researchers, with up-to-date morphological descriptions of the actual urban materials (Kropf 2005) they are dealing with. To do that, we need to *classify systematically* the physical and spatial genera under which contemporary metropolitan development occurs. In a nutshell, we need to be able to produce new, relevant and empirically-derived, contemporary metropolitan *typomorphologies*.

Typomorphology is the study of urban form derived from typical spaces and structures (Moudon 1994). It presumes the existence of certain morpho-structural similarities among the variety of existing built forms, which allow for their grouping into intrinsically distinct classes, or *types*. Under this definition, the type is an elemental object that embodies a morphological idea that has little or nothing to do with function, even if it is sometimes wrongly equated with it[144]. Indeed, buildings and cities are largely independent of their use at one certain moment in time and can shelter many different functions through history, while keeping their form generally intact. In this sense, the type may be seen as a morphological tool in the city-building 'tool-box', at each moment in time.

Urban typomorphological studies are important for two main reasons. First, they constitute a way for understanding the shape of cities and its evolution. They try to classify, i.e. to order into meaningful categories, the fundamental elements that construct the city at each moment in history and the basic physical and spatial relations that they establish between themselves. Secondly, typomorphological studies can also contribute to inform urban planning and design, whether as preliminary analytical procedures informing subsequent planning or design exercises, or as prescription instruments for the implementation of urban plans and policies concerning the physical and spatial structure of the city (Moudon 1989, 1994).

Indeed, to classify is to understand: when one divides a subject of study into meaningful categories, one may grasp order underneath the large diversity of individual phenomena. That is why systematic classification is also one of the fundamentals concerns of science, being absolutely critical in many disciplines, as chemistry, geology, biology, sociology or linguistics, to name just a few. Traditionally, this was achieved through laborious processes of trial and error, conducted by the gradual gathering of empirical evidence in each field of research, confirming or infirming previous classification schemes and eventually suggesting new ones. The main difficulty in such a process has always been the choosing of the relevant (or most discriminant) attributes and the definition of the least (or natural) number of classes that are able to describe the variability of the phenomena under study.

However, the development of high-speed computation had a profound impact on the methods and on the results of classification in many scientific fields. In particular, the computational implementation of unsupervised classification algorithms, in the late sixties and early seventies, allowed for the first time to classify many objects described by very large numbers of attributes. In some disciplines, notably in biology and in linguistics, this has led to true epistemological breakthroughs (Sokal 1966).

[144] Please note that here we are talking about pure morphological types and not spatial-centrality types, of the kind we have studied in the previous chapter and which have an important functional meaning.

But urban typomorphological classification has never attained the degree of rigor and systematization of biological taxonomy or structural linguistics. There are obvious reasons for this, since urban morphology is a recent field of scientific enquiry with a restricted research community, not comparable to those of other social sciences let alone those of the natural sciences. But there are also less obvious reasons. The problem seems rooted in the very definition of which morphological attributes to consider, in the degree of resolution of the desired classification, in the classification criteria themselves or even in the lack of consistency regarding the adopted terminology of types (Marshall 2005). One may also argue that the problem lays in the fact that objects of urban typomorphology are more difficult to define than, say, those of biological taxonomy (e.g. the difference between a plant and an animal) or of geology (e.g. the similitude in the constitution of two types of minerals), or still that urban form is perhaps an intrinsically ill-defined subject. But this seems only poor excuses not to push forward urban typomorphology into the realm of consistent classification, as it has happened in other disciplines which, in their beginnings, were perhaps little defined and not totally objective.

In fact, a recent paper by Gil, Beirão, Montenegro and Duarte (2012), which is a central reference in this chapter, proposes and demonstrates that the same numerical unsupervised classification techniques, used today in many scientific fields, may be also applied with great advantages to the morphological classification of urban forms. In addition, the same paper collates some of the shortcomings of traditional morphotypological analysis reported in the literature[145], which are worth of mentioning here. These include: the laborious and time-consuming nature of traditional analytical procedures, thus limited to small samples and to a few morphological dimensions; their relative opacity and subjectivity, relying mainly on the personal knowledge and ability of the analyst; their strong cultural and geographical context-dependency, thus not obviously applicable in other urban settings; and their subsequent questionable reproducibility or generalization (Gil et al. 2012).

Besides these generic limitations, other authors have yet noted the seemingly inadequacy (or, at least, the lack of application) of traditional morphotypological analysis in contemporary suburban and metropolitan contexts (Levy 1999, Stanilov 2004a), or even its irrelevance when faced with the explosive urbanization patterns of developing countries (Shane 2011). In fact, morphotypological analysis has been almost entirely dedicated to traditional or historical urban contexts, with only a few incursions into the contemporary urban periphery or on the metropolitan scale, some of which were reviewed in Chapter 1. Up till now, the very different morphology of these new urban territories and scales has eluded stringent morphotypological classifications.

In this chapter we will address all the above mentioned issues, through the morphological study and classification of the 4208 individual interventions made to Oporto's metropolitan spatial network, along the last 60 years. The objective will be the definition of a typomorphology of metropolitan incremental developments, based solely on geometric and topological quantifications of their street patterns. We will use simple but clearly-defined quantitative methods in order to separate large public interventions from the background of thousands of small, market-led urban developments. Next, we will use unsupervised classification algorithms to discover morphological regularities among that large number of incremental interventions, in order to produce a systematic typology of metropolitan forms. We will show that such morpho-types, derived exclusively from the quantification of the morphological attributes of those 4208 urban interventions, correspond to clearly different kinds of street layouts - thus to clearly different spatial morphologies - for which we provide semantic characterizations and designations. We will end by showing that the frequency of these morphotypes varies not only across time but also across space, implying the existence of significative temporal and spatial cleavages in city-building *praxis*, on Oporto's metropolitan region.

[145] Namely, in (Maller 1998, Grant 2001, Wineman et al. 2009, Conzen 2010, Osmond 2010).

6.2. COMPOSITIONAL AND CONFIGURATIONAL MORPHOLOGICAL VARIABLES

The main difficulty in any classification exercise is the choosing of the relevant attributes and the definition of the most parsimonious number of classes that are able to describe the variability of the phenomena under study. The latter issue can be tackled by the method we will propose in this chapter, but the former deserves some preliminary discussion.

One of the basic findings of urban morphology is the scale of resistance to change of urban form components. It is well known that the architectural superstructure changes quite often, that the structure of land-tenure is more resilient to change and that the open space system (mainly composed of streets) is the most perennial of all urban form components: once laid out it endures for very long periods of time, ultimately for millennia (Case-Sheer 2001; Whitehand 2001). Consequently, the street system may be taken as the most conditioning, and therefore the most determinant, of all elements of urban form: buildings and even plots may change endlessly, but the street layout is almost indelible.

These are acquired findings. And since streets are the most perennial and determinant of all elements of urban form, studying street patterns in order to define urban typomorphologies seems reasonable. However, pure typomorphological studies of street patterns and layouts, or at least taking street systems as main research objects, are surprisingly rare[146]. The patterns composed by streets are frequently conceived as a subsidiary part of urban tissues, or just as the negative of built forms, in figure-ground representations. They are acknowledged, but seldom analyzed and even more rarely quantified. There are some important exceptions, however. Several authors, as Michael Southworth and Peter Owens (1993), Anne Vernez-Moudon (1994, 2000), Brenda Case-Sheer (2001) or Stephen Wheeler (2008), have addressed the issue of street pattern typomorphologies in contemporary suburban and metropolitan contexts, providing semantic descriptions of the types they have found, as well as some basic quantifications of their morphological characteristics; but always seeing streets as parts of the more complex morphological notion of urban tissue (i.e. including also buildings and land-divisions). But in all these studies, even if the varying typomorphologies are characterized and elementarily quantified, they are also deduced only through visual methods. Thus, they are difficult to reproduce or to transpose to other geographical settings; and consequent annoying doubts on their substantiality are hard to dissipate completely.

The fact of traditional typomorphological analysis being overwhelmingly supported solely by visual observation methods[147] is perhaps its greatest frailty. Moreover, there are certain types of morphological order (e.g. the centrality structures we have explored in the previous chapter) that are simply not visually accessible. Any systematic, consistent and robust classification system should not be based solely on visual perceptions (even is these may prove necessary and useful), but rather in well-defined and non-subjective classification criteria.

In its groundbreaking book, "Streets and Patterns", (another fundamental reference of this chapter) Stephen Marshall (2005) provides perhaps the most proficuous effort to date, for solving the problems raised by the classification of street patterns. After extensively reviewing existing typologies stemming from diverse fields (from transports engineering to urban design), and noting patent inconsistencies in their terminologies (with similar terms referring to different morphological concepts, and vice-versa), the author introduces a basic distinction between *compositional* and

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[146] We refer here to morphotypological studies emanating from the process-typological and historical-geographical approaches to urban form, using Karl Kropf's (2009) classification, which are the traditional sources of urban typomorphological studies. However, even within the space syntax field (or configurational approach, according to Kropf), which is wholly dedicated to the study of street systems, typological classifications of street patterns are extremely scarce.

[147] "Visual observation" is not a pleonasm. Observation, in the scientific sense of the term, is the act of identifying and recording a phenomenon, which may be done by any means other than human visual perception.

configurational pattern descriptors (see Figure 23, Chapter 1, p.44). In his own words, "composition refers to absolute geometric layout, as represented in a scale plan, featuring absolute position, lengths, areas, [etc]. Configuration refers to topology, as represented on a graph, featuring links and nodes, their ordering, […] adjacency and connectivity." Op. Cit, p. 86. The author then shows how existing classifications are in fact mixtures and permutations of morphological characteristics falling into these two basic categories.

These may be seen, in fact, as the two basic quantitative descriptors of form: geometry and topology. Geometry describes the absolute composition of forms, ultimately in such a complete way that only *geometrically equal* shapes (i.e. whose superposition is perfect at all points) may be said to be similar. Geometry deals with sizes, lengths, widths and heights, relative positions (distances) and angles. It aims at describing integrally the metrical attributes of a given shape or space.

Topology, on its part, deals only with the *connectedness*, *continuity* and *boundary* of forms, while ignoring their sizes, areas or volumes, specific directional orientations, or any type of measurable distance within them. Topological properties are the deepest and most invariant morphological attributes of a shape or a space. Topology studies the properties that remain invariant under *continuous deformations*, i.e. deformations such as stretching and bending a given shape, but not as tearing it apart, or gluing one extremity with another. For instance, in topological terms, a square (or a cube) is equivalent to a circle (or a sphere): both separate the plane (or space) in two parts (inside and outside, which is the same to say that they have no holes), and both may be transformed into each other without any tearing of their boundaries: they are said to be topologically homeomorphic. However, an annulus (i.e. a region bounded by two concentric circles), or its tri-dimensional counterpart, a torus (i.e. a solid with the form of a doughnut) are very different from a circle or from a sphere, because they have holes (i.e. they have an interior, but they divide the exterior into two different regions) and may never be transformed into circles or spheres, without puncturing or tearing their boundaries.

It is clear that these two types of descriptions are saying quite different things, but that they may be both relevant in characterizing urban street patterns. One may measure thoroughly all the geometric properties of a given street layout and represent them accurately on a plan. However, such representation, even if depicting the exact shape of the layout, says little about its topology, e.g. about the number of possible routes between each of its streets or about the degree of connectivity or continuity of those streets. These are aspects that are undoubtedly different between a grid-like street pattern and a tree-like street pattern, with many culs-de-sacs. Conversely, we may know exactly the average connectivity of a given street layout and the exact number and type of its junctions, but this tells us almost nothing about its general geometric shape or about the total length of its streets. Thus, both geometrical and topological (or compositional and configurational) descriptions seem necessary, in order to fully discriminate relevant morphological aspects between potentially different types of street patterns.

We used this basic distinction between *compositional* and *configurational* descriptors of street patterns, in order to devise a set of morphological variables for characterizing the 4208 individual interventions made to Oporto's metropolitan spatial network over time. The values of these variables were semi-automatically calculated in GIS for each of the 4208 interventions, and subsequently used to classify them, using supervised and unsupervised classification methods. In order to describe each of these variables we will make use of two hypothetical street layouts with quite different morphological properties, represented in Figure 126 (next page).

When an intervention is made to the metropolitan spatial network through the construction of a new set of streets, two types of characteristics are worth noting: the *internal* (or intrinsic) morphologic characteristics of the intervention (i.e. those that are defined solely by the set of new streets) and the *external* (or extrinsic) morphological characteristics of the intervention (i.e. those that are defined by the new streets and by the existing ones, with which they relate or connect to). In Figure 126, the hypothetical existing grid is represented by thick, black dashed lines; and the newly built streets of the two interventions, by thin black lines (representing axial lines) and by thick light-grey segments (representing axial segments). Thus, we will be looking at compositional and configurational attributes of each intervention, both at the *internal* level (i.e. concerning only the intervention itself) and at the *external* level (i.e. concerning the relations that each interventions establishes with the existing grid).

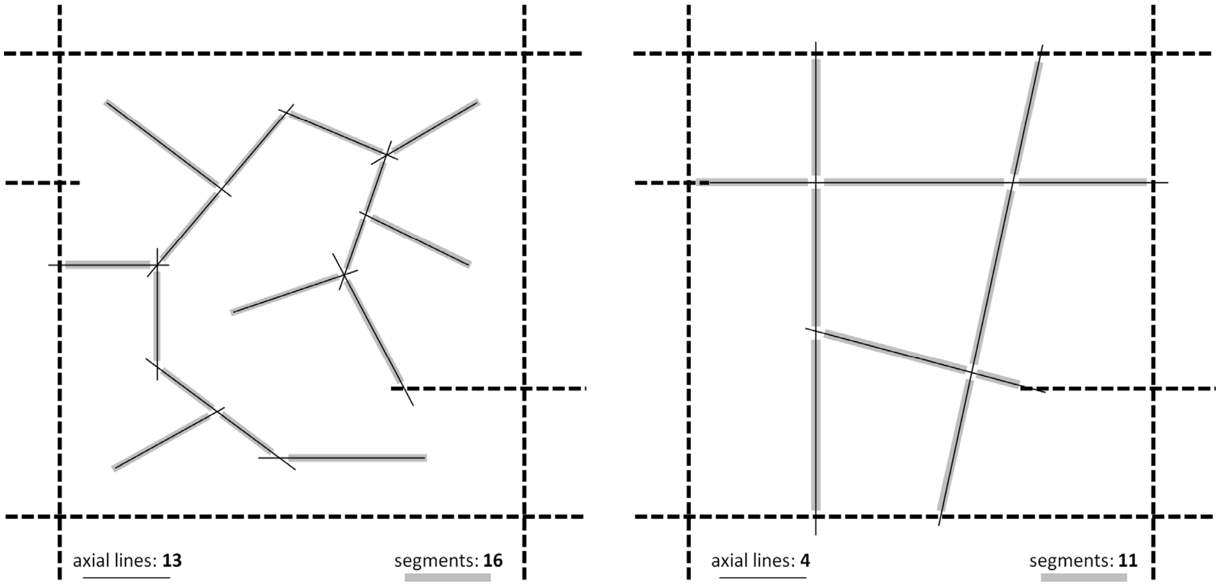

Fig. 126 – Two hypothetical urban development interventions (thin black lines and thick grey line-segments) and their immediate surrounding existent grids (thick black dashed lines).

By looking at Figure 126, it is possible to see that the simple count of the number of axial lines and segments making up each intervention is already a basic description of its morphology. The interventions of Figure 126 have approximately equal sizes (the one on the left is 8% larger), as defined by their road-lengths (the intervention on the left has a length of 35.2 and the one on the right 32.5; values in arbitrary but equal units). However, the intervention on the left has much more axial lines than the one on the right (13 and 4 respectively, thus more than the triple); whereas the difference in the number of segments is much smaller (16 and 11 respectively, a difference of approximately one third).

This happens because the intervention on the left is much more sinuous and curvilinear than the one on the right and has a greater number of internal street junctions (6), while the one on the right has slightly fewer internal junctions (4) but is much more linear and grid-like. However, the number of street-segments between junctions in both cases is similar. We see then, that the simple relation between the number of axial lines and segments composing each intervention is already providing some basic information about their geometry or composition. Another compositional variable immediately accountable for in Figure 126 is the total road-length of each intervention, which is directly related with their sizes (which are approximately equal, in this case).

Figure 127 (next page) shows the same two hypothetical interventions, but now with all the proposed morphological variables accounted for, and with the properties they measure graphically depicted. We have 5 compositional variables, namely: the total road-length of the intervention ("road_len", in Figure 126); the number of axial lines ("ax_count"); the number of axial segments ("seg_count"); the ratio between the number of segments and axial lines ("seg_ax"); and the compactness of the internal blocks (if present) created by the intervention ("iCyc_APR"). All these compositional variables represent internal morphological properties.

In addition, we have 6 types of configurational attributes, divided into 9 independent variables, namely: the number of internal blocks created by the intervention ("int_Cyc"); the number of new sub-divisions of existing blocks created by the intervention ("ext_Cyc"); the ratio between the number of axial lines and the number of junctions (or links) the intervention has with the existing grid ("ax_ExtL"); the number of culs-de-sac, or dead-ends ("d_End"); the type and number of internal junctions ("int_T", "int_X"); and the type and number of external junctions ("ext_T", "ext_X", "ext_I"). Thus, some configurational variables represent internal morphological properties, while others are aimed at the external relations that each intervention establishes with the existing grid.

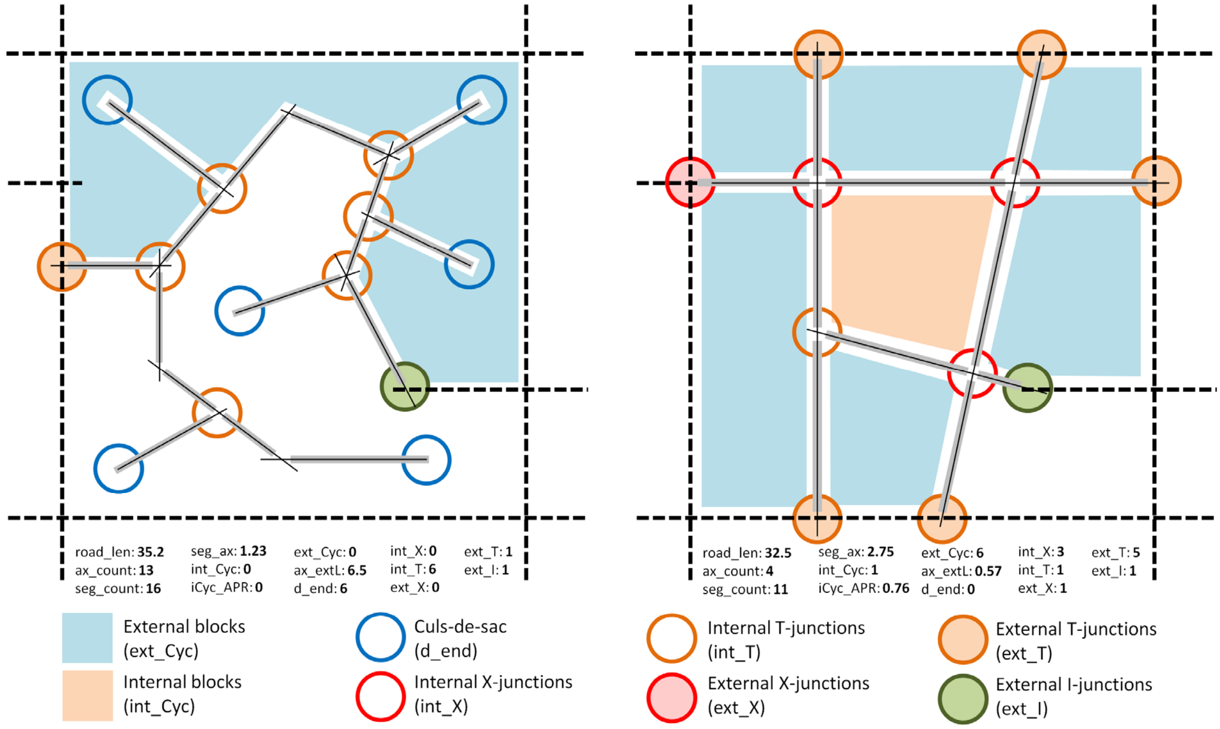

Fig. 127 – Graphical and numerical illustration of the compositional and configurational variables.

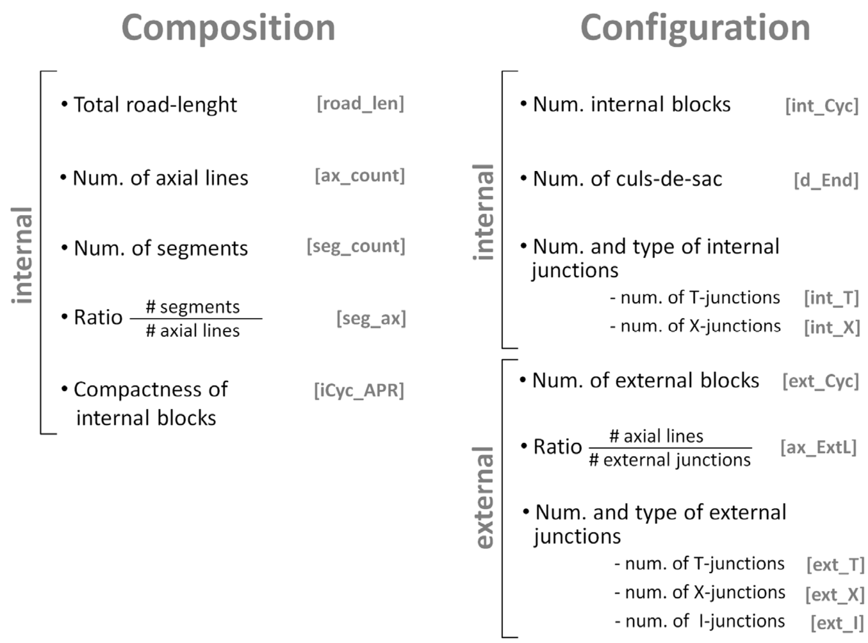

Fig. 128 – Summary of compositional and configurational variables.

In what follows, we will characterize each of these variables, detailing their descriptive purposes. We will refer to the information depicted in Figure 127, which serves as an illustration of the several compositional and topological attributes that each variable is aimed at describing. Figure 128 (previous page) summarizes all the variables, organizing them by their compositional or configurational nature and by the type of property (internal or external) which they describe.

- **Total road-length** [road_len]: the sum of the lengths (in meters) of all the axial segments in each intervention. This variable serves as a proxy of each intervention's size. In Figure 127, the two hypothetical interventions have similar sizes (35.2 and 32.5, in arbitrary units).
- **Number of axial lines** [ax_count]: the count of axial lines in each intervention. This variable serves as an indicator of the degree of linearity of an intervention; predominantly linear interventions have a smaller number of axial lines than predominantly sinuous interventions, of similar sizes and with a similar number of internal street junctions. In Figure 127, the intervention on the left (more sinuous) has 13 axial lines, whereas the one on the right (more linear) has 4.
- **Number of segments** [seg_count]: the count of axial segments in each intervention. When different from the number of axial lines, this variable is an indicator of an intervention's internal connectivity, i.e. of the presence of more or less of internal street junctions (see below). In Figure 127, even if the number of axial lines of each intervention differs significatively (13 and 4), the number of axial segments is much more close (16 and 11) because they have a similar number of internal street junctions (6 and 4).
- **Ratio between the number of segments and axial lines** [seg_ax]: the number of axial segments as a proportion of the number of axial lines. If the intervention has no internal junctions (i.e. if the number of axial lines is equal to the number of segments), its value is 1. However, when internal junctions are present, its value is proportional to the degree of linearity of each intervention: high values ([seg_ax] > 1) indicate predominantly linear interventions (i.e. with more segments than axial lines); values close to 1 indicate predominantly sinuous interventions (i.e. with approximately the same number of segments and axial lines). In Figure 127, the intervention on the left (predominantly sinuous) has a value of [seg_ax] = 1.23, while the one on the right (predominantly linear) has a value of [seg_ax] = 2.75.
- **Compactness of internal blocks** [iCyc_APR]: This variable gives an indication of the compactness of the shape of internal blocks, if present (see below for the definition of internal blocks). It is given by the expression $4\pi A/P^2$, where A is the area and P the perimeter, yielding 1 for a circle (the most compact of all planar shapes). The variable is dimensionless and not affected by size. Square blocks have a value of [iCyc_APR] ≈ 0.79, while very irregular or thin, thread-like blocks (i.e. with low compactness) produce values close to 0. In Figure 127, the single internal block of the intervention on the right has a value of [iCyc_APR] ≈ 0.76.
- **Number of internal blocks** [int_Cyc]: Blocks are islands, or cells, of private space entirely surrounded by streets (or, more generically, by public space). In graph terms, they correspond to cycles, i.e. to rings of linked nodes, representing axial or lines or segments. The *internal blocks* of an intervention are those exclusively surrounded by axial lines or segments belonging to that intervention (i.e. blocks created only by the intervention itself). The number of internal blocks, [int_Cyc], is then the simple count of such features, when present. In Figure 127, only the intervention on the right has internal blocks (1 in that case), represented as a light-red polygon.
- **Number of culs-de-sac** [d_End]: Culs-de-sac are dead-end streets (or axial segments), i.e. streets which do not lead to any other street (or to any other axial segment). In graph terms they represent end-nodes, i.e. nodes without successors or "child nodes", literally end points of the graph. The number of culs-de-sac of an intervention is the simple count of such features, when present. In

Figure 127, only the intervention on the left has culs-de-sac (5 in that case), represented by blue circumferences.

- **Number of internal T-junctions** [int_T]: Internal T-junctions are junctions with three incident streets (or axial segments), belonging to the same intervention. The number of internal T-junctions [int_T] is the simple count of such junctions in each intervention, when present. In Figure 127, only the intervention on the left has internal T-junctions (6 in that case), represented by brown circumferences.
- **Number of internal X-junctions** [int_X]: Internal X-junctions are junctions with at least four incident street segments (or axial segments), belonging to the same intervention. The number of internal X-junctions [int_X] is the simple count of such junctions in each intervention, when present. X-junctions are commonly present in grid-like patterns. In Figure127, only the intervention on the right has internal X-junctions (4 in that case), represented by red circumferences.
- **Number of external blocks** [ext_Cyc]: External blocks are created by the sub-division of existing blocks by an intervention. Thus, they are by definition surrounded both by existing streets and by newly built streets. External blocks are created whenever an intervention has more than one linkage point to the existing grid. Hence, the presence of external blocks is a direct indicator of an intervention's external connectivity: the more external blocks an intervention has the more linkage points to the existing grid it creates. Like internal blocks, they correspond also to graph cycles, only in this case cycles made both by existing and by newly created nodes (i.e. axial lines or segments). The number of external blocks, [ext_Cyc], is equal to the count of such features in each intervention, minus 1 (in order to discount the already existing, and subsequently sub-divided, block). In Figure 127, both left and right interventions have external blocks (1 and 6, respectively), represented as light-blue polygons.
- **Ratio between the number of axial lines and external junctions** [ax_ExtL]: The number of an intervention's axial lines as a proportion of the total number of external links it has (which is equal to the sum of all external junctions, see below). This variable is a measure of the geometrical 'efficiency' of an intervention in creating external connections. It yields low values ([ax_ExtL] < 1) for interventions with more external connections than axial lines, which implies highly linear interventions intersecting several existing streets; and it yields high values ([ax_ExtL] > 1) for interventions with more axial lines than external connections, which implies sinuous interventions with just a few linkage points to the existing grid. In Figure 127, the intervention on the left has only two external connections for a total of 13 axial lines, whereas the intervention on the right creates 7 external connections with just 4 axial lines; accordingly, [ax_ExtL] = 6.5 for the left intervention and [ax_ExtL] = 0.57 for the right intervention.
- **Number of external T-junctions** [ext_T]: The number of T-junctions, or junctions with three incident street segments, that an intervention establishes with the existing grid; thus, junctions with at least one incident existing street segment. In Figure 127, the intervention on the left has 1 external T-junction and the one on the right has 6, represented by brown circles.
- **Number of external X-junctions** [ext_X]: The number of X-junctions, or junctions with four incident street segments, that an intervention establishes with the existing grid. The existence of external X-junctions usually implies the linear extension of existing streets, or at least of spatial continuities with existing streets. In Figure 127, the intervention on the left does not have external X-junctions but the one on the right has 1, represented by a red circle.
- **Number of external I-junctions** [ext_I]: External I-junctions are not street junctions in a strict sense, because they only have two incident street segments (one existent and another one belonging to the concerned intervention); but they represent a possible type of external link, in which an

existing dead-end street is continued by a street belonging to an intervention. In Figure 127, both interventions have one external I-junction, represented as green circles.

The values of all these morphological variables were computed in GIS for each of the 4208 interventions, using semi-automatic analytical procedures[148]. We will end this section with a brief description of these procedures; albeit rather dry and technical, they may be useful for anyone willing to apply the same methods. Moreover, such description also demonstrates that all our variables have an easy algorithmic translation and thus are clearly defined and may be applied in any other research or geographical contexts. Some variables may be seen as *primitives* and others as *derived*, in the sense that the latter are obtained from the former. We will only explain how to compute the values of primitive variables, as the values of derived variables (i.e. [seg_ax], [iCyc_APR] and [ax_ExtL]) are obtained by simple posterior calculations, for which the technical procedures should be obvious. At the end of the current section, Figure 129 (page 199) shows an excerpt of the interventions of $t_{[2,3]}$ with all their blocks and junctions identified and classified, in order to illustrate the output of the GIS methods described below.

- The **total road length** ([road_len]), the **number of axial lines** ([ax_count]) and **the number of axial segments** ([seg_count]) of each intervention, are obtained by aggregating (in GIS terms, by 'dissolving') two datasets, one with all interventions represented by individual axial lines and another by individual axial segments, according to their [**int_ID]** attribute (identifying each intervention's objects and created during the process of diachronic axial modelling, described in Chapter 1). This operation generates new aggregated features, while allowing simple statistic calculations of those features, namely the **count** of aggregated objects and the **length** of the resulting aggregated features. We thus obtain automatically the number of axial lines and axial segments in each intervention, as well as their total road length.
- Counting **internal** and **external blocks**. First, the entire segment networks of each t={2,3,4} (t=1 is omitted, because it has no interventions) are automatically transformed into three new *polygon datasets*[149]. This operation creates a polygon in each closed region, surrounded by axial segments. These polygons are actually *all the blocks* (or graph cycles) of the entire metropolitan spatial network, at each t={2,3,4}. Then, using three other datasets containing only the aggregated interventions of each $t_{[a,b]} \rightarrow a,b \in \{1,2,3,4\} : a < b$, *select by location* (once for each t={2,3,4}) only the polygons which have *at least one side* coincident with *at least one segment* of any of the aggregated interventions of each $t_{[a,b]}$. This operation selects only the polygons corresponding to all interventions' internal or external blocks, while ignoring all the polygons that do not touch any intervention (i.e. that are existent and non-modified blocks); the selected polygons are then exported to new datasets, one for each $t_{[a,b]}$. On those datasets, are selected (again by location, using the aggregated interventions of each $t_{[a,b]}$) only the polygons *that are completely surrounded* by interventions' segments *with the same intervention ID*: these correspond to **internal blocks**; a simple inversion of that selection yields all interventions' **external blocks**, including those that are external because they are completely surrounded by different interventions of the same $t_{[a,b]}$. Having thus identified all interventions' internal and external blocks from each $t_{[a,b]}$, their allocation to their correspondent interventions and subsequent count is a simple matter of *spatially joining* them with the interventions themselves (represented by their axial segments, aggregated accordingly to each intervention's ID).

148 The way to achieve such computations in GIS was pointed to me by my dear friend and colleague Bardia Mashhoodi, to whom I owe the fact of not having lost months doing that through awfully dull manual methods.

149 In ESRI's ArcGIS 10, this is done with the 'feature to polygon' tool.

- Counting **internal** and **external junctions**. First, the entire segment networks of each t={2,3,4} are transformed into *network datasets*[150]. This is not done for network analysis purposes, but simply because that procedure creates a new dataset of points, in which a point is allocated at each segment intersection and at each segment tip. These points are then used to count and to characterize each intervention's street junctions and culs-de-sac. As a first step, the resulting points for each t={2,3,4} which *intersect any intervention's segment* from each $t_{[a,b]}$ are selected, and all the others are deleted. This reduces the initial points to junctions and culs-de-sac pertaining *only to network interventions*. Then, on the resulting datasets (one for each t={2,3,4}) we select by location the points *intersecting segments with [intervention ID] = 0* AND *[intervention ID] ≠ 0* (i.e. intersecting simultaneously the existing grid a segment of some intervention); we add to that selection any other point intersecting interventions' segments *with different [intervention ID]*. With that joint selection, we have isolated all the points corresponding to **external junctions,** including those that are external because they belong to two (or more) interventions of the same $t_{[a,b]}$. We then select all the points intersecting segments *with equal [intervention ID]*: those correspond to **internal junctions** and to **culs-de-sac**. With external and internal junctions thus identified, a spatial join operation is enough to count how many segments each point intersects, denoting the type (or the degree) of the junction. Thus, and regarding **external junctions**: a point intersecting four (or more) segments is an **external X-junction**, a point intersecting three segments is an **external T-junction** and a point intersecting two segments is an **external I-junction**. Regarding **internal junctions**: a point intersecting four (or more) segments is an **internal X-junction**, a point intersecting three segments is an **internal T-junction** and a point intersecting just one segment is a **cul-de-sac** (points intersecting two segments of the same intervention are not junctions and are discarded). Having all interventions' junctions (represented by points) classified as internal and external and by type (I, T, X or Cul-de-sac), their allocation to their correspondent interventions and subsequent count is a simple matter of *spatially joining* them with the interventions themselves (represented by their axial segments, aggregated by intervention ID).

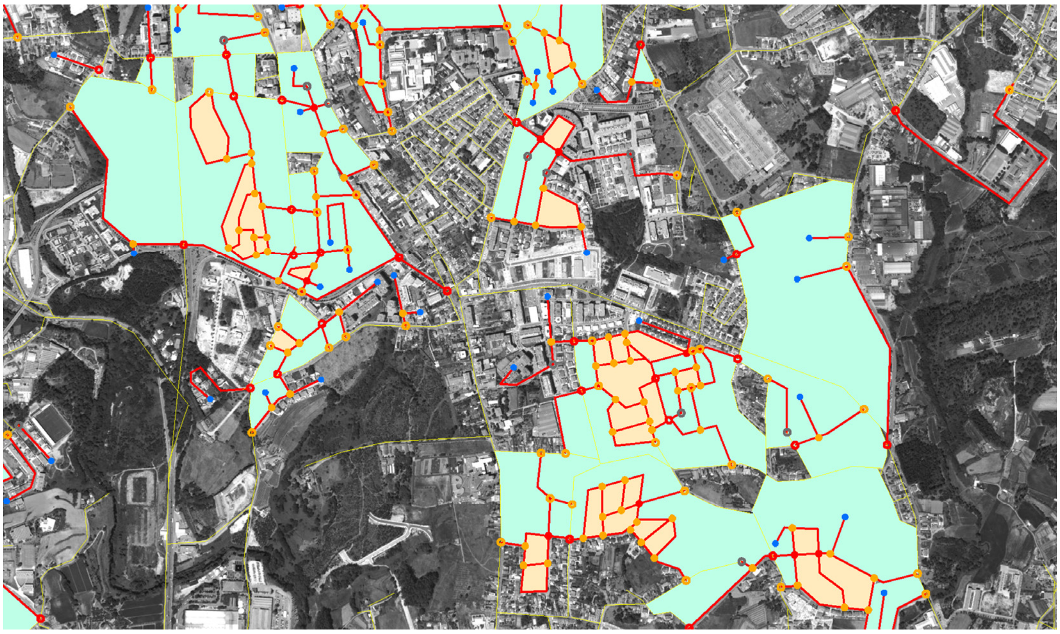

Fig. 129 – An excerpt of the interventions from t[2,3], with new blocks and junctions indentified and classified. The existing network is represented as yellow lines and the interventions as red lines; external blocks are represented as green polygons, internal blocks as yellow polygons; culs-de-sac are blue circles; external junctions are represented as circles and internal junctions as circumferences (red: X-junct.; orange: T-junct.; grey: I-junct).

[150] 'Network datasets' are a particular type of data structure, used in GIS to model geographical networks of any kind (street, rail, infrastructural networks, etc).

6.3. UNPACKING AND CLASSIFYING THE COMPONENTS OF METROPOLITAN SPATIAL GROWTH

Once the 4208 interventions characterized by their values on the variables described above, we can study their general morphology quantitatively and eventually classify them systematically. As mentioned earlier in Chapter 2, unsupervised classification methods have several previous data requirements, namely the absence of significative correlations among variables, the regularity of their scales and variance ranges and the absence of severe outliers in their distributions. All these conditions, if not respected, may lead to spurious and biased clustering solutions.

As a first step, we look at the bivariate correlations of all variables' values (Figure 130). If highly collinear variables are used in cluster analysis, specific aspects covered by these variables will be overrepresented in the clustering solution. In this regard, absolute correlations above r=0.90 are always problematic (Mooi, Sarstedt 2011). The correlation matrix on Figure 130 shows that our morphological variables are in general uncorrelated, with only a few exceptions (correlations above r=0.55 are flagged in red). The highest correlations (i.e. above r=0.85) occur among the first three compositional variables ([road_len], [ax_count] and [seg_count]). In particular, the correlation between [ax_count] and [seg_count] is maximal (r=0.953), showing that they are clearly redundant. Moreover, both variables show also strong correlations with the count of external blocks ([ext_Cyc], r=0.69 and r=0.802 respectively); [seg_count] is also significatively correlated with the count of internal and external T-junctions ([int_T] and [ext_T], r=0.578 and r=0.58 respectively). However, the ratio between these two quantities, [seg_ax], is not correlated with any of the other variables and thus may beneficially replace [ax_count] and [seg_coun]. The total road length of interventions ([road_len]), besides being highly correlated with [ax_count] and [seg_count], is also significatively correlated with the count of external blocks ([ext_cyc], r=0.878), but not with any other variable. Because this variable is a fundamental descriptor of the size of interventions, we will not discard it. But the same does not apply to [ax_count] and [seg_count], which may discarded with advantage.

Correlations

		road_len	ax_count	seg_count	seg_ax	iCyc_APR	ext_cycle	int_cycles	ax_ExtL	dead_end	int_X	int_T	ext_I	ext_T	ext_X
road_len	Pearson Correlation	1	,810**	,844**	,143**	,170**	,878**	,168**	,130**	,038*	,177**	,194**	,379**	,429**	,464**
	Sig. (2-tailed)		,000	,000	,000	,000	,000	,000	,000	,014	,000	,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
ax_count	Pearson Correlation	,810**	1	,953**	,066**	,377**	,690**	,437**	,422**	,203**	,378**	,532**	,353**	,497**	,365**
	Sig. (2-tailed)	,000		,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
seg_count	Pearson Correlation	,844**	,953**	1	,253**	,403**	,802**	,511**	,311**	,178**	,463**	,578**	,368**	,580**	,508**
	Sig. (2-tailed)	,000	,000		,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
seg_ax	Pearson Correlation	,143**	,066**	,253**	1	,103**	,392**	,112**	-,126**	-,037*	,138**	,142**	,100**	,405**	,485**
	Sig. (2-tailed)	,000	,000	,000		,000	,000	,000	,000	,018	,000	,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
iCyc_APR	Pearson Correlation	,170**	,377**	,403**	,103**	1	,120**	,622**	,355**	,064**	,359**	,605**	,047**	,189**	,100**
	Sig. (2-tailed)	,000	,000	,000	,000		,000	,000	,000	,000	,000	,000	,003	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
ext_cycle	Pearson Correlation	,878**	,690**	,802**	,392**	,120**	1	,090**	-,071**	-,099**	,158**	,161**	,403**	,603**	,700**
	Sig. (2-tailed)	,000	,000	,000	,000	,000		,000	,000	,000	,000	,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
int_cycles	Pearson Correlation	,168**	,437**	,511**	,112**	,622**	,090**	1	,359**	,110**	,677**	,808**	,021	,174**	,099**
	Sig. (2-tailed)	,000	,000	,000	,000	,000	,000		,000	,000	,000	,000	,164	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
ax_ExtL	Pearson Correlation	,130**	,422**	,311**	-,126**	,355**	-,071**	,359**	1	,460**	,199**	,390**	-,058**	-,181**	-,124**
	Sig. (2-tailed)	,000	,000	,000	,000	,000	,000	,000		,000	,000	,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
dead_end	Pearson Correlation	,038*	,203**	,178**	-,037*	,064**	-,099**	,110**	,460**	1	,220**	,291**	-,093**	-,106**	-,065**
	Sig. (2-tailed)	,014	,000	,000	,018	,000	,000	,000	,000		,000	,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
int_X	Pearson Correlation	,177**	,378**	,463**	,138**	,359**	,158**	,677**	,199**	,220**	1	,483**	,115**	,244**	,154**
	Sig. (2-tailed)	,000	,000	,000	,000	,000	,000	,000	,000	,000		,000	,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
int_T	Pearson Correlation	,194**	,532**	,578**	,142**	,605**	,161**	,808**	,390**	,291**	,483**	1	,109**	,296**	,139**
	Sig. (2-tailed)	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000		,000	,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
ext_I	Pearson Correlation	,379**	,353**	,368**	,100**	,047**	,403**	,021	-,058**	-,093**	,115**	,109**	1	,093**	,176**
	Sig. (2-tailed)	,000	,000	,000	,000	,003	,000	,164	,000	,000	,000	,000		,000	,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
ext_T	Pearson Correlation	,429**	,497**	,580**	,405**	,189**	,603**	,174**	-,181**	-,106**	,244**	,296**	,093**	1	,345**
	Sig. (2-tailed)	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000		,000
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208
ext_X	Pearson Correlation	,464**	,365**	,508**	,485**	,100**	,700**	,099**	-,124**	-,065**	,154**	,139**	,176**	,345**	1
	Sig. (2-tailed)	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	,000	
	N	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208	4208

**. Correlation is significant at the 0.01 level (2-tailed).

Fig. 130 – Bivariate correlations' matrix.

Leaving out these two obviously redundant variables, we get rid of most of the highest correlations (flagged by light-red rectangles, in Figure 130). The remaining significative correlations seem somewhat inevitable. The count of internal blocks ([int_cyc]) is correlated with the compactness of internal blocks ([iCyc_APR], r=0.622), with the count of internal T-junctions ([int_T], r=0.605) and of internal X-junctions ([int_X], r=0.808). But these correlations are easily explainable because non-zero values on these variables either depend on the existence of internal blocks in the first place, or are much more probable in interventions with internal blocks. For the same reason, the count of external blocks ([ext_cyc]) shows a significative correlation with the presence of external T-junctions ([ext_T], r=0.603) because external blocks occur only in interventions with at least two external links, which are most frequently T-junctions; and also with the total road length of interventions ([road_len], r=0.878), because the occurrence of external blocks is obviously more probable in long, large-sized interventions. However, it seems unreasonable to ignore the size of interventions, the count of internal and external blocks, as well as the count of street junctions by their type, just because these properties are bounded to occur simultaneously. In fact, their correlations are explainable by that fact and not because they truly represent similar things. We thus discard only the count of segment and axial lines ([seg_count] and [ax_count]) as dispensable variables, while keeping all the others. The remaining highest correlations are all below 0.7, except between [road_len] and [ext_cyc] (r=8.78), and between [int_cyc] and [int_T] (r=0.808); but these are explainable by the intrinsic spatial, geometric and topological constrains of street networks, as explained above.

Having screened the morphological variables by their bivariate correlations, we now turn to the inspection of their frequency distributions. Figure 131 shows the histograms of all variables as well as small box-plots, where the presence of outliers is easily ascertainable. All variables show extremely right-skewed distributions and thus all have countless positive outliers. Moreover, they also reveal quite different scales and ranges of variance (e.g. [road_len] varies within [0,47500], while [int_X] varies within [0,12]).

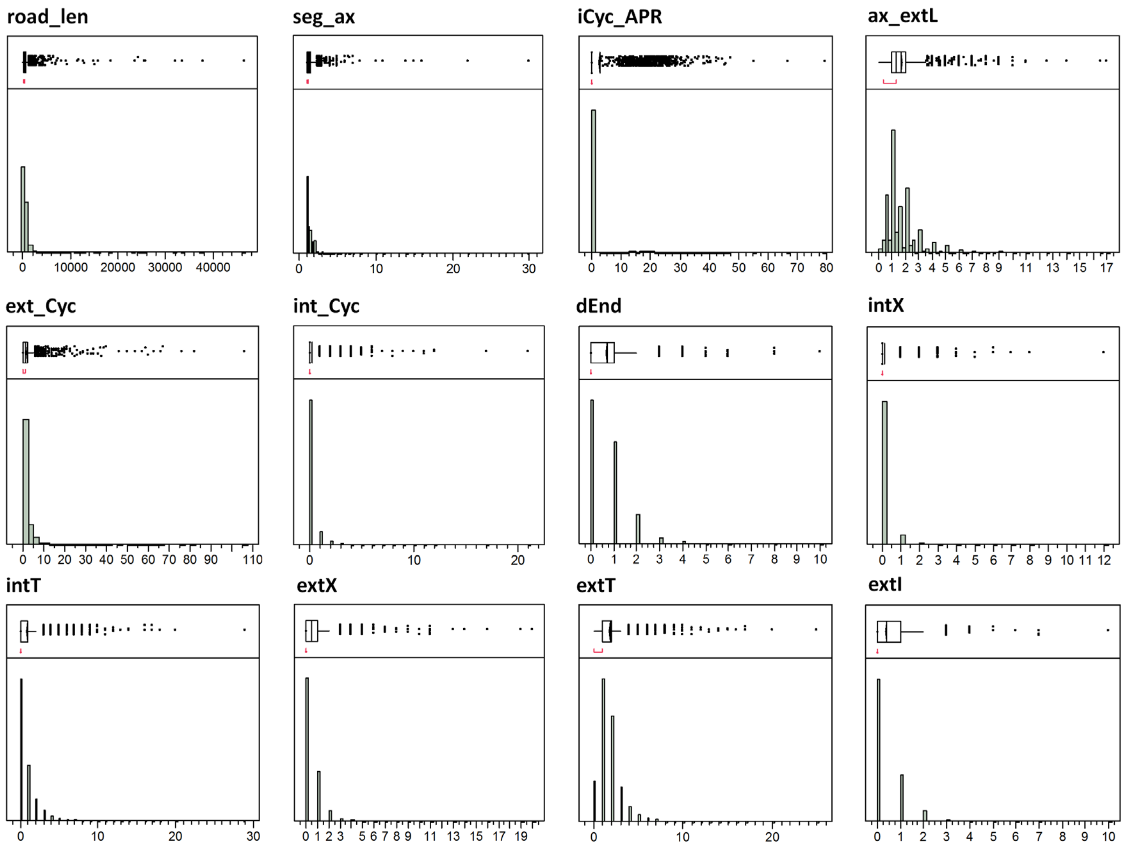

Fig. 131 – Distributions of the values of all morphological variables.

As mentioned before, these are both deleterious circumstances in data to be used for clustering. However, a simple logarithmic transformation of all variables' values is enough to stabilize their variances within similar ranges and to strongly reduce the number of positive outliers. Also, some of the previous distributions become normal (e.g. log[road_len]) or quasi-normal (e.g. log[ax_ExtL] or log[ext_T]). Figure 132 shows the variables' frequency distributions after such transformation.

However, there are three variables which continue to show abnormal and extremely right-skewed distributions, also with a still unacceptably large number of positive outliers (see Figure 132). We refer to the logged versions of the count and compacity of internal blocks (log[int_Cyc] and log[iCyc_APR]) and of the count of internal X-junctions (log[int_X]). In fact, more than being simply right-skewed, these variables seem to follow bi-modal distributions, characterized by an overwhelming frequency of zero values, followed by a long distribution of much less frequent, higher-than-zero values. In Figure 132, this is quite noticeable in the histograms of these variables (where the zero-peaks are flagged with red dashed ellipses) as well as in their box-plots, showing that all non-zero values on these variables are outliers (also flagged in Figure 132).

Now, what these three variables have in common is that they all describe properties pertaining to *internal blocks*; namely, the count and the geometry of internal blocks (i.e. [int_cyc] and [iCyc_APR]) and the count of a type of junction that typically occurs only when internal blocks are present (i.e. internal X-junctions, [int_x]). Thus, what the bi-modal distributions of these three variables seem to be revealing, is the existence of a *basic morphological divide* within the sample of all 4208 network interventions, which as to do with the *probability of occurrence* of network interventions *with internal blocks*. Interventions that create new urban blocks within their own street grids - and not just through the subdivision of previously existing blocks - seem to be extremely rare, at least when compared to the high frequency of interventions without internal blocks. In fact, the latter represent 88% of the entire sample of network interventions.

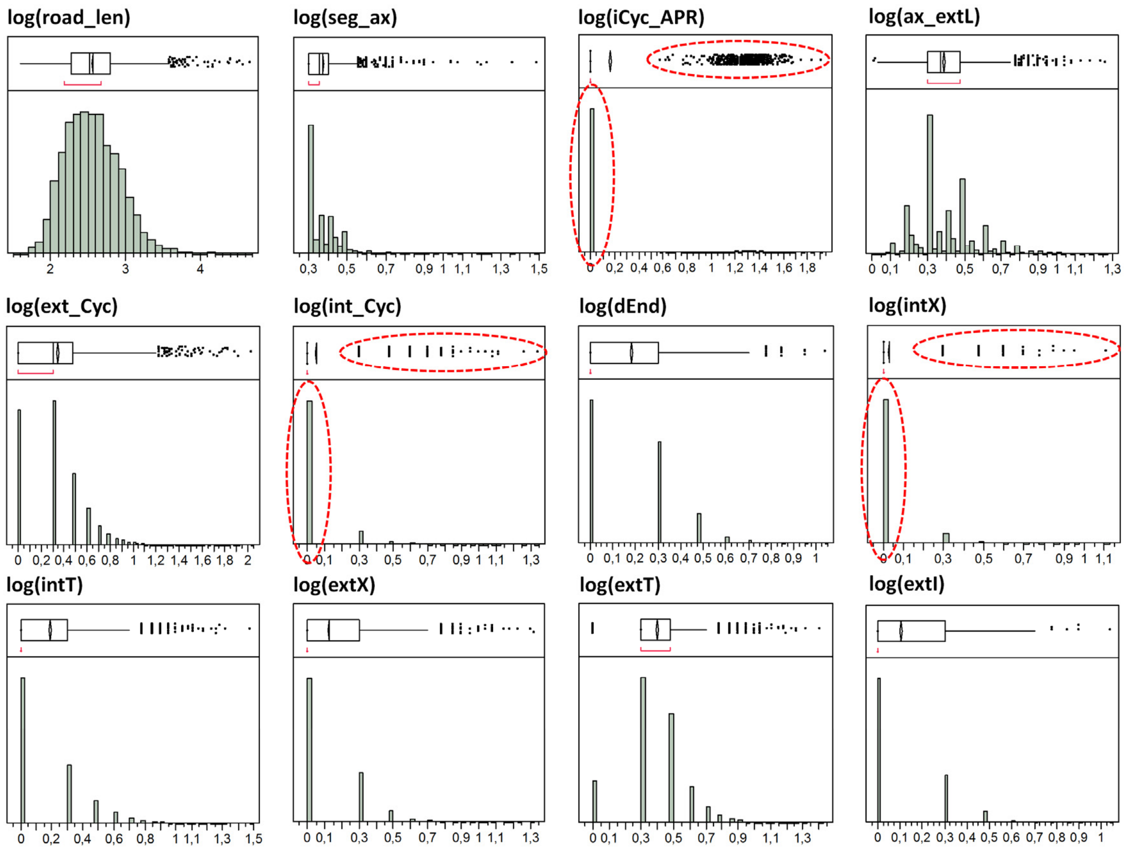

Fig. 132 – Distributions of the values of all morphological variables, after logarithmic transformation.

The very different frequencies of interventions with and without internal blocks may be partially explained by the larger average size of the former (mean road length 1142m) when compared to the latter (mean road length 424m). As interventions without internal blocks are (in average) smaller, they correspond (again, in average) to also smaller capital investments and thus are more frequently produced. However, the differential is so great that one can say that the creation of urban blocks entirely surrounded by new streets is truly exceptional; or, in other words, that the integral creation of new urban blocks is definitely not a common city-building *praxis* in the case under study. Therefore, it seems pointless to use automatic classification methods in order to differentiate things that are, right from the outset, obviously different. Moreover, the conflation of interventions with and without internal blocks biases the variables' distributions. Note that all variables have many positive outliers, but only those flagged in Figure 132 show such a profound difference in the frequencies of zero and non-zero values. A better option is to immediately separate interventions *with* and *without internal blocks* - to which we will call, henceforth, *cellular* and *linear* interventions[151] - and to investigate what happens to the variables' distributions. The results of that operation are eloquent (Figure 133).

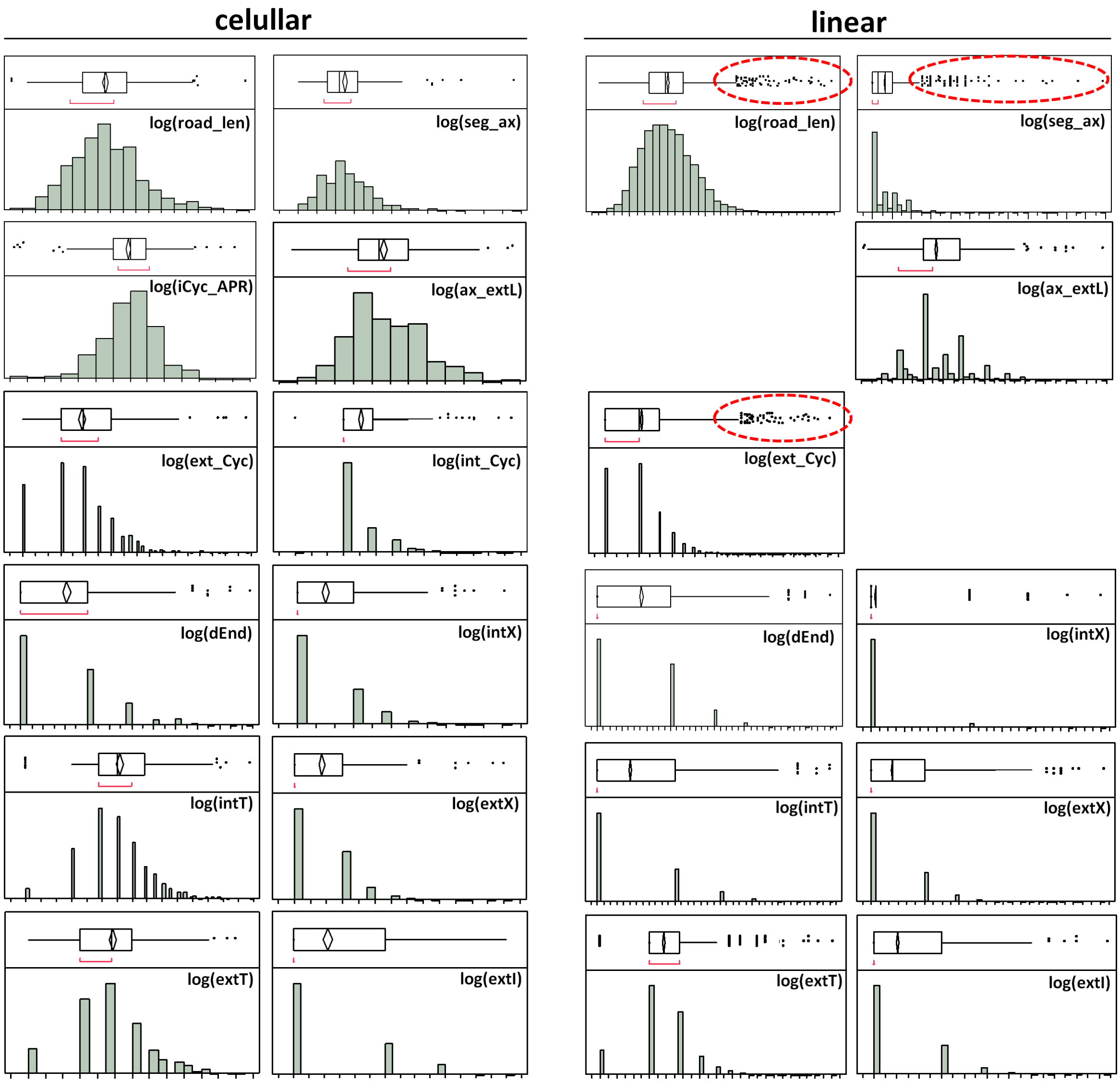

Fig. 133 – Distributions of the logged values of all variables, after dividing the interventions as cellular and linear

[151] *Cellular*, because their graphs have internal cells, or cycles; *linear*, because their graphs are acyclic, with linear branches that do not form closed paths. These terms are subsidiary of denominations of elemental patterns coined by Stephen Marshall (2005) in his book "Streets and Patterns".

Regarding the sub-set of *cellular interventions* (i.e. with internal blocks, on the left in Figure 133), corresponding only to 12% of the total sample, almost all distributions become normal and the number of outliers is drastically reduced. The same happens, albeit to a lesser extent, in the sub-set of *linear interventions* (i.e. without internal blocks, on the right in Figure 133), corresponding to 88% of the total sample. In particular, it is interesting to note how the distribution of internal X-junctions is different in the sets of cellular and linear interventions: in the first case, these are now much more frequent, confirming their predominant occurrence in cellular interventions; in the second case, they remain extremely sporadic, with just a few non-zero occurrences which remain severe outliers. We do not show the distributions of the variables describing internal blocks' properties (i.e. [int_cyc] and [iCyc_APR]) for linear interventions, because their values are all obviously zero

These results make clear that the initial separation of cellular and linear interventions is not only advisable for technical reasons relating to their posterior unsupervised classification. It also corresponds to a real morphological cleavage, identifiable empirically through the intrinsically different morphological characteristics and frequencies of occurrence of cellular and linear interventions, and therefore constitutes a first meaningful classification division. Figure 134 shows the spatial distributions of cellular and linear interventions on the study area.

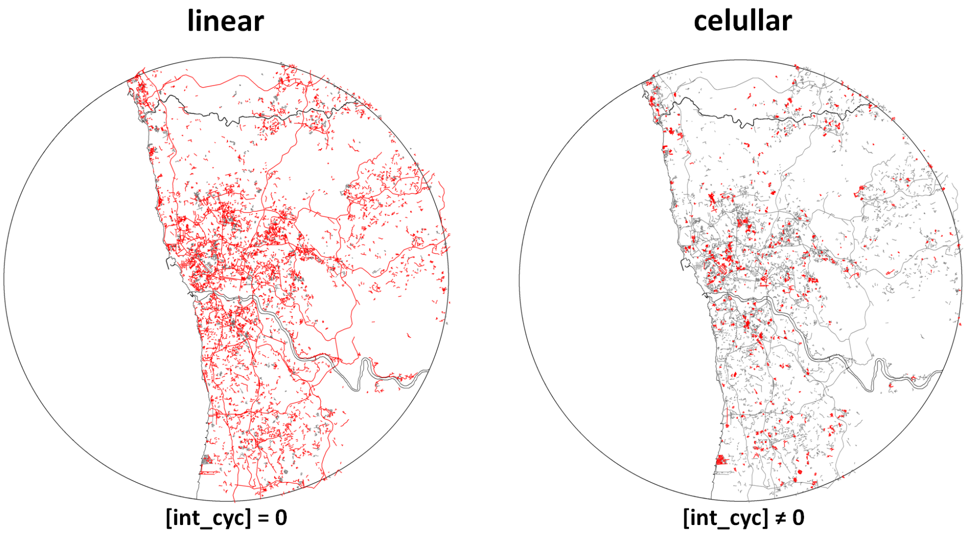

Fig. 134 – The spatial distributions of cellular and linear interventions.

This basic distinction between cellular and linear interventions explains (and eventually normalizes) some of the initial abnormal distributions, simultaneously eliminating many of their countless outliers. But there are still some variables showing a very large number of positive outliers, suggesting still more morphological cleavages in our sample of network interventions. In particular, it is noticeable in Figure 133 (previous page) that the sub-set of linear interventions continues to show an abnormal number of positive outliers on three variables: total road length ([road_len]), number of external blocks ([ext_cyc]) and the ratio between the number of segments and axial lines ([seg_ax]).

In fact, the visualization of these outliers reveals that they correspond to yet another different kind of network intervention. In order to study them, we compute the z-scores of the transformed variables, and visualize in GIS the interventions with z-scores higher than 2.55 on [road_len], [ext_cyc] and [seg_ax] (these variables do not have negative outliers); Figure 135 (next page) shows the result. This very simple procedure is enough to reveal another very significative conceptual and morphological divide. All linear interventions in these circumstances are *extremely long, planned public interventions*, including the entire metropolitan motor-way system and other regional roads (corresponding to [road_len] and [ext_cyc] outliers) and other sporadic major public interventions, creating long and very connective new urban streets (also present in the two previous variables, but especially corresponding to [seg_ax] outliers).

These are a very different kind of network interventions, not comparable to the myriad of incremental, non-planned and market-led interventions constituting the bulk of the observed metropolitan development. They are not just rare occurrences of very long new roads; they are also - and above all - the products of centrally-planed decisions, built in a non-incremental and forthright way. They should not be considered for the clustering procedure in any case, not only for technical reasons (i.e. for being statistical extreme cases) but also for conceptual reasons. These interventions are driven by very large financial resources, collective purposes and political voluntarisms, and thus are not incremental and spontaneous but suddenly built and thoroughly planned. However, the bulk of metropolitan growth (at least in the present case) is fundamentally spontaneous and emergent, produced by private agents acting at the micro-scale. Our objective in this chapter is to find underlying morphological regularities among that non-planed, market-led segment of metropolitan spatial growth.

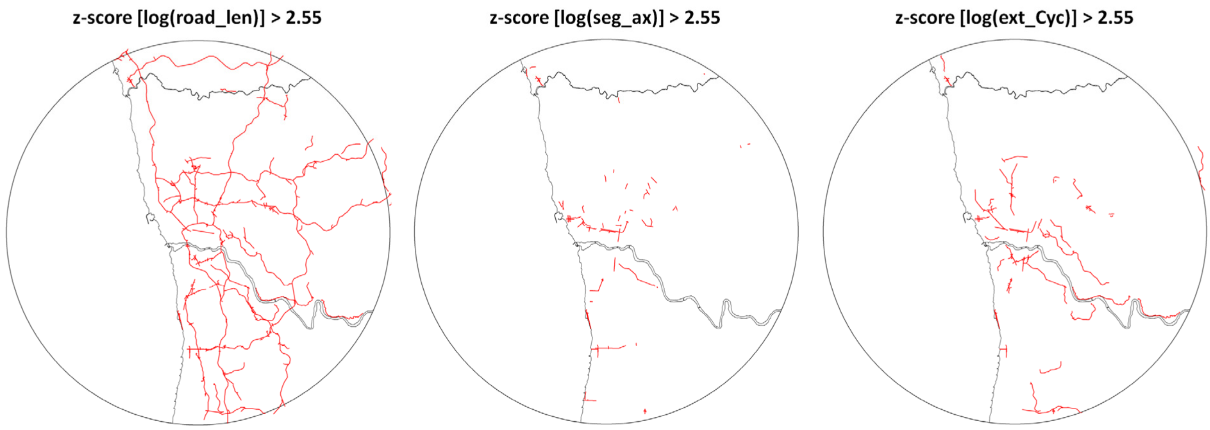

Fig. 135 – Linear interventions with outlier values on log(road_len), log(seg_ax) and log(ext_cyc) variables.

Of course, we cannot claim to have identified all public interventions made to the metropolitan spatial network with such a simple method. Surely there must be many others, which are not outliers in any of our morphological variables. The point here is not exactly to distinguish which interventions are of public or private promotion, but rather which are planned and non-planned; i.e. to ensure that interventions involving such high levels of collective purposes, financial resources and territorial scope, unconceivable to private agents, are not mingled with the background of thousands of market-led, non-planned interventions, whose morphology we aim at exploring and classifying. There is no point in exploring the morphological differences between a new motor-way and a new small urban development with a couple of streets, because they are trivial: their sizes are enough to tell them apart. Thus, to select the interventions with z-score[log(road_len)] > 2.55 is enough to isolate the entire metropolitan motorway network. Linear interventions that are outliers on the variable describing the ratio between the number of segments and axial lines ([seg_ax]) are not so obviously interpretable, even if many of them are also outliers on the two other variables. Those are not motorways, but long and rectilinear new streets or road-stretches, creating many intersections with the surrounding grid (i.e. with many new segments and few axial lines, hence the high [seg_ax] values). This type of intervention is also neither incremental nor market-led, but planned and of public promotion. It corresponds to new important streets and roads not obviously associated with immediate building-construction, although entailing the sub-division of many existing blocks (hence the also high [ext_cyc] values), consequently interfering with many land-owners. This is of course not common in market-led urban developments, the reason why the large majority of all interventions have much lower [seg_ax] values; but it is exactly what happens when, by public or collective agency, new long streets or avenues are planned and constructed. Finally, the spaces corresponding to outliers in the variable describing the number of new external cycles ([ext_cyc]) are also in large part of the above mentioned type, but also long regional roads albeit not of the motorway type (i.e. allowing crossroads). Because they are considerably long (the large majority of these interventions are also outliers on the variable [road_len]), they create many new connections with the existing grid and thus many new external cycles. We therefore consider these three types of infrastructures as differentiated *a priori* as large, sporadic planned interventions, and will not include them in the clustering procedure.

In all the other variables, the remaining outliers correspond either to the same interventions depicted in Figure 135 (which are outliers on almost all variables) or simply to common cellular or linear interventions with marginally higher or lower values in any of the concerned variables. Positive cellular outliers are (in some rare cases) also distinctly public promotions, in the guise of large social housing projects or of clearly planned industrial compounds. But these are indeed very rare cases, of which we could identify with certainty only six exemplars. Moreover, there is no theoretical reason for not including them in the set of interventions to be classified by clustering, because they do not have incommensurably different morphological characteristics; they are just marginally different, with one or two morphological properties slightly exacerbated or diminished.

Once the interventions depicted in Figure 135 (N=146, 3%) are separated from the sub-set of linear interventions (N=3560, 85%), the number of outlier values in all variables is reduced to an acceptable level. But before proceeding with the unsupervised classification of the remaining interventions (N=4062, 97%), we should stress that the simple analysis of the distributions of the proposed variables, was already capable of identifying basic morphological cleavages in our sample of metropolitan network interventions (Figure 136), which may constitute the initial super-classes of a systematic classification.

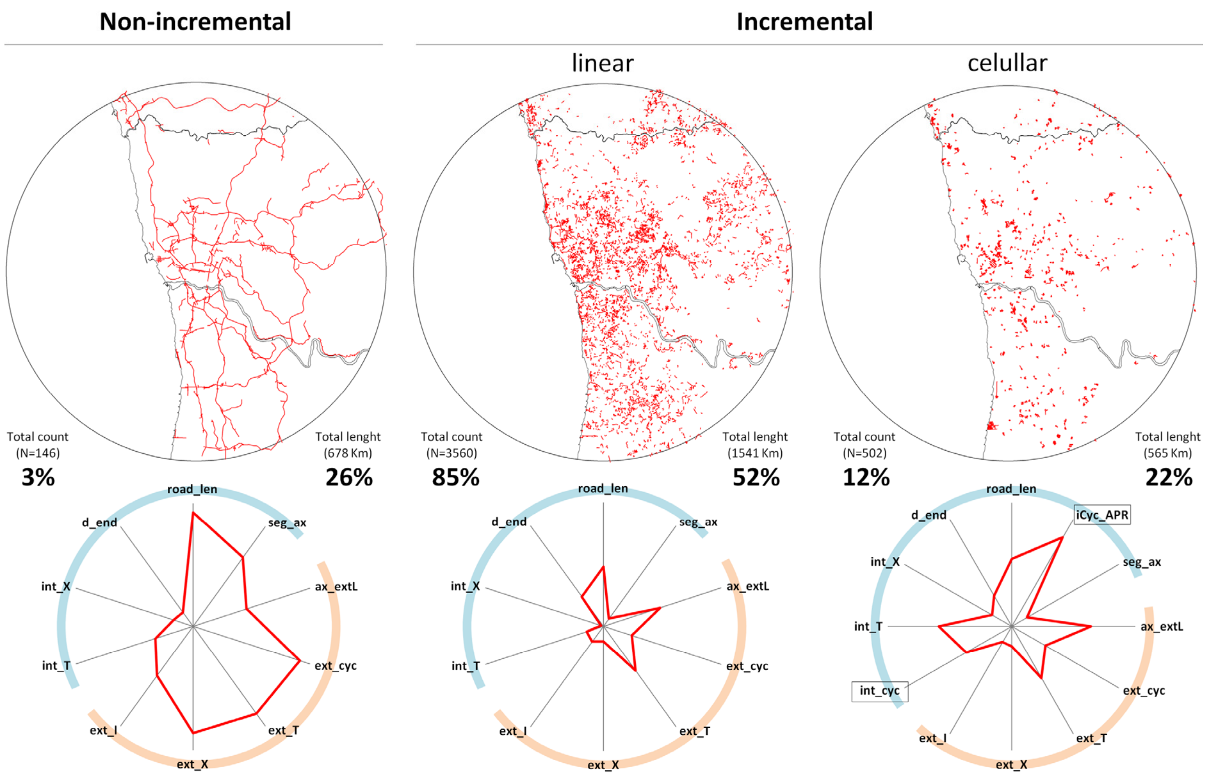

Fig. 136 – Non-incremental and incremental linear and cellular interventions: spatial distributions (above) and average profile on all morphological dimensions (below); the variables describing internal properties are flagged in blue on the radar-plots, and those describing external properties in yellow (cellular interventions are described by two more dimensions pertaining to internal blocks, [int_cyc] and [iCyc_APR], also flagged on the radar-plot).

The sample may be divided into *non-incremental interventions* - sporadic (3%), very long and/or extremely connective interventions, with clear collective purposes, planned and coordinated at the national or municipal levels and built in a single time-interval $t_{[a,b]}$; and into *incremental interventions* - very frequent (97%) and much smaller interventions, which are overwhelmingly non-planned private initiatives, urbanizing the metropolitan territory in an incremental and non-coordinated way. These incremental interventions have previously shown to be also divisible into two different classes, of very different frequencies and morphological characteristics: *linear interventions* - the most frequent type of intervention (85%), with smaller street layouts that do not form internal urban blocks (i.e. their graphs have no cycles), but that commonly lead to the sub-division of existing blocks, thus to the creation of new cycles in the metropolitan spatial network; and *cellular interventions* - larger and much less frequent (12%), whose street layouts form internal blocks and thus are more complex and interconnected, while also commonly sub-dividing existing blocks. The different spatial distributions and frequencies of these classes are summarized in Figure 136, as well as their profiles, i.e. their mean values on all morphological dimensions (represented on radar-plots). The shares of each class (i.e. the proportion of the total sample that each class represents) are also indicated on Figure 136, as percentages regarding the count of interventions in each class and the total road-length they represent.

The very different morphological nature of these three super-classes is evident on their profiles (with equal scales), depicting their mean values (standardized between [0,1]) on all morphological variables. *Non-incremental interventions* are much larger than the others (very high [road_len]), tending to geometrical straightness and linearity (high [seg_ax]), very connective externally (high values on all external junctions and [ext_cyc]) but with simple internal structures (relatively low values on all internal variables, except [road_len]); the occurrence of external X-junctions is high, which suggests the creation of continuities with existing streets in this type of intervention. *Linear incremental interventions* are the smallest (minimum [road_len]) and have reduced values on all variables; externally, they are moderately connective, but internally they are virtually devoid of any structure (very low values on internal junctions); however, they have the maximum average number of culs-de-sac per intervention (maximal [d_end]). *Cellular incremental interventions* are in average larger, also moderately connective in external terms, but with richer internal structures; they have internal blocks ([int_cyc]), which are in general geometrically regular (high [iCyc_APR]) and also many more internal junctions, on average. However, the number of internal X-junctions ([int_x]) is low which suggests, together with the also low [seg_ax] values, that grid-like cellular layouts are very rare. Unlike non-incremental interventions, both linear and cellular incremental interventions have very few external X-junctions, indicating that they seldom create spatial continuities with existing streets.

The shares of each super-class are also quite revealing, especially when the count shares (i.e. the number of interventions in each class as a percentage of their total number) and the road-length shares (i.e. the sum of interventions' lengths in each class as a percentage of total road-length built) are compared. *Non-incremental interventions* represent only 3% (N=146) of the total number of interventions (N=4208), but they account for more than a fourth (26%, 678 Km) of the total length of roads constructed (2784 Km); thus, they are very sporadic but their impact must be huge. In contrast, *linear incremental interventions* are overwhelming prevalent (N=3560, 85%) but they account for just over half (52%, 1541 Km) of the total length of new roads; thus, they are very frequent but their individual impacts must be marginal. While cellular incremental interventions, much less frequent (12%, N=502), turn out to represent more than 20 % (565 Km) of length of new roads; thus they are not so frequent, but their individual impacts should not be negligible.

These two subsets of linear and incremental interventions were selected as objects of the subsequent unsupervised classification exercise. We used the same technique described in Chapter 3, so we will not delve its technical details now. However, there are some methodological options regarding the following clustering procedure that we should be state at the onset.

We opted for classifying all incremental interventions together, independently of their period of construction. Only after their simultaneous classification would they be analysed by time interval $t_{[a,b]}$. This option implies that the moment of construction is not taken into account in the definition of the clusters eventually to be found. Firstly, this guarantees that the consistency of our classification will not be affected by eventual different morphological frequencies in different temporal moments (e.g. if a certain morphological type is much less present at a certain time, it might not be detected). Secondly, the obtained classification will be more robust, because we will be using a single, large dataset of metropolitan interventions, instead of the smaller and size-variable datasets of each time interval $t_{[a,b]}$. And thirdly, it also allows the posterior investigation of potential variations in the frequency of clusters over time and space, eventually revealing potential temporal and/or spatial shifts, corresponding to time or space-dependent trends of the city-building *praxis*. The potential drawback of such methodological option is that it may also imply the forcing of artificial time-independent regularities in our data. But we have taken some precautions for controlling and avoiding this possibility, described below.

A second basic option was to use the k-means algorithm as the main clustering procedure, even if the size of our sample now allows the use of hierarchical clustering methods (commonly preferred, when the size of datasets is small). The reason for this is that the k-means algorithm is *prototype-based*, i.e. it is based in the search of *K* representative prototypes of *K* potential clusters in a dataset (Tan et al. 2005). These prototypes, in fact the centroids of the clusters to be found, constitute the points in the space of variables where the multivariate property described by each cluster is better represented on all dimensions. Thus the object closer to each cluster's centroid may be seen as the *archetype* of that cluster. This is obviously useful because our aim is to discover and eventually define morphological types, which may then be illustrated by a real example, namely each type's archetype.

However, as mentioned in Chapter 5, the K-means algorithm is very sensitive to the initial definition of the *K* centroids and also to the presence of outliers, whose effects are mainly concerned with spurious attractions or repulsions they may impend on the movement of the centroids across the space of variables (Tan et al. 2005). But this difficulty may be avoided if the initial centroids are judiciously defined. In order to achieve this we used the same method described in Chapter 5, namely the initial definition of the centroids' positions through the use of a hierarchical clustering method, in this case Ward's minimum variance method. Only now, instead of using a reduced sample like we did in Chapter 5 (because then the involved datasets were too large) we used the *entire* sample of network interventions, but only after removing *all variables' outliers* (positive and negative).

Once the initial centroids thus rigorously defined, we used them to cluster with *K*-means *all* incremental interventions, including the outliers removed before (except of course those corresponding to incremental interventions). Because the remaining outliers are not many and not severe, and because the initial centroids were defined without their presence, we may be fairly sure that they will not affect the *K*-means solution. Additionally, this first step also allowed inspecting the behavior of potential clustering solutions on the subsets of the interventions of each time interval $t_{[a,b]}$. Figure 137 (next page) shows the dendrograms resulting from the hierarchical clustering of all linear and cellular interventions (excluding all outliers) and also of the sub-sets of linear and cellular interventions occurring at each $t_{[a,b]}$. For both time-independent sub-sets (above, on Figure 137) a solution with four clusters seems very clear; but also for the sub-sets separated by time interval (below, on Figure 137). Four clusters are evident at all time intervals, except perhaps for linear interventions at $t_{[3,4]}$, which could be dived into three clusters. But the $t_{[3,4]}$ interval is the shortest and thus has also the smallest sub-sample of interventions. And the dendrogram shows that a solution with four clusters is also perfectly reasonable.

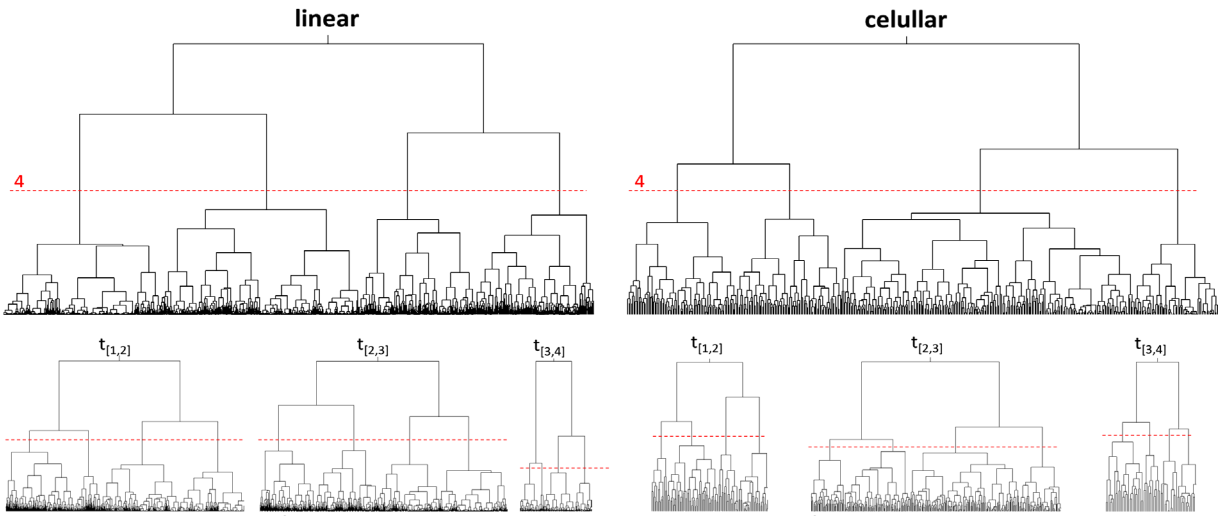

Fig. 137 – Dendrograms of all linear and cellular interventions (above) and of the same interventions separated by period of occurrence (below), using Ward's minimum variance method.

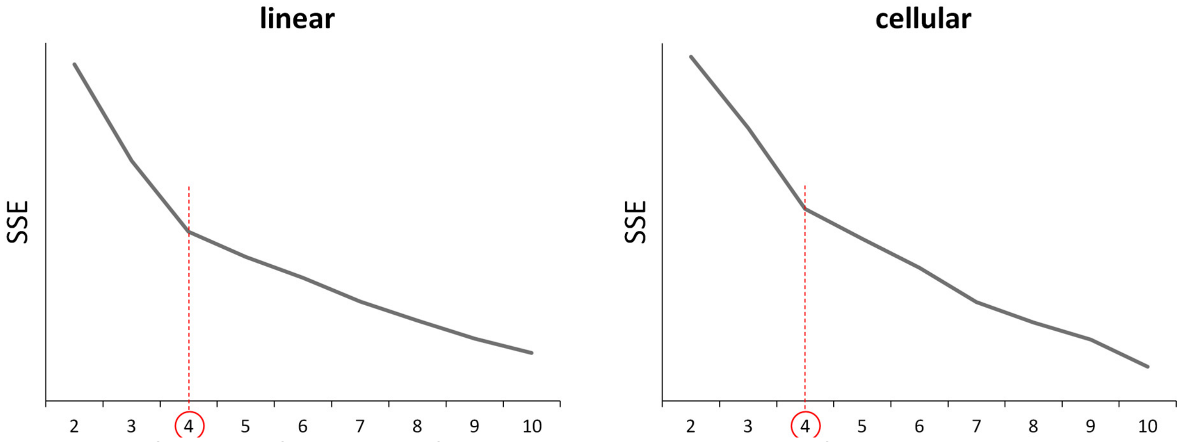

Fig. 138 – Scree plots for the range of 2 to10 K-means cluster solutions, of linear and cellular interventions.

Thus, a solution with four clusters both for linear and for cellular interventions seems quite stable through time. Notwithstanding this promising result, the centroids for a range of solutions (from 2 to10) were defined with Ward's method and subsequently used for clustering with K-means the linear and cellular interventions of all periods together (now *also* with the outliers removed before). Figure 138 shows two scree plots, depicting the evolution of the sum of squared errors along the range of studied solutions.

Again, the signal of two solutions with four clusters, both for linear and cellular interventions, is made evident through the significative reduction of the curves' slope beyond that point. Therefore, we extract four clusters for the linear and cellular sub-sets and add the resulting classifications to our GIS database of metropolitan network interventions, as two new attributes recording the cluster to which each intervention belongs. Figure 139 (next page) shows the profiles of these clusters on the several morphological dimensions, where one can easily state their different morphological natures. The most evident difference between clusters is *the size* of the interventions they gather (as expressed by [road_len]). Both in the cellular and linear sub-sets there are two clusters scoring low on [road_len] and two other scoring higher; thus, we may qualify the interventions in these clusters simply as *small* or *large*.

But the clusters also differ through the *external connectivity* of the interventions they gather; i.e. the relations those interventions establish with the existing grid, as expressed by the number of external junctions [ext_T, ext_X, ext_I], number of subdivisions of existing blocks [ext_cyc] and the ratio between the number of axial lines and external links [ax_extL] (on this variable low values indicate high external connectivity). Both in the linear and cellular sub-sets, we have two clusters with high external connectivity and two others with low (external variables are flagged in yellow on Figure 139).

Moreover, these different external connectivities are concomitant with also different *internal structures*, as expressed in particular by the by number of culs-de-sac ([d_end]), both in the linear and cellular sub-sets; but in the cellular case, also by the number of internal X_junctions ([int_X]) and by the shape of internal blocks ([icyc_APR], internal variables are flagged in blue on Figure 139). Both in the linear and cellular sub-sets, the two clusters with high external connectivity show also few culs-de-sac (and, in the cellular case, also more internal X-junctions and more regular internal blocks); and the two clusters with low external connectivity show also many culs-de-sac (and, in the cellular case, also few internal X-junctions and irregular internal blocks). Hence, besides the distinction between large and small interventions, our clusters are also distinguishing *conjunctive interventions* (i.e. with strong external connections and with few culs-de-sac) from *disjunctive interventions* (i.e. with weak external connections and with more culs-de-sac).

Something is *conjunctive* when it joins or unites other things; something is *disjunctive* when it serves for separating, or is incapable of uniting, other things. By *conjunctive interventions*, we mean those which, by virtue of the abovementioned connective properties, 'sew' the existing grid; i.e. they create new connections between existing streets and sub-divide existing blocks, enhancing the existing grid's connectivity. By *disjunctive interventions*, we mean those that, on the contrary, are linked to just one (or to very few) points of the existing grid, and thus do not create (or create very few) new connections between existing streets; i.e. they use the existing grid for their own 'irrigation' but they 'hang loosely' from it, without significatively changing its existent connectivity state.

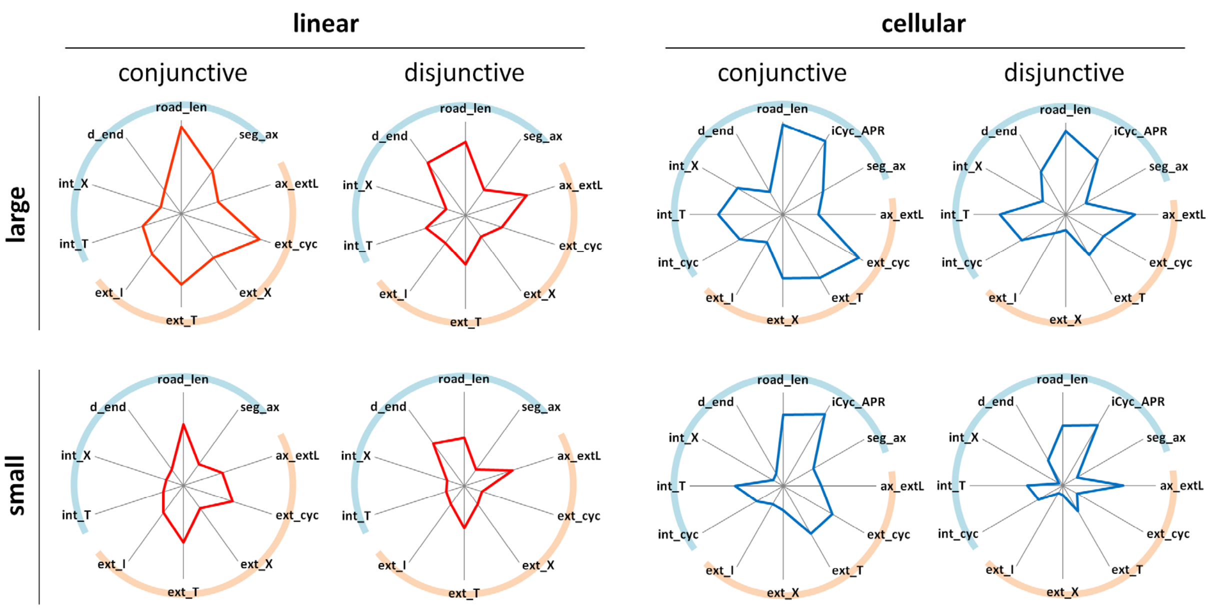

Fig. 139 – Profiles of the 8 clusters of linear and cellular interventions.

6.4. A TYPOMORPHOLOGY OF METROPOLITAN INCREMENTAL URBANIZATION

In this section we will try to demonstrate that the clusters defined before correspond to specific morphologies of street layouts and that the interventions in each cluster have a strong, temporal-independent, typomorphological consistency; in spite of obvious differences - yet superficial, we believe - between the built forms associated with them.

The spatial morphologies that these clusters and their archetypes describe are *elemental*. They are only distinguished by the presence or absence of internal blocks, by the size (i.e. the road-length) of the interventions and by very basic geometrical and topological characteristics of street layouts. Yet, such minimal parameters seem sufficient to encapsulate a high degree of morphological *regularity within variability*, graspable after a first glance[152]. Because they are elemental in nature, describing only baseline morphological properties, because they are empirically derived and because they pertain only to the patterns created by streets[153], they could easily be included in urban planning exercises, for instance as examples of desired or undesired street pattern morphologies, or even as benchmarks for assessing new proposals of urban development.

On the following pages, Figures 140 to 143, show all the clusters profiles together with an aerial photograph of their corresponding archetypes from each $t_{[a,b]}$. In pages 214 and 215, we provide semantic descriptions of the interventions gathered by each cluster, detailing the morphologic properties that each cluster represents. These descriptions serve as extended captions for Figures 140 to 143, in order to facilitate their reading and interpretation (the roman numerals in the descriptions' texts, refer to the actual values of the concerned variables, given in small font at the end of each description).

The street layouts on each of the following Figures are all different, but those pertaining to each cluster share a clear morphological 'family trait'. Their resemblances are visually graspable but not easy to seize in words. However, it is rather obvious that the archetypes of each cluster share the same sizes, the same geometric tendencies for more or less regularity and the same type and number of junctions. However, other morphological aspects apparent on the photographs vary a lot; for instance, the structure of land-parcels or the mass, form or architectonic style of the associated buildings.

A first obvious morphological regularity between the several clusters is that *large* or *small* interventions of the same *internal ciclicity* and *connectivity* types (i.e. the linear/cellular and conjunctive/disjunctive), clearly have the same characteristics modulated only by size. For example, *large linear disjunctive* interventions (Figure 141, left), share pretty much the same characteristics of *small linear disjunctive* interventions (Figure 141, right), only they are larger and thus all their morphological properties are augmented; i.e. both have few connections to the existing grid, both have many culs-de-sacs, both have none (or very few) internal X-junctions but several internal T-junctions, and thus both have dendritic, tree-like internal structures. The same remarks might be made about any other pair of clusters of the same connectivity type, with or without internal cycles. So we see that the clusters are indeed strongly discriminated by size, yet size alone does not exhaust their morphological specificity.

(Main text continues on page 218)

[152] This is, in part, facilitated by the graphic representation of junctions with coloured circles, but by no means caused only because of that. Moreover, such graphic representation corresponds to an actual topologic property of the street layouts, not just to a graphical artifact.

[153] In Portugal, the streets created by an urban development project become, at the end of construction, property of the Municipality where it occurs. Thus, municipal planning officials have particular prerogatives on that theme.

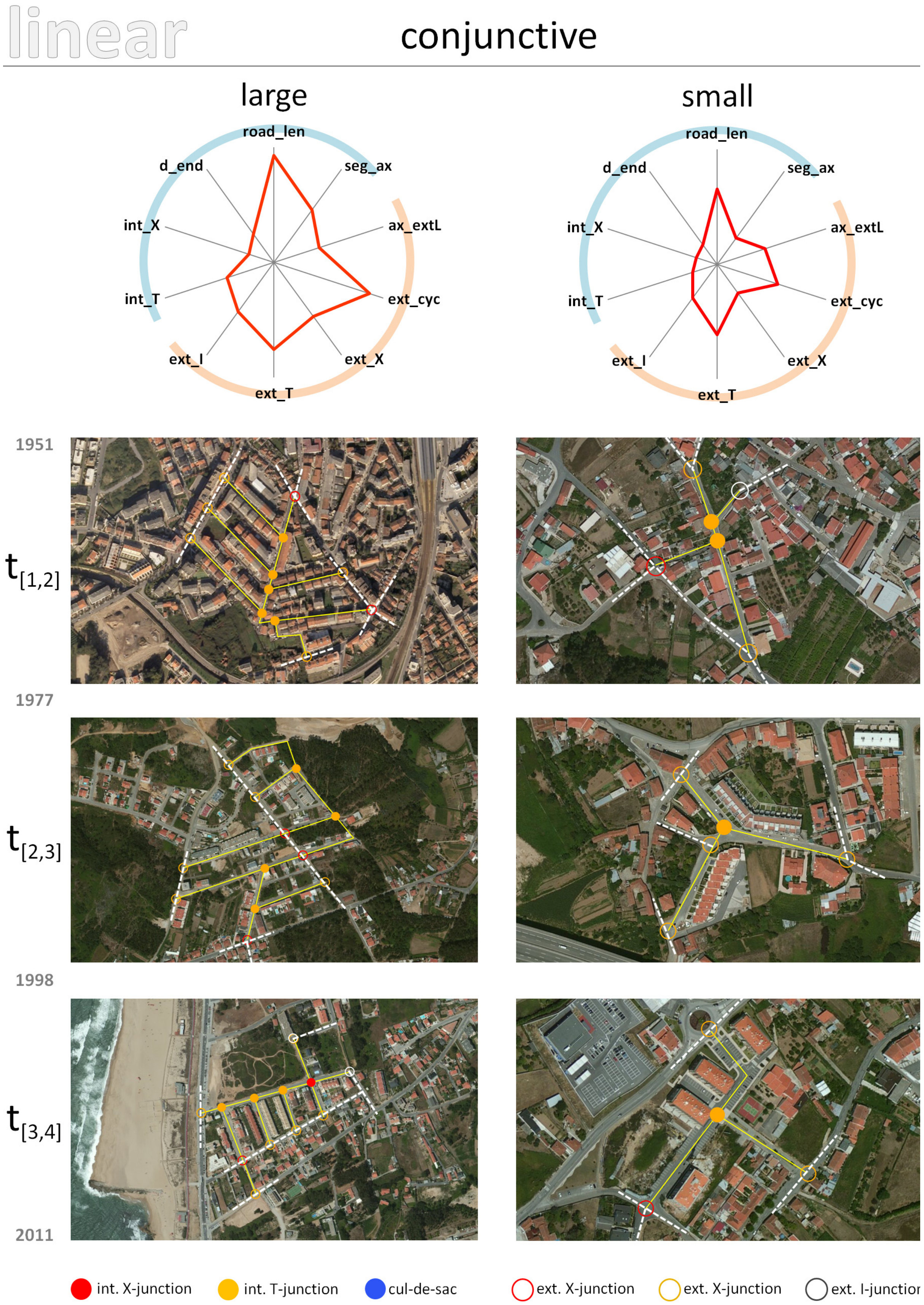

Fig. 140 – Archetypes of linear / conjunctive, large and small clusters, at each $t_{[a,b]}$.

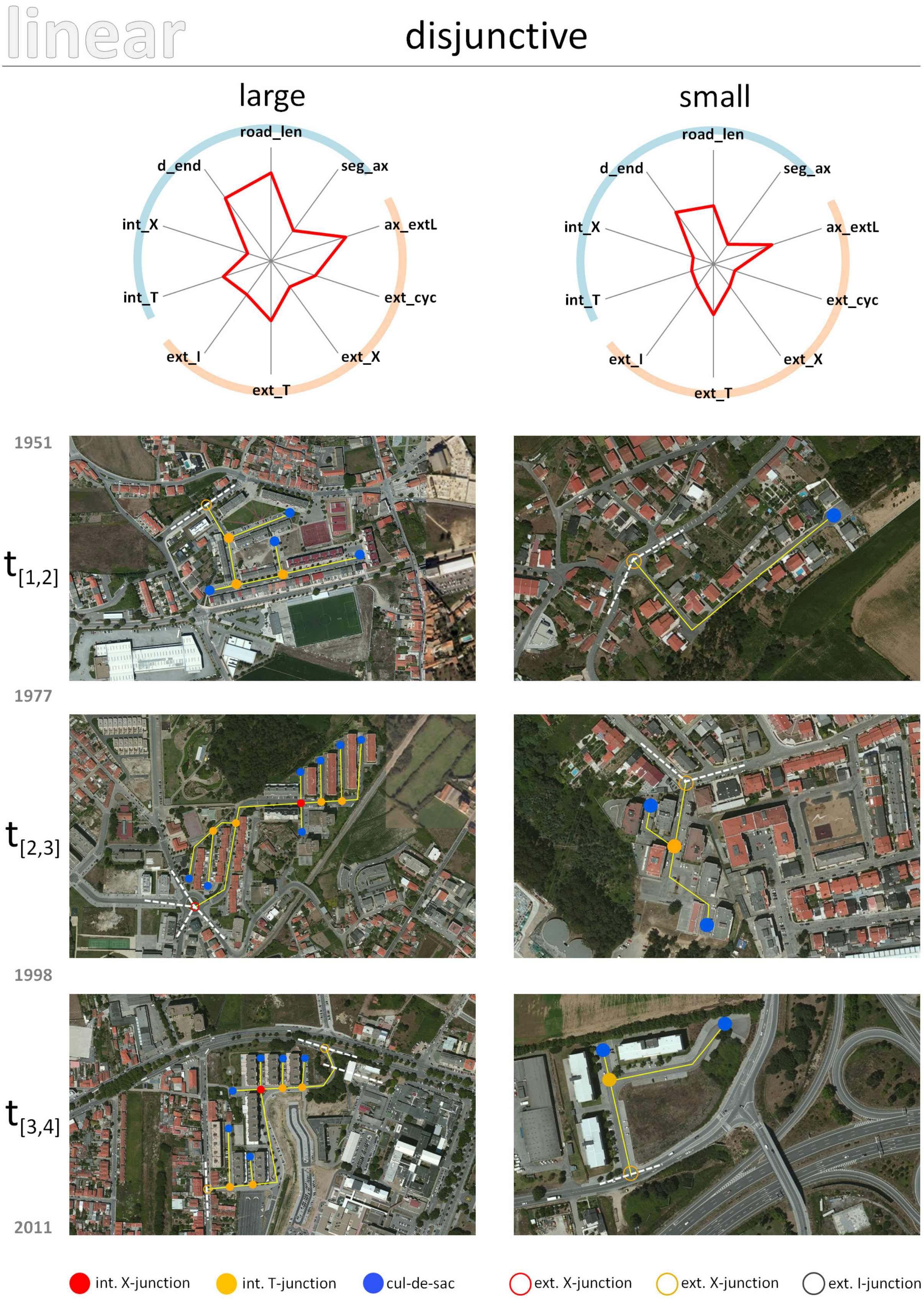

Fig. 141 – Archetypes of linear / disjunctive, large and small clusters, at each $t_{[a,b]}$.

- **Large | linear | conjunctive** (Figure 140, left; page 212)

  Interventions with very long street-lengths, made up of several streets, tending to geometrical regularity but without internal blocks (I). They have strong external connections, always linking several existing streets, thus always sub-dividing existing blocks (II). External T-junctions prevail but external X-junctions are also quite present (III), denoting the creation of spatial continuities with existing streets. The internal structure is acyclic but with some complexity, showing frequent internal T-junctions but rare X-junctions or culs-de-sac (IV).

  I - {**[road_len]** mean 1126m, std.dev. 479m; **[seg_ax]** >> 1}
  II - {**[ext_cyc]** mean 5, std.dev. 4.1}
  III - {**[ext_T]** mean 3.1, std.dev. 2.2; **[ext_X]** mean 1.4, std.dev. 1.7}
  IV - {**[int_T]** mean 1.6, std.dev. 1.1; **[int_X]** mean 0.1, std.dev. 0.4; **[d_end]** mean 0.4, std.dev. 0.8}

- **Small | linear | conjunctive** (Figure 140, left; page 212)

  Interventions with short street-lengths and without internal blocks, composed by just one or very few streets, but with high external connectivity. They always create new connections between existing streets (I). Also, they maximize the creation of new external links for the respective number of new streets (II), thus showing strong geometrical linearity. External connections are almost exclusively T-junctions (III). They have very simple internal structures (or even none, in the case of single streets), with rare internal junctions or culs-de sac (IV).

  I - {**[road_len]** mean 287m, std.dev. 132m, **[ext_cyc]** mean 1.4, std.dev. 0.7} **II** - {[ax_extL] maximal}
  III - {**[ext_t]** mean 1.7, std.dev. 0.9; **[ext_X]** mean 0.3, std.dev. 0.5}
  IV - {**[int_T]** mean 0.2, std.dev. 0.4; **[int_X]** mean 0.01, std.dev. 0.1; **[d_end]** mean 0.06, std.dev. 0.2}

- **Large | linear | disjunctive** (Figure 141, left; page 213)

  Interventions with long street-lengths, but seldom creating new connections between existing streets (I). They have week external connectivity, with the lowest number of external links in relation to the number of axial lines, denoting geometrically irregular layouts (II). External T-junctions prevail, albeit always in low number (III). Their internal structures are complex and dendritic (usually pure trees), with very frequent occurrence of culs-de-sac; internal T-junctions prevail while internal X-junctions are very rare (IV).

  I - {**[road_len]** mean 968m, std.dev. 235m} **II** - {**[ax_extL]** minimal, **[seg_ax]** low}
  III - {**[ext_T]** mean 1.3, std.dev. 0.9; **[ext_X]** mean 0.2, std.dev. 0.4}
  IV - {**[int_T]** mean 1.7, std.dev. 0.8; **[int_X]** mean 0.1, std.dev. 0.3; **[d_end]** mean 1.7, std.dev. 0.9}

- **Small | linear | disjunctive** (Figure 141, left; page 213)

  Interventions with very short and quite recurrent street lengths (i.e. with low variability), composed by just a few streets and usually not creating new connections between existing streets (I). They have very week external connectivity, frequently just one or two T-junctions (II). Their internal structure is minimal (or null, in the case of single streets), but the occurrence of culs-de-sac is quite frequent. Internal T-junctions are rare (max. 1) and internal X-junctions extremely rare (III).

  I - {**[road_len]** mean 156m, std.dev. 61m; **[ext_cyc]** mean 0.03, std.dev. 0.2}
  II - {**[ext_T]** mean 0.1, std.dev. 0.3; **[ext_X]** mean 0.07, std.dev. 0.3}
  III - {**[int_T]** mean 0.7, std.dev. 0.4; **[int_X]** mean 0.1, std.dev. 0.3; **[d_end]** mean 1.1, std.dev. 0.4}

- **Large | cellular | conjunctive** (Figure 142, left; page 216)

Interventions with the longest street-lengths and with several internal blocks (mean 3.5, max. 21), which tend to geometrical regularity (I); they have very high external connectivity, creating numerous connections between existing streets (II). External T and X-junctions occur in similar proportions and both in high number (III), revealing the frequent creation of spatial continuities with existing streets. They internal structures are complex, cyclic and highly connective, with prevalence of internal T-junctions, frequent X-junctions and a moderate occurrence of culs-de-sac (IV).

I - {**[road_len]** mean 2498m, std.dev. 864m; **[int_cyc]** mean 3.5, std.dev. 3.2; **[iCyc_APR]** mean 0.6, std.dev. 0.4}
II - {**[ext_cyc]** mean 9.9, std.dev. 6.9} **III** - {**[ext_T]** mean 5.7, std.dev. 2.7; **[ext_X]** mean 3, std.dev. 3.4}
IV - {**[int_T]** mean 5.7, std.dev. 2.7; **[int_X]** mean 3, std.dev. 3.4; **[d_end]** mean 3, std.dev. 3.4}

- **Small | cellular | conjunctive** (Figure 142, left; page 216)

Interventions with medium to short street-lengths and a small number of internal blocks (max. 3), tending to be geometrically regular (I); but externally they are well connected, always dividing existing blocks and linking existing streets (II), most frequently through external T-junctions (III). Internal structure is simple but with cycles, with a strong prevalence of internal T-junctions and with rare culs-de-sac (IV).

I - {**[road_len]** mean 811m, std.dev. 275m; **[int_cyc]** mean 1.3, std.dev. 0.6; **[iCyc_APR]** mean 0.6, std.dev. 0.3}
II - {**[ext_cyc]** mean 3.1, std.dev. 1.4} **III** - {**[ext_T]** mean 3, std.dev. 1.5; **[ext_X]** mean 0.6, std.dev. 0.7}
IV - {**[int_T]** mean 3.4, std.dev. 1.6; **[int_X]** mean 0.4, std.dev. 0.6; **[d_end]** mean 0.3, std.dev. 0.2}

- **Large | cellular | disjunctive** (Figure 143, left; page 217)

Interventions with long-street lengths and with several internal blocks (max. 17), albeit less regular than those of the cellular conjunctive types (I). They are poorly connected to the existing grid (II), having few external links (commonly T-junctions) and rarely sub-dividing existing blocks (III). But their internal structures are complex, cyclic and strongly connective, with prevalence of T-junctions (IV). They have the maximal average occurrence of culs-de-sac (mean 3.2, max. 10).

I - {**[road_len]** mean 1882m, std.dev. 345m; **[int_cyc]** mean 3.4, std.dev. 2.7; **[iCyc_APR]** mean 0.25, std.dev. 0.5}
II - {**[ext_cyc]** mean 1.5, std.dev. 0.3} **III** - {**[ext_T]** mean 2.3, std.dev. 1.3; **[ext_X]** mean 0.4, std.dev. 0.6}
IV - {**[int_T]** mean 6.7, std.dev. 3.6; **[int_X]** mean 1.4, std.dev. 1.8; **[d_end]** mean 3.2, std.dev. 3.4}

- **Small | cellular | disjunctive** (Figure 143, left; page 217)

Interventions with medium to short street-lengths, having a small number of internal blocks (max. 3), albeit less regular than those of the cellular conjunctive types (I). They are very poorly connected to the existing grid, usually not creating new connections between existing streets, with external T-junctions prevailing (II). Their internal structures are simple, with cycles but low connectivity and almost only with internal T-junctions; they show a moderate occurrence of culs-de-sac (IV).

I - {**[road_len]** mean 578m, std.dev. 153m; **[int_cyc]** mean 1.4, std.dev. 0.4; **[iCyc_APR]** mean 0.6, std.dev. 0.7}
II - {**[ext_cyc]** mean 0.6, std.dev. 0.6} **III** - {**[ext_T]** mean 1.2, std.dev. 0.7; **[ext_X]** mean 0.2, std.dev. 0.4}
IV - {**[int_T]** mean 2.1, std.dev. 1.2; **[int_X]** mean 0.1, std.dev. 0.3; **[d_end]** mean 0.8, std.dev. 0.7}

cellular conjunctive

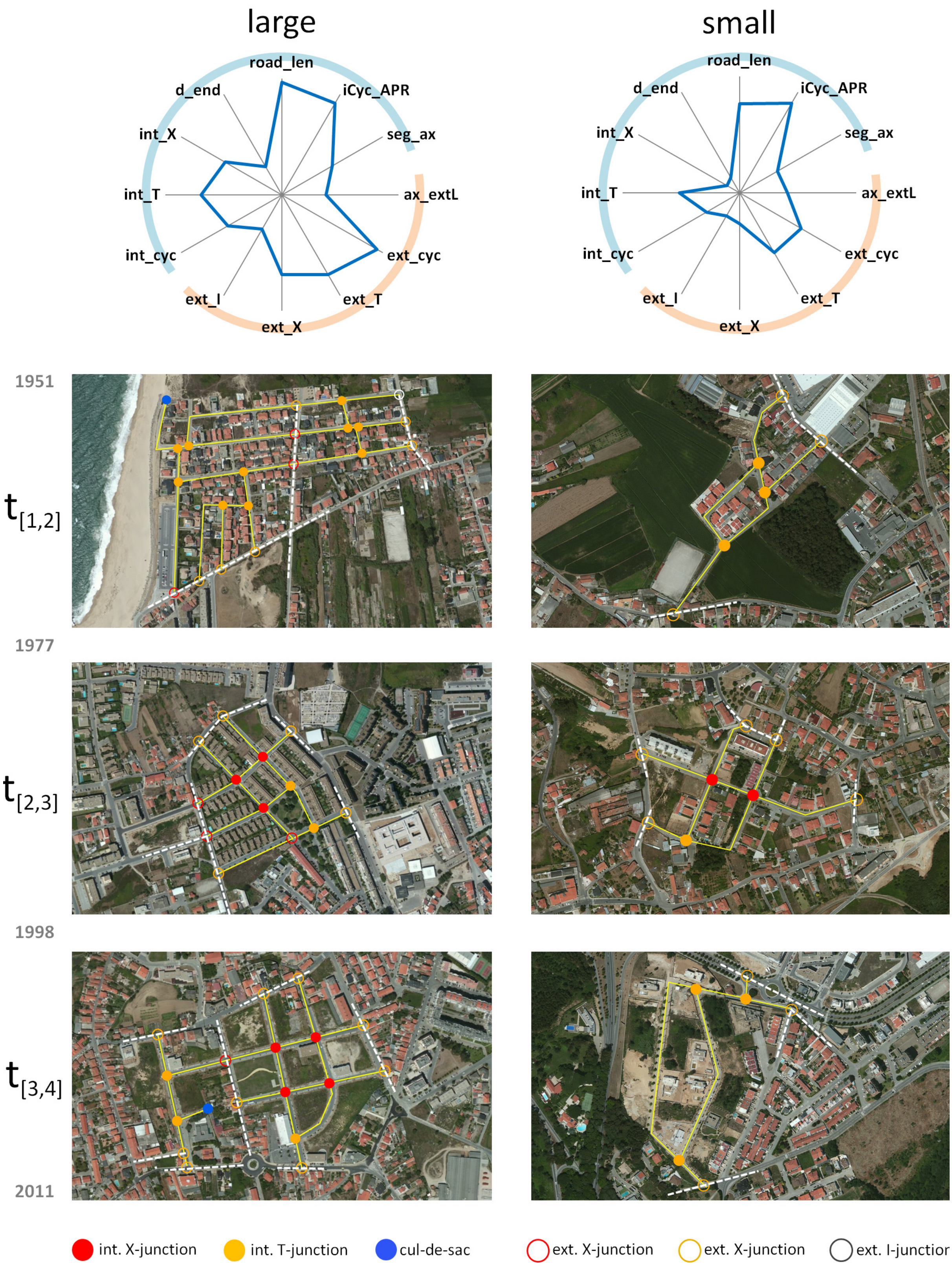

Fig. 142 – Archetypes of cellular / conjunctive, large and small clusters, at each $t_{[a,b]}$.

cellular disjunctive

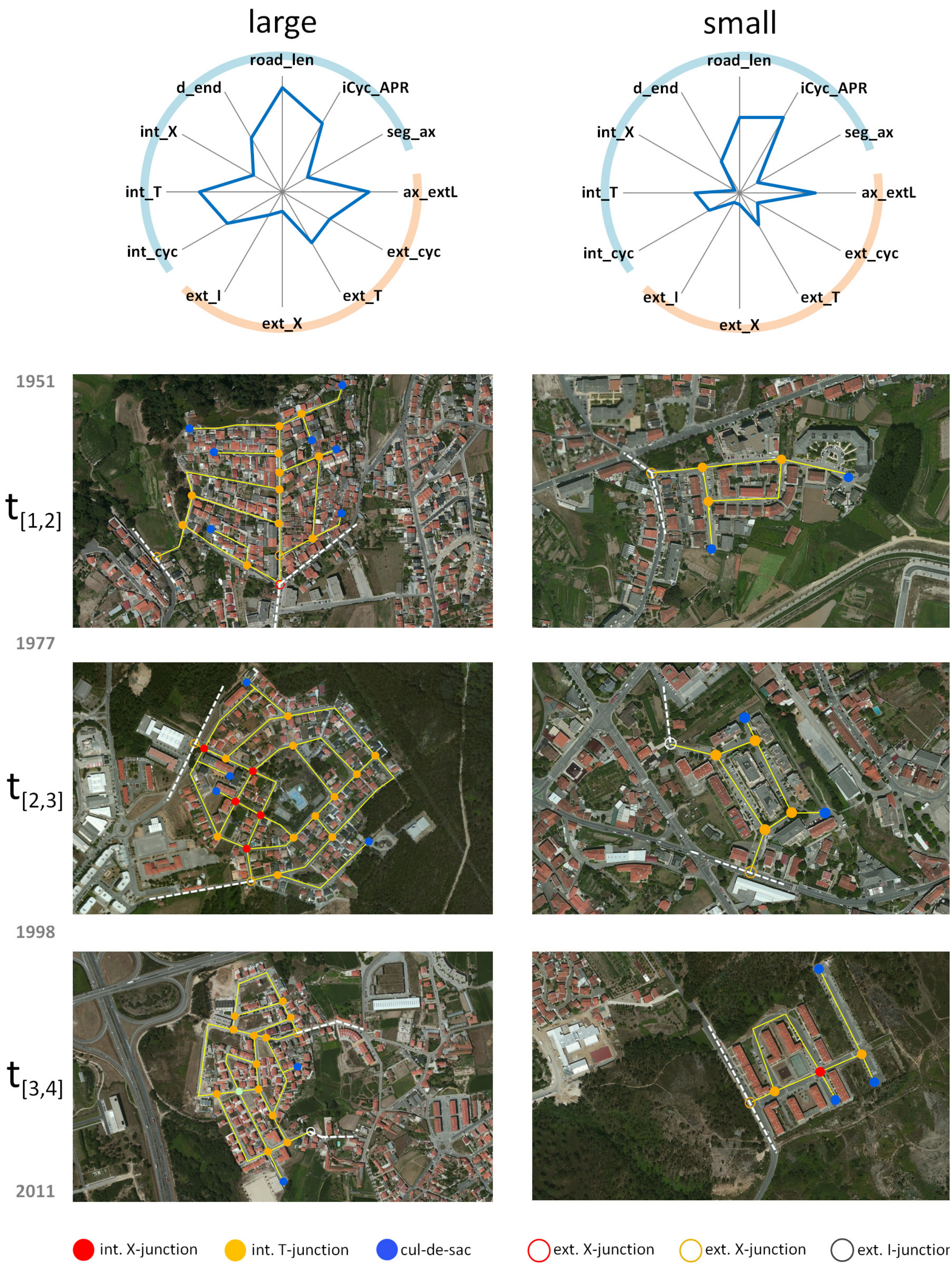

Fig. 143 – Archetypes of cellular / disjunctive, large and small clusters, at each $t_{[a,b]}$

A second regularity pertains to the stability of the *conjunctive* and *disjunctive* types, under variations of size and ciclicity (i.e. with or without internal cycles). For example, *large linear conjunctives* share many of the characteristics of *small cellular conjunctives*, except size and the presence of internal blocks; i.e. they are both well externally connected, linking several previously separated streets, both sub-dividing existing blocks. The differences pertain to the extent to which these characteristics are met (in large interventions they are obviously more present) and to the existence (or absence) of internal blocks, which entails other differences of internal structure. Thus, interventions may be large or small, cellular or linear, but these classifications do not limit the value of their characterization as *conjunctive* or *disjunctive* interventions.

A third morphological regularity pertains to the stability of all types through time. Independently of the fact that the clustering procedure has been performed on all interventions from all temporal periods together, it is clear that the archetypes of each $t_{[a,b]}$ share the same spatio-morphological characteristics at the level of their street patterns, but not at the level of the constructions associated with them. The built-forms of each archetype from each $t_{[a,b]}$ evolve clearly through time, their architectonic characteristics changing both in structure and style, showing that they belong to obviously different historical moments. However, the form of their spatial ‘skeletons’, i.e. the basic morphology of their street patterns, is quite stable. Moreover, as we will see later, the frequencies of each type at each time-interval $t_{[a,b]}$, even if revealingly variable, do not show extreme variations which would indicate strong time-dependencies among our types.

The combination of just three elemental morphological attributes - *size*, *ciclicity* and *connectivity* - seems therefore enough to produce consistent typomorphologies of street patterns, yet endowed with a significative degree of *flexibility*. This flexibility, which seems truly necessary when classifying so diverse and heteroclite urban forms, arises from the fact that such types are defined quantitatively (not visually) through numeric values on a series of objective morphological dimensions. Each type corresponds to a combination of *intervals of variability*, bounded by the limits of each cluster on all morphological dimensions, which are able to accommodate a wide range of possible spatial forms without loss of coherence. Moreover, those limits are defined through automatic numerical methods, which are capable of finding underlying affinities among sets of apparently rather different objects. Those kinds of affinities are not easy to spot through visual analysis, among samples of highly heterogeneous urban forms; only after their classification with the abovementioned methods do their resemblances become apparent, when one looks closely at the composition of their street patterns.

Formally, the proposed types are best defined by numbers, through the mean values on all morphological variables of the interventions in each class (as depicted on the radar-plots of the previous Figures). The combination of these values constitutes what we could call a ‘morphological vector’ with 8 or 10 dimensions (for the linear and cellular cases), describing each type’s archetypal behavior on the several morphological variables. These vectors (one for each morphological type) could be used to automatically assess and classify the morphology of any future incremental intervention made to the street network (e.g. using discriminant analysis or any other type of supervised classification). This could have potential applications in supporting day-to-day urban management activities and decisions. Obviously, for this to be possible, a much more thorough work of empirical validation would be needed, as well as a clear understanding of each type’s potential qualities and defects. But it could be done, resulting in a direct practical outcome of the proposed method, applicable in any geographical or cultural context.

We will end this section with the organization of the several types of street patterns under a hierarchical classification scheme, constituting the proposed typomorphology of metropolitan incremental urbanization. The hierarchical relations between types on that scheme were not found with any unsupervised method (or with any other automatic method, for that matter). They are just a way of organizing the several types into a single representation, in order to make clear the full set of morphologies concerned and the basic parameters distinguishing them, i.e. *size*, *ciclicity* and *connectivity*.

We have seen how the *size* of interventions is an highly discriminant attribute, both for the linear and cellular sub-sets of our sample of network interventions, with all types occurring under two manifestations - one *large* and one *small* - sharing the same overall characteristics. We thus take size as the first fundamental divide in our hierarchical organization of the types, splitting all possible metropolitan incremental network interventions at the onset, as large or small. This is will be the first level of the proposed typomorphology.

The separation by size holds even when linear and cellular interventions are set side-by-side, although their sizes vary significatively, as we have seen before (cellular interventions are, in general, larger). Figure 144 shows four plots, depicting the average road-lengths of each type as well as the firsts (up and lower) standard deviations, represented as error-bars.

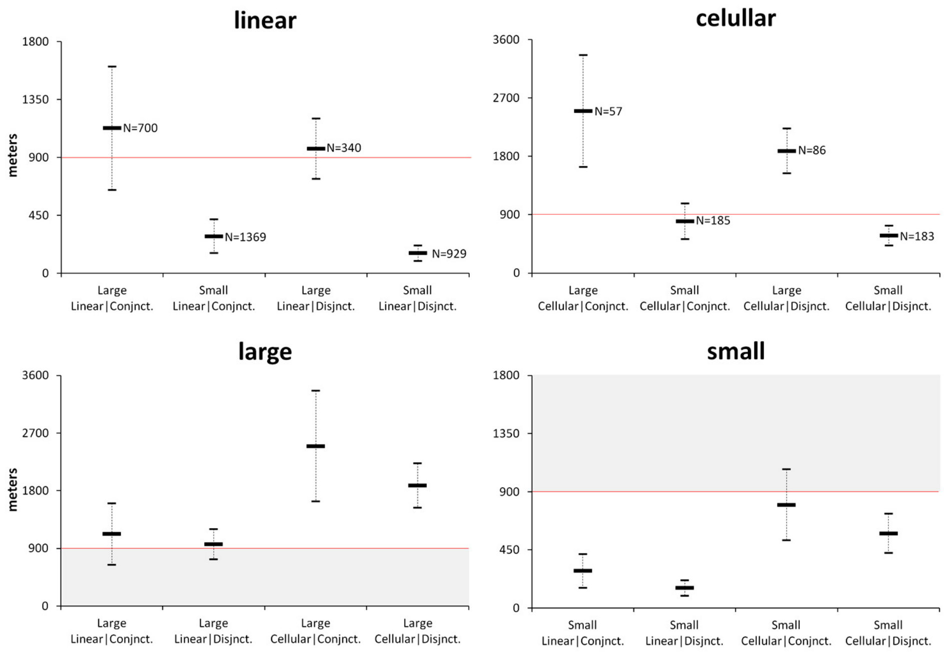

Fig. 144 – Means and standard deviations of the size of interventions in each cluster.

In the upper plots of Figure 144, we show the sizes of each type of linear and cellular interventions, making clear the different road-lengths of large linear or cellular types, when compared to their small counterparts. The different sizes of linear and cellular interventions are immediately made clear by the different yy scales (in meters) of their respective plots (the yy scale of cellular interventions is twice longer). One interesting finding is that even if large interventions (both linear and cellular) are much less numerous than small interventions (again, of both ciclicity types), their sizes vary significatively more (i.e. they have higher standard deviations). While small interventions, which are overwhelmingly more common, are much more constant in terms of size (the number of interventions of each type is indicated on the upper plots of Figure 144).

This seems to be largely independent of the size of each class (i.e. their respective number of objects), because it occurs on the classes of large linear interventions (conjunctive N=700, disjunctive N=340) and also on the classes of large cellular interventions (conjunctive N=57, disjunctive N=86). Perhaps, because large interventions correspond to sporadic major investments, their sizes may vary more, at the whim of promoters' individual expectations or financial resources. On the other hand, small interventions correspond to every-day small investments, and their lower variability may reflect an average financial risk that promoters are willing to take without great concern.

The consistency of the division of the several types by size is made more explicit on the lower plots of Figure 144, which show the same information of the upper plots, but now organized by large and small types of intervention (linear or cellular, conjunctive or disjunctive). It becomes clear that *all* large types have their mean road-lengths above 900 meters, and *all* small types below that limit. This shows how, in spite of their variable frequencies, geometries and topologies, all types of street network interventions may be effectively divided according to their respective road-lengths, or sizes, in two very broad initial classes of *large* and *small* interventions.

The second level of our typomorphology will separate *linear* from *cellular* interventions. Even if this distinction was made prior to any other and the interventions thus characterized classified independently, it seems, in the end, that ciclicity could be subordinated to the more discriminant attribute of size. Whether or not an intervention has internal blocks is, first of all, a characteristic clearly related with its possible size (cellular interventions are larger in average) and, in second place, a pure choice of street layout design. Undoubtedly, the very different frequencies of linear and cellular interventions are revealing in that sense, even allowing for their different characteristic road-lengths. But because road-length (i.e. size) is more discriminant, potentially more relevant for each intervention's potential impact and has an easier translation in terms of the resources involved, we consider ciclicity a less determinant morphological characteristic.

The third, and last, level of the proposed typomorphology, finally separates all interventions according to their internal and external connectivities, i.e. as *conjunctive* or *disjunctive*. We reach here the level where automatic classification has made the bulk of the work, in revealing the eight different morphological types, which hardly could be identified in any other way. Figure 145 (next page) shows the final hierarchical organization of the proposed typomorphology of metropolitan incremental street-network interventions, that this Chapter set out to achieve at the beginning.

The components of a typomorphology (i.e. the types themselves) should have names, or designations, based on each type's content and meaning, so that we may know what each one represents. If these names are capable of reflecting the position of the type in a potential hierarchical typomorphology, the better. For example, in biological taxonomy, the name of a species is always composed by two Latin terms[154], the first one indicating the genus[155] to which the species belongs and the second one denominating the species itself, usually according to some particular characteristic. We, humans, call ourselves with haughtiness *Homo sapiens* because we belong to the genus *Homo* and we are *sapiens*. Following this good idea of long tradition, we propose a trinomial nomenclature[156] based on the three hierarchical levels enunciated above, namely: size (or road-length), the topological property of ciclicity (i.e. the presence or absence of internal blocks) and the general connectivities represented by the several types. Actually, this are the names we have been calling so far to the types of street patterns discovered by unsupervised clustering, now stated in a more formal way.

The nomenclature results from the eight possible combinations of three pairs of adjectives, concerning the three levels of the hierarchical typomorphology represented on Figure 145. We determine the name of each type by combining the terms: Large/Small → Linear/Cellular → Conjunctive/Disjunctive. By following the hierarchy from top to bottom, one can find the name of each type (e.g. "small linear conjunctives" or "large cellular disjunctives").

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[154] Such naming system is called the "standard binomial nomenclature". It was formally introduced by Carl Linnaeus in 1753.

[155] In biology, the *Genus* is a low-level taxonomic rank, standing between the lowest level of the *Species* and the upper level of the *Family*.

[156] But we do not go as far as to propose such a nomenclature in Latin. After a first moment of enthusiasm, we realized that designations like *Magna linearia conjunctiva* or *Parva cellularia disjunctiva* would be inappropriate.

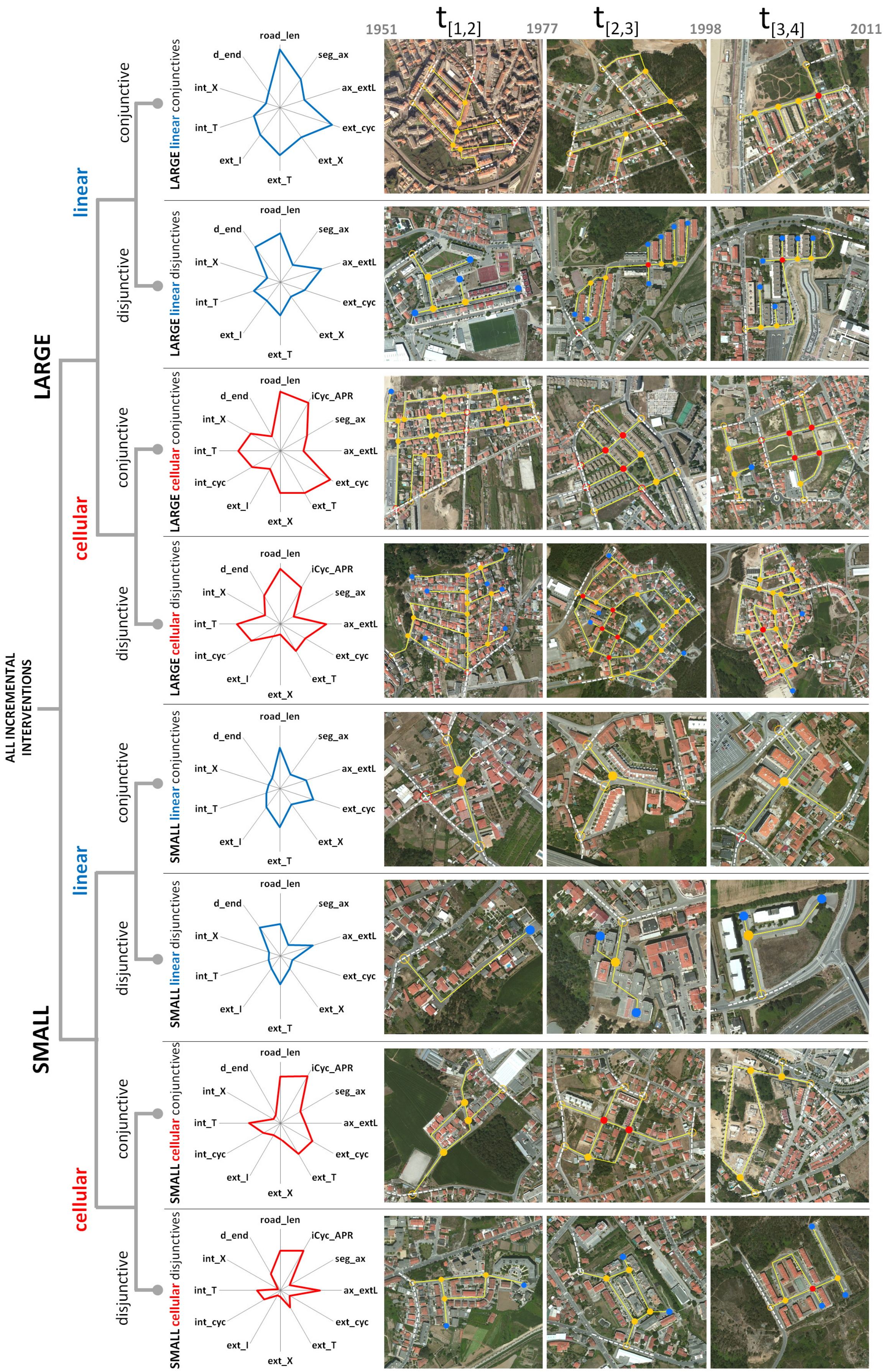

Fig. 145 – Hierarchically organized typomorphology of metropolitan street network interventions.

Fig. 146 – 48 examples of the several morphological types of network interventions, from all time-intervals.

6.5. FREQUENCIES OF THE MORPHOTYPES ACROSS TIME AND SPACE

The morphological types defined and described in the previous section have a high degree of consistency. This was already shown through some real examples, namely the archetypes of each morphological class for each time interval $t_{[a,b]}$ (Figures 140-143 and 145). But those are archetypical cases, the ones that best represent each type in terms of their values on the several morphological dimensions that were used to define them. In order to make clear that we are in fact talking about highly stable street-layout morphologies, occurring systematically and independent of time, we have gathered a larger number (48) of additional examples, shown on Figure 146 (previous page).

A close inspection of that collection of cases shows that in spite of a considerable degree of freedom and variation, the street-layouts occurring under each class definitively belong to the same morphological 'family'. In particular, the occurrence of similar morphologies of street layouts in different temporal moments but with clearly different and datable associated buildings, is a strong indication that the proposed types indeed correspond to essential and time-independent urbanization *praxes* - that is, to specific ways of constructing the city - which are typical and endemic of the geographical and socio-cultural contexts considered in this study. Naturally, we cannot claim their generalization outside those bounds, and we must stress that we are only studying street layouts described by baseline geometrical and topological properties, not broader and more complex morphological subjects (which could include buildings, the structure of land-tenure or land-uses). But the consistent occurrence of such morpho-types across time clearly allows for the study of their temporal and spatial frequencies, in order to explore potential cleavages or regularities on those two dimensions. This could reveal that in physical and spatial terms, the metropolization process of Oporto's urban region is not isotropic, or random and shapeless, but has local and temporal morphological specificities. That will be the exploration subject of this last section.

This will be done through two types of analysis. First, by accounting the numerical frequencies of each type through time, i.e. their shares at each time-interval. These are simply the *count* of interventions in each class as a percentage of the total number of interventions at each $t_{[a,b]}$, and also the *sum of the road-length* produced by each class as a percentage of the total road-length produced at each $t_{[a,b]}$. These two types of share (count and road-length shares) are quite different, because the typical road-lengths of each class vary considerably, as we have seen before. Thus, the count share gives us an idea of the prevalence of the use of each morpho-type, among the other several typical *morphological options* on how to physically implement urbanization operations, at each moment in time; in other words, the number of times a certain type was (designedly or not) chosen as morphological 'template' for each incremental intervention. This may reveal dominant temporal morphological trends. While the road-length share give us an idea of the actual physical impact of such morphological choices, which may be roughly approximated by the actual total length of new roads and streets produced by each type at each temporal moment. Therefore, the count and road-length shares of each type indicate their aggregated frequency and potential physical impact through time, but not their respective spatial distributions.

To study these, we will use two other types of analysis, namely the visualization in GIS of the actual spatial distributions of each type, supported by a spatial analysis technique known as *hot-spot analysis*. Such technique is one of the several available *spatial statistical methods* implemented in GIS. Spatial statistics comprise a set of techniques for describing and modelling spatial data which, in many ways, simply extend what the mind and eyes do, intuitively, in accessing spatial patterns; only they do it in numerical objective terms. That is, these methods evaluate proximity, orientation or spatial relationships between objects in a spatial dataset, but they integrate such parameters directly in the mathematics used for establishing the rejection (or the non-rejection) of well defined statistical null-hypothesis, which are commonly stated as random (or trivial) spatial distributions (Scott and Janikas 2010).

Specifically, hot-spot analysis is based on the Getis-Ord Gi* statistic[157] (Getis, Ord 1992). This method evaluates if each feature in a spatial dataset represents an abnormally high or low occurrence, *within* the context of its neighboring features. In other words, the statistic compares local averages to global averages, identifying if a local pattern is statistically (and significantly) different to what is generally observed across the whole study area, and if that difference is negative (cold-spot) or positive (hot-spot). In the case of the Getis-Ord Gi* statistic, the null-hypothesis (H_0) is *complete spatial randomness*, i.e. that eventual local concentrations or voids observed in a spatial dataset are no more than fortuitous random effects. For each spatial feature, the statistic produces a z-score and a p-value, with the z-score representing the local deviation from the mean of the overall set and the p-value the statistical significance of such deviation. If the z-score if sufficiently high (or low) and if its associated p-value is significant, we may reject H_0 (within a well defined confidence level) and therefore conclude that a given area truly shows an abnormal high or low concentration of the values under study (i.e. is a hot or a cold-spot), which very hardly could be due to mere chance.

Hot-spot analysis assesses whether high or low *values associated with a given spatial feature* (i.e. described by a certain attribute field of that feature) cluster spatially. In this sense, it may serve to evaluate high or low population occurrences within census tracts, for instance. But in other situations (as it is the case here) we may be interested in the *spatial clustering of the features themselves* (in our case, network interventions) and not in the spatial clustering of any particular value associated with those features. In this case, the previous aggregation of the concerned features according to some spatial rule is necessary, in order to *count their incidence of occurrence across space*. There several ways to do this; we have chosen one of the possible methods, namely the superimposition of a lattice of square polygons (600x600 meters) over the whole study area, with which we have counted the interventions of each type occurring within, or intersected by, each of the polygons (see Figure 147).

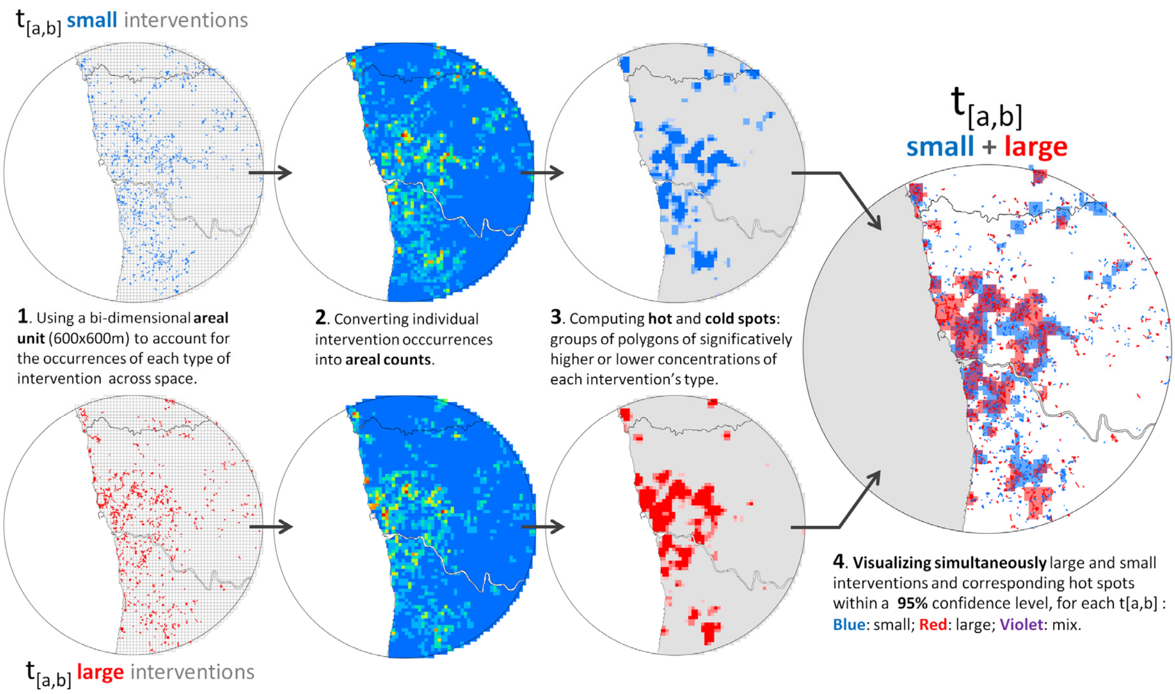

Fig. 147 – Method for visualizing spatial concentrations (hot-spots) of typomorphologies.

[157] In 'Getis-Ord Gi*' statistic (pronounced G-I-star), the 'G' stands for the name a specific family of spatial statistics defined by Arthur Getis and J. K. Ord, the 'i' stands for the local sub-areas i = { 1,2, ..., n} where each occurrence is observed, and the star '*' is used to differentiate the method from the more general case of the 'Gi statistic', where only the neighbours of each feature are included in the calculations (and not also the feature itself, as in the Gi* case).

The choice of a lattice of square polygons with 600 meters of side has two reasons. First, 600 is a multiple of the study area radius (30.000 meters), which allows covering the area evenly; but also because 600 meters is half of the upper limit (1200 meters) of the neighbourhood scale, defined in Chapter 3. Thus, a square of four polygons with a side of 1200 meters corresponds to that previously indentified, natural centrality scale of the metropolitan spatial network. The choice of using a two-dimensional areal unit to count interventions (and not reducing them to one-dimensional points and then aggregating the points by proximity, which would be another possible approach) has to do with concerns in maintaining the spatial integrity of the network interventions themselves. In fact, these are two-dimensional objects with varying spatial extents. A large intervention may therefore occupy several polygons (i.e. 'occurring' at several polygons at the same time), while a small intervention may well be contained within a single polygon. In this way, the size of each intervention is indirectly included in the counting method. Moreover, in this way we can count the network interventions as they are (i.e. sets of interconnected streets, represented by line-segments) and not as one-dimensional points, which would be a hardly acceptable and drastic dimensional reduction, potentially inducing spatial bias in the results[158].

Using these two analysis methods, one purely numerical (accounting of shares) and another visual but supported by spatial analysis (studying spatial distributions), we will explore the variation of the frequencies across time and space of the morphological types defined before. This will be done in progressive levels of specificity. We will start by looking at all interventions of each time-interval $t_{[a,b]}$, simply distinguishing between incremental and non-incremental interventions. This will give us a first and general idea of the potential spatial and temporal cleavages in the distribution of metropolitan network growth.

Then, we will proceed through the several levels of our hierarchical typomorphology of incremental network interventions, sequentially inspecting the shares and the spatial distributions of each super-class of large / small, cellular / linear, and conjunctive / disjunctive interventions. At this stage, we will not distinguish between each of the final eight morpho-types, but just between interventions pertaining to the abovementioned super-classes. Finally, we will investigate in detail the temporal shares and spatial distributions of each individual morpho-type.

Figure 148 (next page) shows the count and road-length shares of incremental and non-incremental interventions at each time-interval $t_{[a,b]}$. Additionally, it also shows two other plots (Figure 148, lower images) depicting the count and the road-length of these two types of interventions, divided by the number of years in each time-interval, $\Delta t_{[a,b]}$ (i.e. their count and road-length per year). These plots (which will also be shown for all other types of interventions) are complementary to the share plots (showing the reciprocal proportions of types through time, but not their amounts), because they give information about the *intensity* or *rate of production*, of each type of intervention at each time-interval.

The overwhelming prevalence of the number of incremental over non-incremental interventions, already mentioned before, is once again evident on their share plots. But the latter type increase steadily through time. Particularly regarding their road-length share, non-incremental interventions attain almost half of the length of new roads produced during $t_{[3,4]}$. As can be seen by the plot depicting the road-length built per year at each time-interval (Figure 148, bottom right), non-incremental interventions attain its maximum production rate at $t_{[3,4]}$ (24 Km p.a.).

[158] The conceptualization of spatial relationships for the hot-spot analysis were based on *first order polygon contiguity*. That is, only polygons sharing a border with the polygon assessed at each iteration of the algorithm are taken into account in the calculations. In our case, using a lattice of square polygons, this results in a *von Neumann neighbourhood* for each cell (i.e. a cross, with the central polygon being assessed), while no type of distance is defined because the spatial relationship is purely topological.

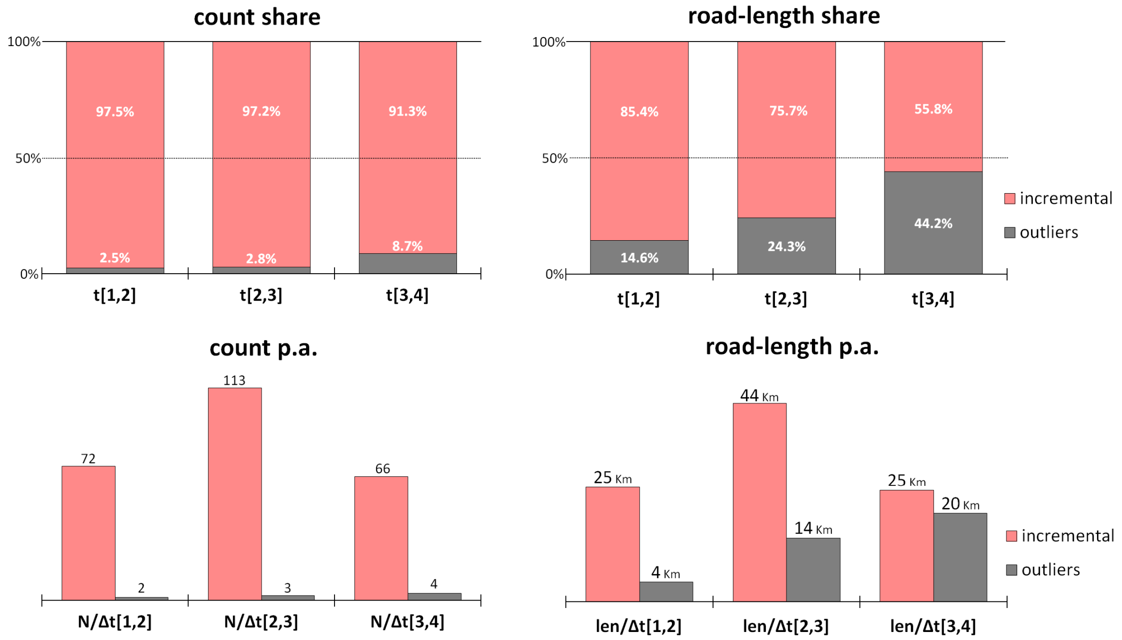

Fig. 148 – Shares of incremental and non-incremental interventions at each $t_{[a,b]}$.

Even during the period of most intense network growth - $t_{[2,3]}$ - where incremental interventions attain their maximum production rate (44 Km p.a.), non-incremental interventions show a strong increase of road-length share (but not of count share, because of the maximum intensity of incremental interventions at the same period; far more numerous, but shorter). What these figures show is that the amount of public investment in the construction of the metropolitan spatial network (albeit more in the form of heavy-duty road infrastructures than of more traditional 'urban materials') has strongly and steadily increased over time. The metropolitan network, which at t[1,2] was overwhelmingly produced by private means, has therefore become more and more the shared product of private and public investment. But these are simple facts, moreover already touched upon before. The evolution of the spatial distribution of the two types of interventions (Figure 149, next page) reveals more interesting patterns.

The upper images of Figure 149 show the spatial distributions of incremental and non-incremental interventions at each time-interval; while the lower images show the results of the hot-spot analysis for just the incremental type, with the non-incremental interventions layered over. Looking at the top images, one can see that the spatial distributions of incremental interventions are quite different at each time-interval: rather intense but somewhat dispersed at t[1,2], even more intense but more concentrated at t[2,3] and, finally, apparently weaker but again more dispersed at t[3,4]. However, the relatively weaker production of t[3,4] (as we have noted before) is just a consequence of the shorter time-span of that time-interval, not a real absolute decrease in network growth. Also, the progressive increase in the production of non-incremental interventions at all time-intervals is quite visible. But the most noticeable fact is that growth happens clearly everywhere and at the same time, even if some concentration is visible at the metropolitan core. This seems in clear contradiction with the common image of metropolitan growth expanding from the core as an 'oil-blot', i.e. as mere extension of the core's urban body. On the contrary, the process seems much more synchronic and global, even if under eventually different rates at different places.

The lower images of Figure 149 make easier the interpretation of the different spatial distributions. At t[1,2] large hot-spots are visible at the metropolitan core, but also across the entire study area (albeit smaller and less intense). These are areas of strong spatial concentration of network interventions, thus areas of intense urban growth.

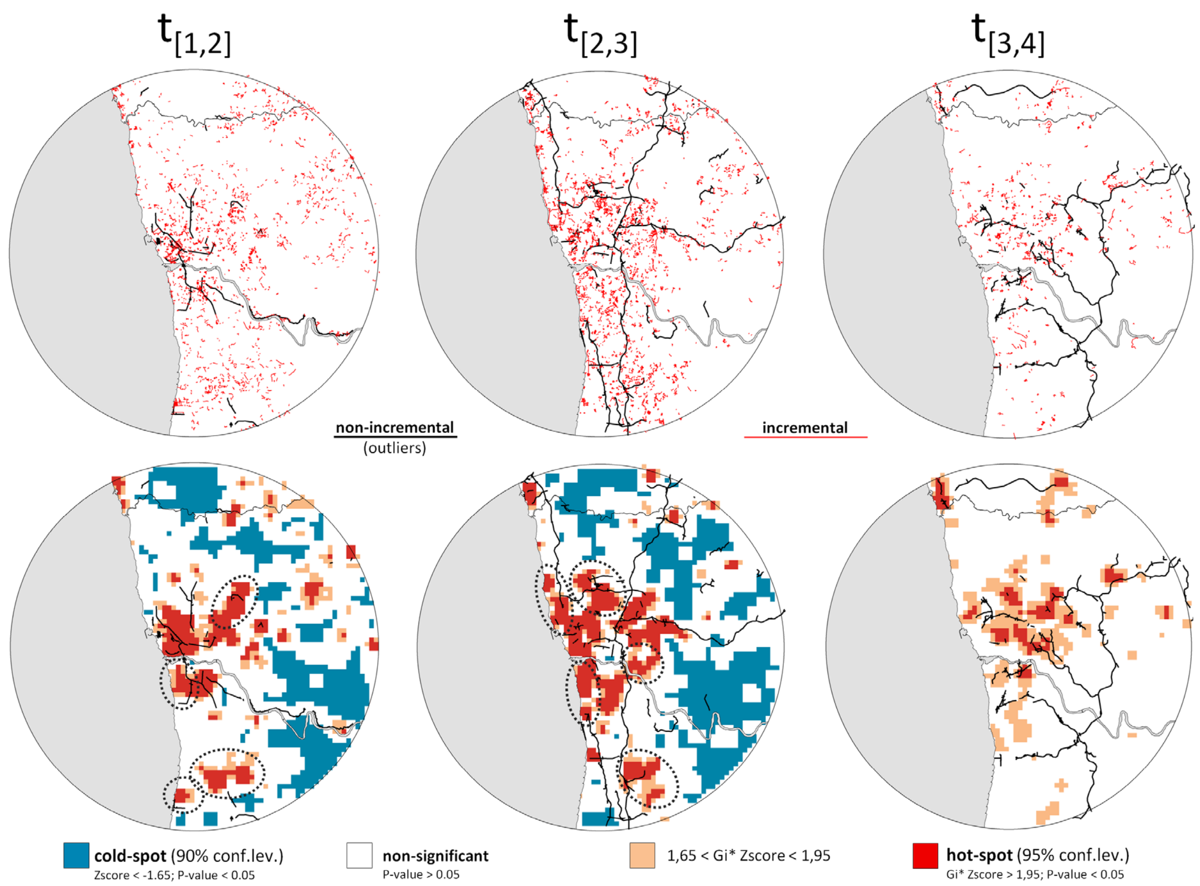

Fig. 149 – Spatial distributions (top) and hot-spot analysis (bottom) of incremental and non-incremental interventions at each $t_{[a,b]}$.

The relation of these areas with the non-incremental interventions created during this period is quite clear at the centre of the study area, particularly towards the coast. But everywhere else hot-spots appear independently of non-incremental interventions. Those hot-spots correspond in general to expanding settlements of historical foundation, but also to areas without previous historical urban backgrounds (flagged on the image with dotted ellipses; those not flagged correspond to existing settlements). By t=1 (1951) these areas were hinterland rural zones of dispersed settlement pattern or small seasonal fishing settlements, when on the coast.

But 26 years later, by t=2, they had become areas of intense urban development, as the bottom left image of Figure 149 shows. The same process is still in action at $t_{[2,3]}$, with the emergence of more new growth zones. Again, those corresponding to new urban areas are flagged on the image. The relation between the hot-spots of $t_{[2,3]}$ and the non-incremental interventions of the same time-interval is again noticeable at some points, but not glaringly evident. However, urban growth is now clearly more concentrated around the metropolitan core and there are fewer hot-spots at the periphery. Also, cold-spot areas (in blue on the image) are now wider and more continuous than before. These are areas were the occurrence of network interventions is systematically very low, or even null; so much lower than the overall observed average, that they are considered statistically abnormal low occurrences. Indeed they are different, because they correspond to zones of mountainous terrain (northeast and southeast of the study area) or of highly productive rural land (at north), where very few network developments occur. But the fact that these areas become wider and more continuous at $t_{[2,3]}$ means that urban growth, besides being more intense, is also more concentrated during this time-interval; in other words, that the number of interventions occurring outside the main growth foci has diminished and the number of those occurring therein has augmented.

Finally, at the last time-interval - $t_{[3,4]}$ - the pattern changes again significatively. The most obvious difference is the total absence of cold-spots. Actually, there are areas of negative z-scores, but they are not statistically significant and therefore are not shown. But what this means is that the spatial pattern created by the interventions of $t_{[3,4]}$ is much more sparse (i.e. with less interventions[159]) and also more dispersed. Thus, the average occurrence of network interventions is much lower and not sufficiently different from places with very few occurrences, or even none. This is in large part caused by the smaller size of this period's sample but also by the more dispersed pattern, as revealed by the smaller size of hot-spot areas (which could be more intense if the distribution was more concentrated). No new significative foci of urban development appear at this last time-interval and the relation of those that are visible and the non-incremental interventions remains vague.

However, that relation is not obvious only because it is not instantaneous, but *cumulative through time*. Figure 150 shows the same analysis of the incremental interventions of each time-interval, but now superimposed with the *growing* system of non-incremental interventions, and not only with those of each period. What happens is that some of those non-incremental interventions (metropolitan motorways, for the most part) seem to have impact only in the period *subsequent to their construction*, or even later, when integrated in the progressively connected motorway system. The several zones of congruence between urban growth hot-spots and the metropolitan motorway system are flagged in Figure 150. The impact of such system on urban growth becomes now evident; but, naturally, it should not be seen as the only driving force of urban expansion, as many urban growth foci remain without a clear relation with it.

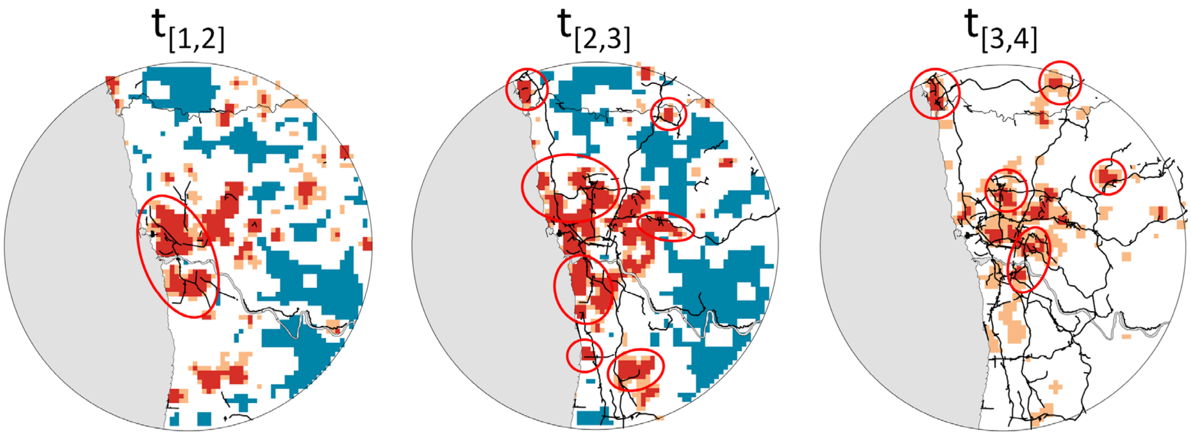

Fig. 150 – Hot-spots analysis of the incremental interventions of each $t_{[a,b]}$, overlayered with cumulative non-incremental interventions from each time-interval.

Actually, even if the correlation between the metropolitan motorway system and the occurrence of areas of intense urban growth seems undeniable, that is not enough to decide what causes what. The temporal resolution of this study is not enough to answer that question, which is a causality dilemma very much of the 'chicken and the egg' type. Some growth areas seem triggered by the appearance of motorways (and of their local connections, of course), others seem to precede and to actually justify them, and still others seem to grow indifferently of their absence. As we have seen in Chapter 3, the metropolitan spatial network has centrality patterns that are far more complex than simplistic road hierarchies, and there are many types of highly central roads and streets which are not motorways but that may be active urban growth inductors.

We now inspect the evolution of the first level of our typomorphology, namely the super-classes of *large* and *small* interventions. Figure 151 shows their shares at each time-interval; we have also included in the figure two plots depicting the means of the road-lengths of the interventions of both

[159] With the less interventions because the extent of the time-interval is shorter; not because urban growth is less intense.

classes (Figure 151, left), which show that they are rather stable through time. Large interventions of all periods have a mean road-length of 934 meters (maximum variation of 220 meters) and small interventions of all periods have a mean road-length of 370 meters (maximum variation of 110 meters). So we may look at their road-length shares with confidence.

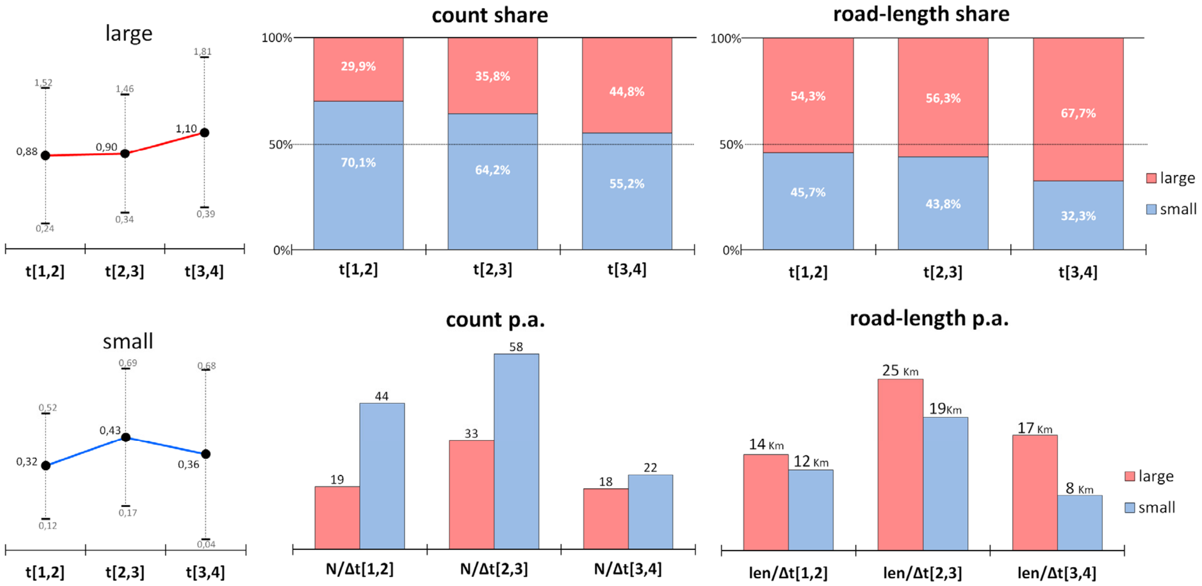

Fig. 151 – Shares of large and small incremental interventions at each $t_{[a,b]}$.

The obvious observation is that large interventions - the minority at $t_{[1,2]}$ - gradually become more common, until attaining almost half of the count share at $t_{[3,4]}$. Regarding their road-length share, they are always prevalent, but very marginally at $t_{[1,2]}$ while attaining almost 70% of the total length of new roads at $t_{[3,4]}$. The lower plots on Figure 151 (and also those on the left) show that large interventions also become increasingly larger through time, besides their increasing prevalence. Their counts per year at $t_{[1,2]}$ and $t_{[3,4]}$ are almost equal, but the road-length produced per year at $t_{[3,4]}$ is significatively higher. In contrast, small interventions suffer a marginal increase in average length through time, but they become much less prevalent. What all this indicates is that, independently of any other morphological characteristic (i.e. ciclicity and connectivity) and considering only their sizes, the interventions made to the metropolitan spatial network clearly tend to be more extensive through time, both in absolute terms but also through the progressive prevalence of large interventions. If we look again at the upper images of Figure 149 (page 227), the very small size of interventions at $t_{[1,2]}$ is quite evident, when compared to those of the subsequent time-intervals.

It is if the first generations of incremental interventions, especially those from $t_{[1,2]}$ but also from $t_{[2,3]}$, were characterized by a timid - or perhaps cautious - urban development *pathos*. Many of the small interventions of $t_{[1,2]}$, especially those located far from existing urban areas or at their peripheries, are 'clandestine'[160] urban operations, promoted by private developers still free from the strict control of municipal agencies. These were small, rather precarious and piecemeal divisions of rural land, absolutely non-planned and erratic, clinging to the existing street network where the opportunity arose. But besides this type of illegal urban development, quite common during $t_{[1,2]}$, also the generality of all incremental interventions from that time-interval are rather small. Perhaps private developers, during the 60s and 70s, were still probing the new economical affluence of a country that had lived for four

[160] In Portugal, 'clandestine' allotments, occurring typically at the hinterlands of Lisbon and Oporto's metropolitan areas, are a specific and datable kind of urban development, common in '60s and '70s. At that time, public agencies were still far from the territorial control they have today. The demand for decent housing conditions by an increasingly affluent working class (very poor until then), gave rise to a wave of speculative, piece-meal and non-legal urban developments, which constituted at the time an affordable housing alternative.

decades under an absolute social immobility and economical stagnancy, imposed by the isolationist dictatorial regime of Oliveira Salazar[161].

But after the democratic revolution of 1974 (occurring at the end of $t_{[1,2]}$), the size and scope of metropolitan incremental urban development changes, driven by the rising demand of an emerging middle class, by the inflow of rural populations to Oporto and Lisbon's growing metropolitan areas and also by the novelty of housing loans. The results depicted in Figure 151 clearly reflect that change. We may thus identify a second generation of metropolitan incremental interventions, appearing during $t_{[2,3]}$ but definitively installed at $t_{[3,4]}$, among which the 'large' super-class prevails and which are responsible for almost 70% of the total road-length produced during the last time-interval.

The evolving spatial distributions of the two super-classes of small and large interventions, depicted in Figure 152, also reflect these historical transformations. On that Figure, as well as on those following, we use a technique which allows visualizing simultaneously the hot-spots[162] and the interventions of two morphological classes, in this case small and large interventions. The technique is fully described in Figure 147 (page 224) so we will not delve its details now, but just draw attention to the legend of Figure 152, which should be sufficient to allow its interpretation.

At $t_{[1,2]}$ small interventions and their corresponding hot-spots (in blue) occur predominantly outside of the metropolitan core or of other urban centres, tending clearly towards the periphery of the study area. Some areas of overlap of small and large hot-spots (in violet) occur also at the core. But large interventions and their corresponding hot-spots (in red) are rare outside that area, while small interventions clearly prevail. At $t_{[2,3]}$ a strong increase of large intervention's hot-spots (in red) is noticeable, especially around the metropolitan core. Small interventions are still very present, with large areas of overlapping hot-spots (both small and large, in violet) around the core and still some isolated peripheral concentrations of small interventions. But the pattern has clearly changed, when compared with the previous one. At t[3,4] the change is complete and many more hot-spots of large interventions are visible, while the areas of concentration of small interventions have strongly receded; the last pattern is almost the chromatic inverse of the first one.

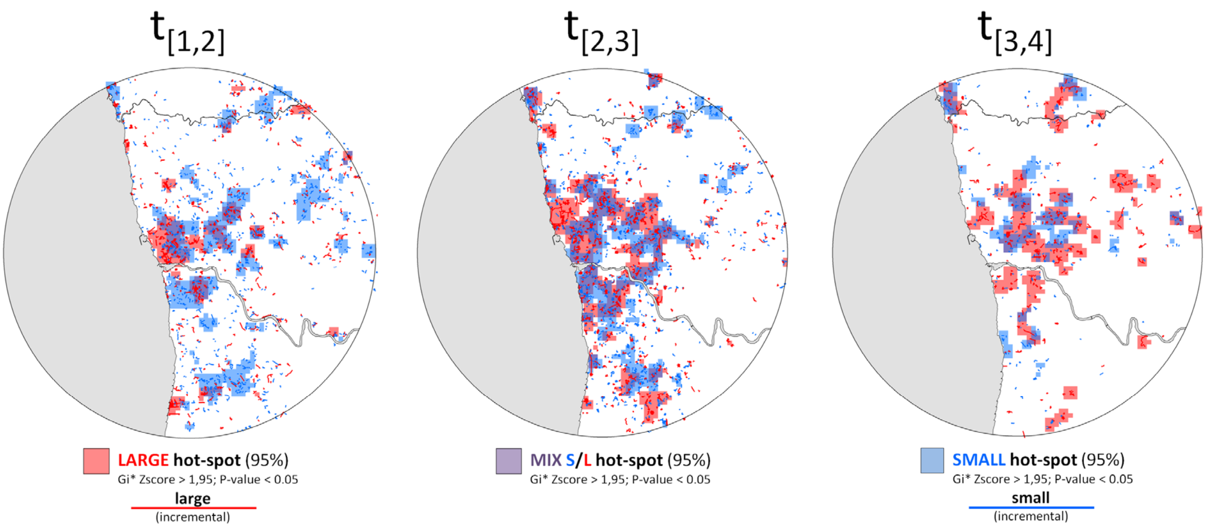

Fig. 152 – Hot-spot analysis of large and small incremental interventions at each $t_{[a,b]}$.

[161] António de Oliveira Salazar (1889-1970) ruled Portugal from 1932 to 1968 with tight grip, under a single-party regime of proto-fascist matrix. The dictatorship was only overthrown in April 25th of 1974, in a peaceful revolution that implemented a modern democratic regime.

[162] Because the sets of network interventions isolated according to the several morphological super-classes and by time-interval are much smaller than those shown on Figures 25 and 26, cold-spots (i.e. areas with z-score < -1.65) are always non-significant in statistical terms (i.e. their P-values are always higher than 0.1). Thus, on Figure 28 and on the following, only hot-spots are shown.

Regarding the super-classes of *cellular* and *linear* interventions a different type of regularity is noticeable (Figure 153). In contrast with the variability of large and small interventions, we observe now an almost invariant pattern. The rarity of cellular interventions, i.e. interventions with internal blocks, seems to be permanent in temporal terms. There is an increase in their count share and also (albeit to a smaller extent) in their road-length share from the first to the second time-intervals, but it stabilizes afterwards. At all temporal periods cellular interventions are always a minority, never attaining even a fifth of the occurrences of linear interventions. And even if the average road-length of cellular interventions (1084m) is almost three times longer that of linear interventions (384m), their maximum road-length share (attained at $t_{[2,3]}$) is just 32,3%. Thus, although reflecting the urban growth intensity peak at $t_{[2,3]}$ and becoming more common afterwards, interventions with internal cycles are always exceptional.

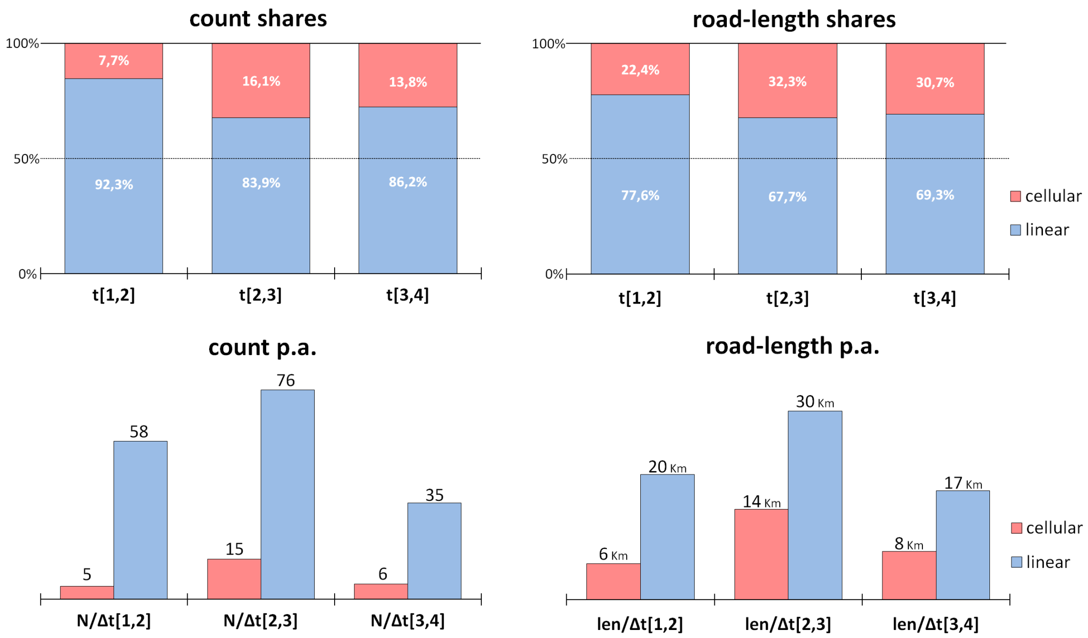

Fig. 153 – Shares of cellular and linear incremental interventions at each $t_{[a,b]}$.

It is important to stress that the creation of new urban blocks is not an exclusive attribution of cellular interventions. Linear interventions, especially of the conjunctive type, always create new cycles in the metropolitan network (external cycles, on that case); and even linear disjunctive interventions (which are acyclic by nature) may end up contributing to the creation of new cycles, through their accumulation through time or through the posterior connection with conjunctive interventions. The only attribute that is exclusive to cellular interventions, is that they create new blocks *within* the intervention itself; i.e. their layouts are defined in such a way as to produce internal blocks. And it seems to be that street layout design option, albeit possibly often constrained by the size of the available land parcels[163], that is truly exceptional. In the absence of comparative cases, we can only interpret this fact as a specificity of the metropolitan region under study; perhaps a local cultural idiosyncrasy, perpetuated by some endemic scarcity of resources or of entrepreneurism boldness. But this is a cursory and little scientific hypothesis, that we only put forward after failing in finding a more satisfactory answer for this fact. In any case, it is a fact, plainly demonstrated by our results.

[163] As already mentioned in Chapter 1, the structure of land-tenure in Oporto's region and, in fact, in all Peninsular northwest above the Douro river (which, up to 1139, was integral part of the Kingdom of Léon), is characterized by quite small and irregular land parcels, whose genesis is very ancient (dating at least from the post-Roman, Suevic and Visigothic periods, 409-507 AD). At these remote times of weak and little centralized secular power, agricultural land was divided at the individual family level, producing a micro-scaled and irregular land-tenure structure, which in many areas survived until today.

The spatial distributions of cellular and linear interventions reflect their shares' temporal behaviour (Figure 154). The maps of all time-intervals are dominated by blue hot-spots representing concentrations of linear interventions, while showing just a few areas where cellular interventions create significative concentrations (in red). At $t_{[1,2]}$ cellular interventions show some tendency to occur at the metropolitan core and on other urban centres, but that tendency seems to decrease from $t_{[2,3]}$ on and is no longer noticeable at $t_{[3,4]}$. An interesting addition that the maps of Figure 154 make to what has been said before is that cellular interventions, besides being rare, apparently cluster very little (hence the scarcity of red hot-spots on the maps of Figure 154). They appear occasionally, here and there over the entire study area, but seldom so close to each other as to produce hot-spots. Looking closely at the maps of Figure 154, it is possible to see several isolated cellular interventions (in red), but enough separated from the next one to be non-relevant occurrences in terms of spatial clustering.

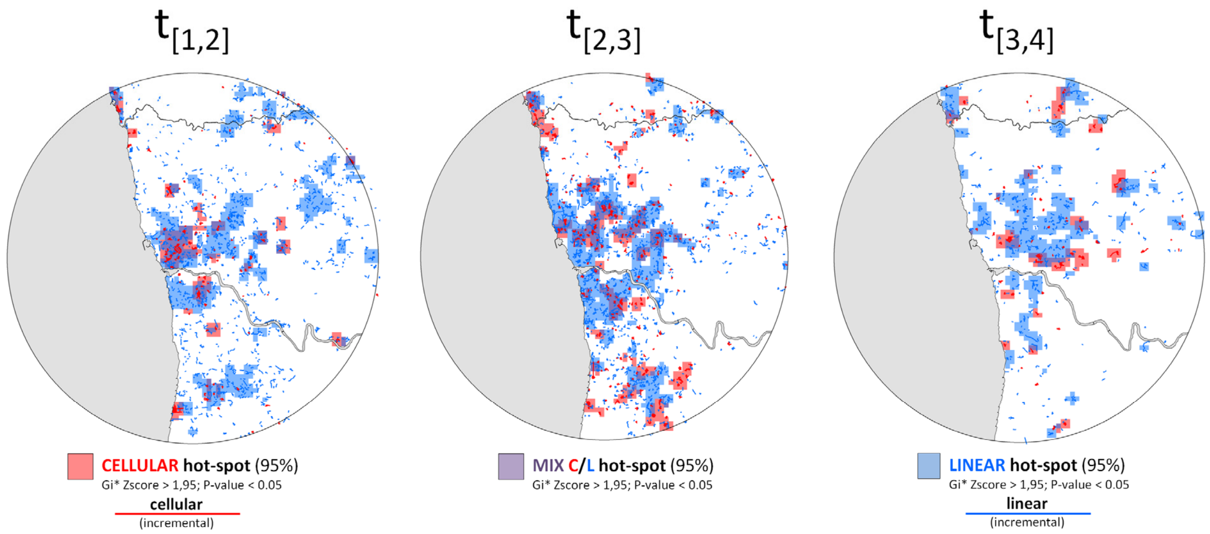

Fig. 154 – Hot-spot analysis of cellular and linear incremental interventions at each $t_{[a,b]}$.

We now look at the last hierarchical level (or at the last two super-classes) of our typomorphology of metropolitan network interventions, which separates them in terms of their internal and external connectivities, as *conjunctive* or *disjunctive* interventions. We recall that disjunctive interventions (be them large or small, cellular or linear), are mainly characterized by the fact that they connect to the existing grid, so as to provide public access to their own street layouts, but in doing so they do not create (or create very few) new connections between existing streets. The same is to say that they do not create new circulation alternatives (or at least not significant ones) because, by definition, their street layouts lead only to 'themselves' and not to any other place. Conversely, conjunctive interventions (again, of any size or ciclicity class) always create new connections between existing streets, sometimes several and quite significative ones, thus modifying the existing local connectivity state and potentially creating new circulation alternatives within the metropolitan spatial network. In terms of their internal connectivities, conjunctive and disjunctive interventions also differ, namely through the absence of culs-de-sac in the former type, and by their recurrent presence in the latter type (besides other internal and external specific characteristics, already detailed in Section 4.4.).

Resorting once again to biological metaphors, we could say that disjunctive interventions are like parasite organisms, using their host's circulatory system for their own good without providing anything in return. And we could say that conjunctive interventions are like symbiont organisms, beneficial biological partners using their host's circulatory system for their own ends but in return improving and expanding it. Metaphors have a limited scientific value of course, but a careful observation of the 48 intervention examples provided in Figure 146 (page 222) shows that this is not too far from the relationships that conjunctive and disjunctive interventions establish with the existing street network.

These *qualitative* differences between conjunctive and disjunctive interventions are important because they refer to completely different network structures: highly connective, cyclic and continuous structures in the case of conjunctive interventions; and little connective, acyclic and less continuous structures in the case of disjunctive interventions. Their different prevalence at different moments in time and at different zones of space, may therefore also imply different local network structures. And, in fact, these two super-classes of network interventions show significative temporal and spatial variations.

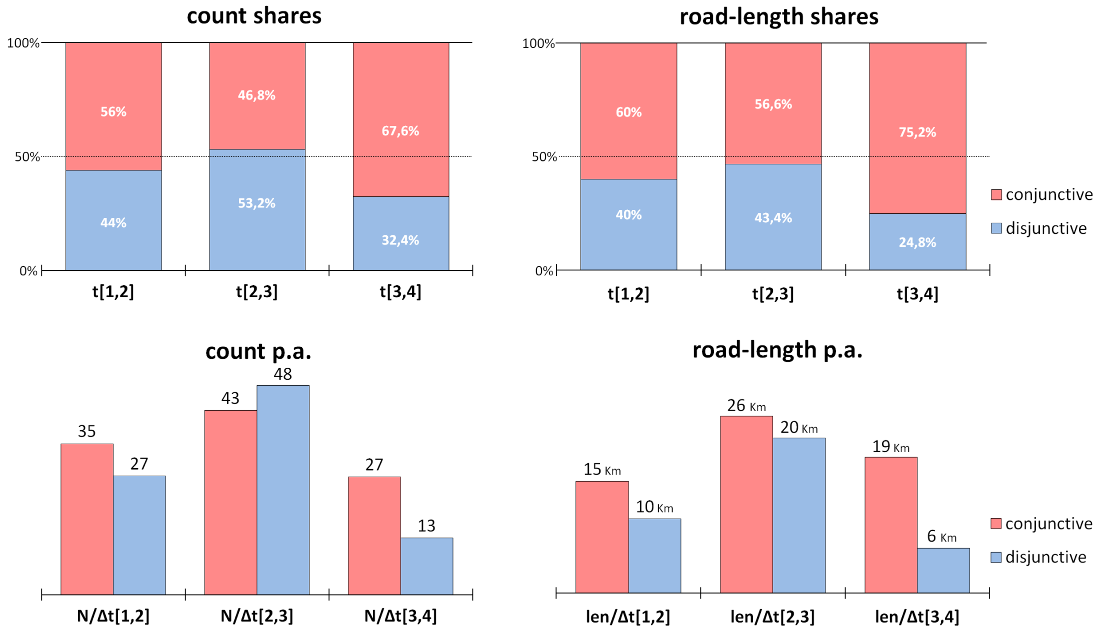

Fig. 155 – Shares of conjunctive and disjunctive incremental interventions at each $t_{[a,b]}$.

Figure 155 shows the shares of conjunctive and disjunctive interventions. The two super-classes show very significative variations at each time-interval. In terms of the count of their occurrences, conjunctive interventions are prevalent at $t_{[1,2]}$, with a difference in share from disjunctive interventions of 12%. But at $t_{[2,3]}$ they are surpassed by disjunctive interventions by 6,4% (which have a share variation of +9,2%). And then, at $t_{[3,4]}$, disjunctive interventions are again overrun by conjunctive ones, plunging with a share variation of -20,8%. The road-length shares show a very similar variation pattern; but conjunctive interventions have always higher shares, even if during $t_{[2,3]}$ the difference is reduced to 13,2% (representing only 63 Km, in a total of 955 km produced at $t_{[2,3]}$). This is explained by the different average lengths of each super-class (382m for disjunctive interventions and 547m for conjunctive ones). The same reason explains why the count per year of disjunctive interventions surpasses that of conjunctive ones at $t_{[2,3]}$, but not the number of kilometers produced per year, on which conjunctive interventions are always more prolific.

In terms of variability and amplitude, these temporal changes in the shares of conjunctive and disjunctive interventions are clearly the most significative of all super-classes. Moreover, they pertain to quite specific morphological characteristics and not to general ones, as the size or the internal ciclicity of the interventions. Even if accounted in a very aggregated way (i.e. concatenating all types of conjunctive and disjunctive interventions), they suggest pronounced morphological cleavages between different temporal moments, that were by any means so clear in the previously analyzed super-classes.

The prevalence of disjunctive interventions at $t_{[2,3]}$ is very significative, because that is the time-interval when urban growth was more intense and when the largest share of the metropolitan network was produced (48,5% of the total road-length created by all incremental interventions along 60 years). Thus, we now know that it has been predominantly produced in a *disjunctive* way. But the immediately subsequent reduction in the production of disjunctive interventions at $t_{[3,4]}$ is simply remarkable: 20,8% is by far the strongest absolute amplitude of variation in count share observed, the second highest being 9%[164].

The reduction of disjunctive interventions from $t_{[2,3]}$ to $t_{[3,4]}$ is so drastic, that one could believe it to be the outcome of some draconian and blindly followed planning directive, aimed at fighting the disjunctive morphologic type. However, nothing could be more far from the current planning or political realities of Oporto's metropolitan region (or of Portugal, for that matter), not to mention those realities at the decades corresponding to $t_{[2,3]}$ (1977-1998). If, in any case, the observed variation was caused by urban planning influence, then such influence has been exerted in a completely unspoken and uncoordinated way. But if, on the contrary, it has nothing to do with urban planning influence[165], then it is all the more surprising; because it can only result from the even more uncoordinated actions of individual private developers, acting only according to their own financial goals and to their own readings of the local urban market demands.

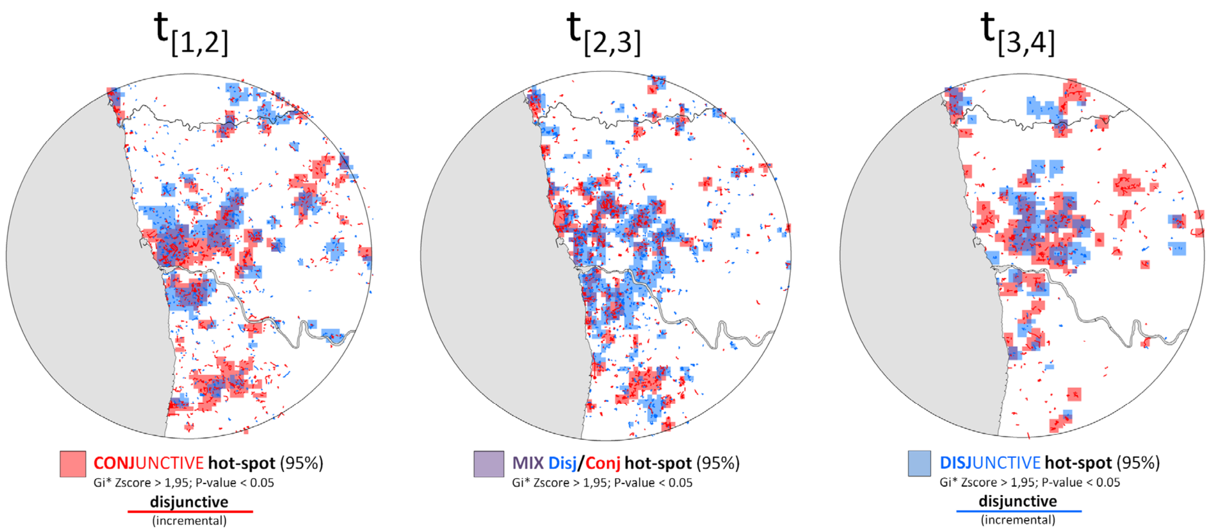

Fig. 156 – Hot-spot analysis of conjunctive and disjunctive incremental interventions at each $t_{[a,b]}$.

The evolution of the spatial distributions of these two morphological super-classes (Figure 156) reveals yet other unexpected peculiarities. First, in spite of some large areas where concentrations of both classes overlap (in violet), the total area *predominantly* constructed by just one of the two classes (i.e. corresponding to conjunctive or disjunctive hot-spots, but not to both) is significatively larger at each time-interval. The percentage of overlapping hot-spot polygons at each $t_{[a,b]}$ is always less than one quarter of the total (22.4% at $t_{[1,2]}$, 21.3% at $t_{[2,3]}$ and 15% at $t_{[3,4]}$). Second, there are also some few areas that are hot-spots of just one of the two classes, at *two consecutive* time-intervals (most notably, the constant conjunctive hot-spot at the south of the study area). The percentage of polygons that are hot-spots of the same class both at $t_{[1,2]}$ and $t_{[2,3]}$ is 8.2%, and the same percentage from $t_{[2,3]}$ to $t_{[3,4]}$ attains 10.1%. At all periods, the zones of stronger overlap occur within the large new urban areas around the metropolitan core and at the centres of the expanding peripheral towns.

[164] Observed for large interventions, as the increase of their count share from $t_{[2,3]}$ (35.8%) to $t_{[3,4]}$ (44.8%).

[165] From our personal knowledge of the local planning reality, we would say that this second hypothesis is far more probable.

The areas of purely conjunctive or disjunctive concentrations tent to occur at the borders of these main growth centres, i.e. at their immediate expansion fronts. At $t_{[1,2]}$ some of these areas are conjunctive, others disjunctive, without clear prevalence among classes. However, at $t_{[2,3]}$ a disjunctive 'blue ring' is clearly noticeable around the City of Oporto. This is the period when the metropolitan core coalesces into a continuous structure, formed by Oporto and its immediate surrounding towns, to which we have called 'inner satellites' on Chapter 3, and that we see here being predominantly produced by disjunctive types. At the periphery, this period's growth foci still show an even distribution of disjunctive and conjunctive hot-spots. But at $t_{[3,4]}$ the number of conjunctive hot-spots becomes much higher, at all points of the study area, clearly surpassing the occurrence of disjunctive concentrations.

These varying spatial distributions of disjunctive and conjunctive interventions are perhaps even more surprising than their temporal share variations. In terms of their spatial distribution, one would expect a more-or-less random mix of the two classes at places where urban growth is more intense, simply because there is no obvious reason for local preferences on so specific morphologies. In fact, that is what happens at the nuclei of the most intense growth foci, where the occurrence of both types is equally probable. But at their fringes and outside those areas, sharp differentiations between the occurrence of conjunctive and disjunctive interventions are evident.

Location differences between large or small interventions are understandable: they imply quite different levels of investment, which may be better reproduced on some places than on others; hence the prevalence of large interventions at the metropolitan core and other urban centres. However, as we have seen with cellular and linear interventions, spatial cleavages between specific morphologies are improbable: cellular interventions were simply less common than linear ones and showed no specific location pattern. But regarding conjunctive and disjunctive interventions (whose respective proportions are much more even than those of cellular and linear interventions), areas of overlapping hot-spots are not the rule and it seems clear that such morphological cleavages at the spatial level indeed do exist.

Before proceeding with the last step of the analysis produced in this section, namely the exploration of the temporal and spatial evolution of the eight individual morpho-types defined before, we provide in Figure 157 (next page) a summary of all the spatial distributions discussed above. That image shows how the distributions of the three morphological super-classes follow closely those of all non-incremental interventions (depicted in the upper row of Figure 157); these describe the spatial dynamics of metropolitan growth, by making explicit the areas of most (or of least) intense production of streets through time. Such concordance is, of course, only to be expected; other result would be a clear sign of incoherency. But the image also shows that the dual attributes described by each super-class have quite different location patterns across time and space. Except in the case of cellular interventions, whose spatial distributions seem essentially aleatory, large/small and conjunctive/disjunctive interventions reveal clear and time-changing spatial cleavages.

The degree of information in these images is high, indeed surely more than were able to extract. But we believe that those images leave also little doubt that detailed metropolitan morphologies, if well defined, numerically quantified and rigorously spatially visualized, may become accessible objects of scientific inquire. And that we may definitely begin to explore them, systematically and at a truly metropolitan territorial scale.

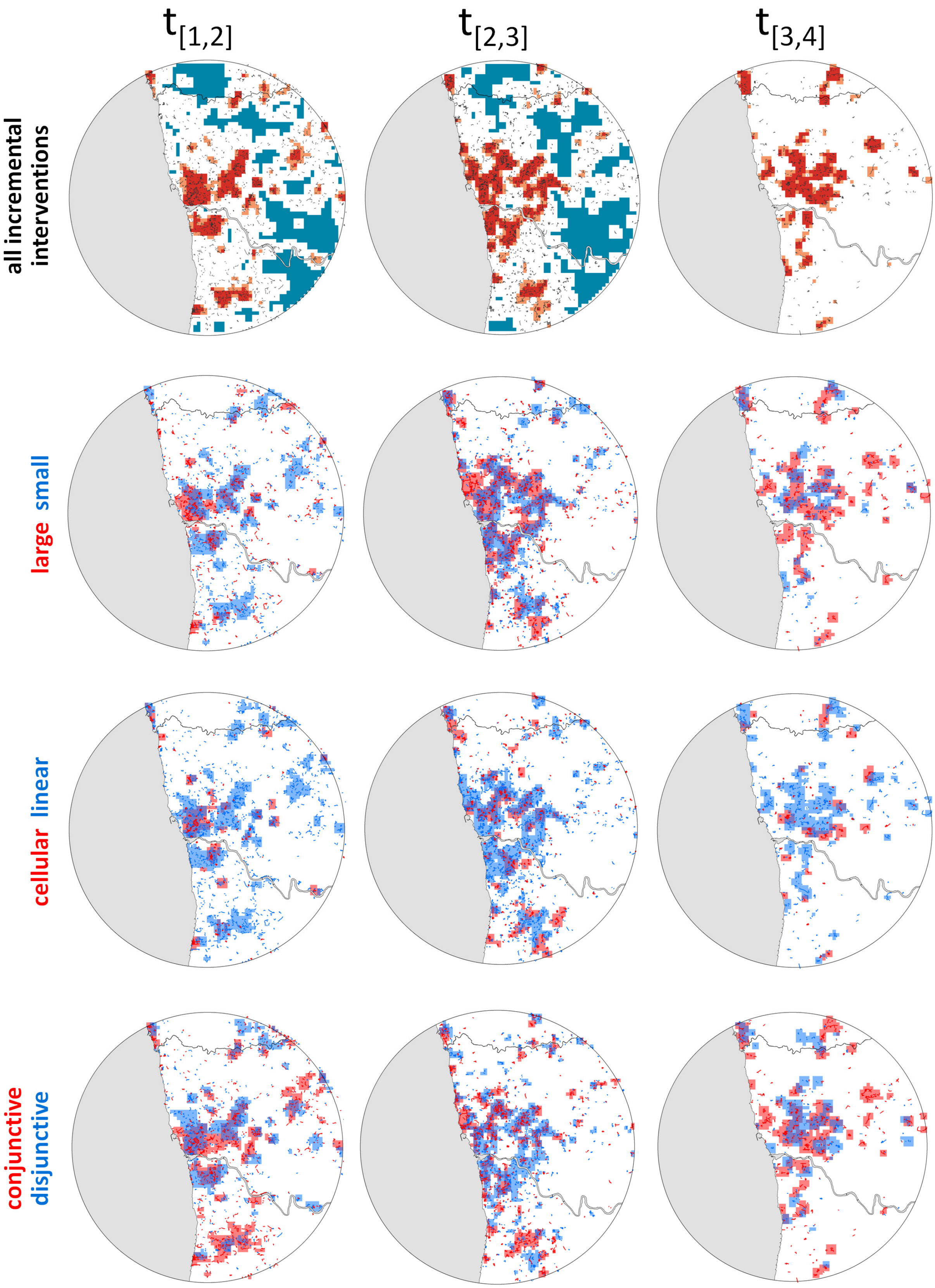

Fig.157 – Hot-spot analysis of all types of incremental interventions at each $t_{[a,b]}$.

We now reach the last level of our typomorphology of metropolitan network interventions: their division into eight different morpho-types, corresponding to the eight possible combinations of the classification sequence [large/small] → [cellular/linear] → [conjunctive/disjunctive]. Figure 158 shows the evolution of the count and road-length shares of the eight morpho-types, at all time-intervals. Each of the four plots represents two types of interventions (thus, describing all the eight types), distinguished by their respective count and road-length shares. Separated in this way, the occurrences of several types show further temporal variations. We can now see that the general pattern observed before for the super-class of conjunctive/disjunctive interventions - that is, prevalence of conjunctives $t_{[1,2]}$, then of disjunctives at $t_{[2,3]}$ and then again (quite abruptly) of conjunctives at $t_{[3,4]}$ - has actually internal differentiations.

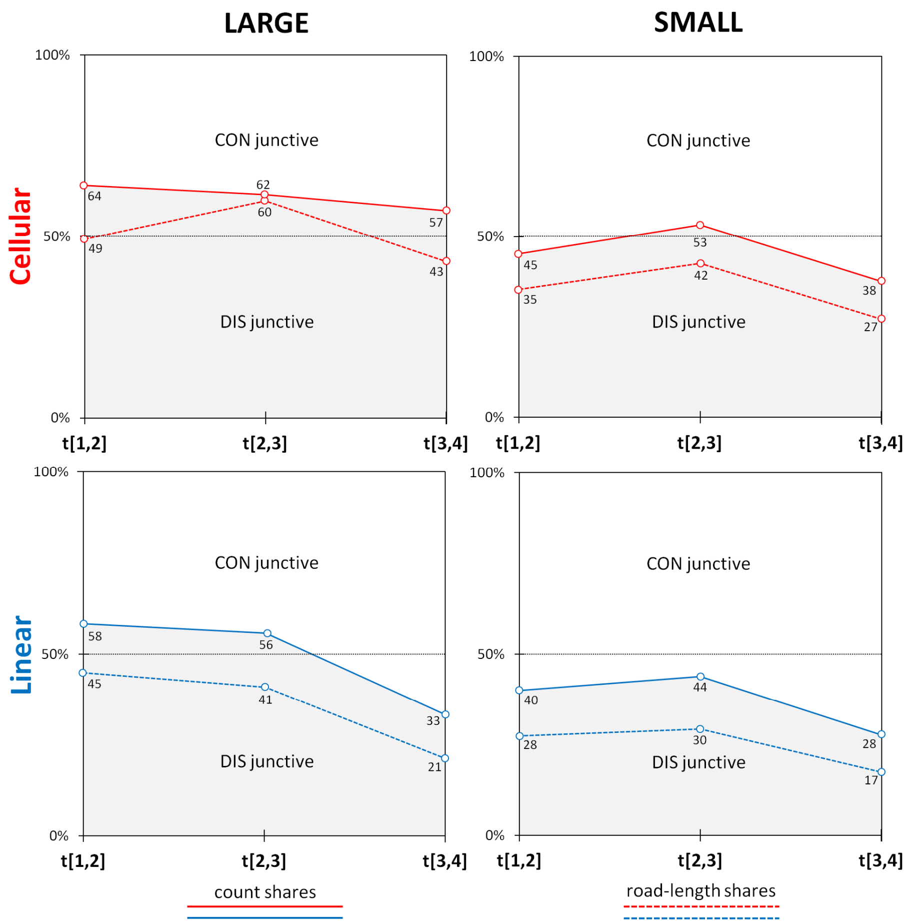

Fig. 158 – Shares of all types of conjunctive and disjunctive incremental interventions at each $t_{[a,b]}$.

The prevalence of disjunctive interventions at $t_{[2,3]}$ is confirmed for all morpho-types, except in the single case of small linear disjunctive interventions. However, it now becomes apparent that one type is *always* predominantly disjunctive: **large cellular disjunctive** interventions (Figure 158, top left); it becomes slowly less predominant through time, but shows at $t_{[2,3]}$ an even higher road-length share than its conjunctive analog. Furthermore, there is also one disjunctive type which is *never* predominant: **small linear disjunctive** interventions (Figure 158, bottom right). They show also an increase at $t_{[2,3]}$ but do not surpass their conjunctive counterparts. Actually, and besides this fact, small linear disjunctive interventions show a significative drop at $t_{[3,4]}$ (-16%), reaching then the lowest count share of all disjunctive types (28%). For their part, **large linear disjunctive** interventions (figure 158, bottom left) prevail during the second but also during the first time-intervals; but then they endure the strongest decrease (-23%) at the last time-interval, reaching the second lowest level of all disjunctive types (33%). Finally, **small cellular disjunctive** interventions (Figure 158, top right), are the only that truly follow the previously observed pattern, with an almost equal share to their conjunctive counterparts (albeit lower) at $t_{[1,2]}$, an increase that makes them slightly prevalent at $t_{[2,3]}$ followed by an accentuated drop and loss of share dominance at $t_{[3,4]}$.

In all cases, except in the surprising exception of **large cellular disjunctive** interventions, the road-length shares are always about 20% less than the count-shares, making all disjunctive types the minority in that respect. As already mentioned, disjunctive types have shorter average road-lengths; besides, their road-length and count share's curves are parallel, which shows robustness in both results. But one could argue then that the compared impact of conjunctive interventions would be higher, or at least equal, to that of disjunctive interventions. However, this is not an obvious or linear conclusion. Because in all networks - even in highly geographically constrained street networks - local changes or additions may have very different structural impacts, not only locally but also at far more extensive scales. And what is factual, is that the count shares indeed reveal the frequent - and at certain times clearly prevalent - choice for disjunctive morphologies, each time that an incremental intervention is made to the metropolitan street network.

To which extent we may really call 'choice' to the act of designing a disjunctive street layout, as we have come to define it, is difficult to ascertain. Is it an individual or a collective choice? Made by an urban design team or by an administration board? Is it, in fact, a choice at all (in the sense of conscious, deliberate choice)? These are important and relevant questions, however out of the scope of this work.

Nevertheless, our results show (rather explicitly, we believe) that the several disjunctive types of interventions are indeed morphologically different from their conjunctive counterparts; and we recall that those types were defined by objective methods and not solely by the analyst's 'eye', and thus they are surely not 'in the eye of the beholder'. They are substantive, empirically derived urban morphological classes, based on a very large sample of observations. Thus, whether the product of deliberate design choices or of the whims of unaware urban developers, the discovered street-layout morphological types are real. Additionally, their frequencies through time and space have shown plausible variations (even if eventually unexpected): not too faint as to be trivial neither to rampant as to be unlikely. Therefore, not only they reveal recurrent and endemic morphological trends in the urban operations that have constructed Oporto's metropolitan spatial network along 60 years, as they constitute evident objects of appropriation by urban planning (at least at the region under study), in the sense that they constitute empirically derived and reliable knowledge about existing city-building *praxes*, liable of being regulated, fostered or mitigated.

As final result of this Chapter's exercise, Figure 159 (next page) shows the synchronic spatial distributions (i.e. all time-intervals together) of the eight morpho-types of metropolitan network interventions. The reason why these are shown synchronically is due to the fact that they isolated samples by time-interval are in some cases rather small, making their spatial analysis by hot-spots impracticable (i.e. statiscally meaningless, or highly not recommended). We will not comment in detail the several spatial distributions, because many of the patterns they convey have already been described; but also because our intention is not exclusively to dwell on those patterns, but above all to make clear that they exist. Especially in the case of all linear interventions and on that of small cellular interventions (which have significantly large samples), the patterns depicted by their hot-spots have a strong degree of reliability (namely 90% of confidence that they are not caused by aleatory effects). As it is possible to observe, those patterns are all quite different, showing that the several morpho-types undeniably occur with different frequencies on different areas of the metropolitan region. Therefore demonstrating that, at the scale of the micro-components of metropolitan spatial growth, there are unexpected but real morphological regularities with specific location patterns, which may now begin to be further studied and understood.

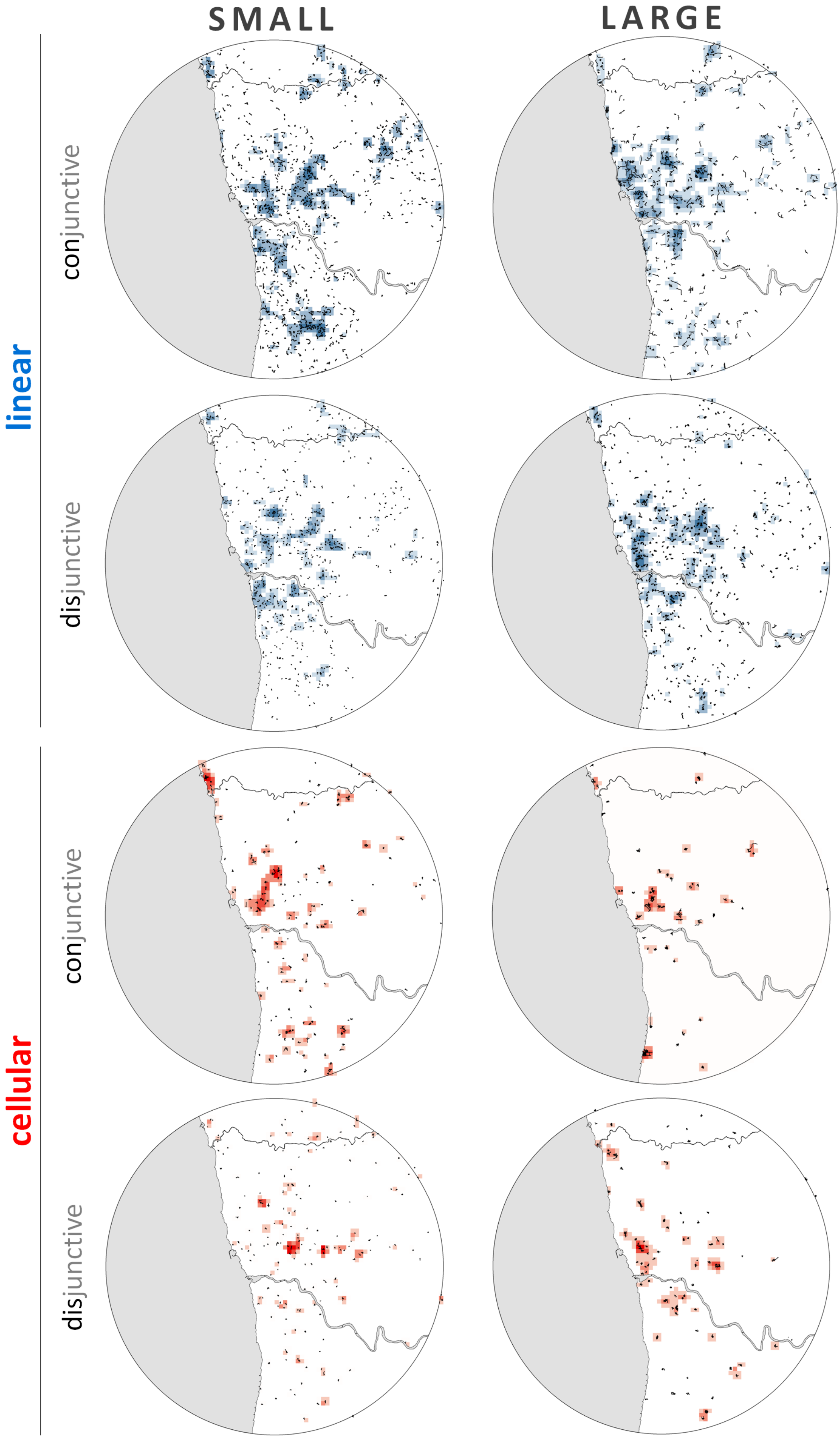

Fig. 159 – Synchronic hot-spot analysis of all types of incremental interventions.

7

CONCLUSIONS

7.1. GENERAL DISCUSSION AND CONCLUSIONS

This work set out to define an integrated framework for metropolitan morphology. Such objective was established from the verification of two current knowledge gaps: one concerning the notorious lack of understanding of the intrinsic morphological characteristics of contemporary metropolitan regions; and another concerning the methodological and analytical fragmentation of the discipline of urban morphology, whose aim is to understand the physical and spatial structures of urban objects. From the beginning it became clear that the former issue was, to a large extent, a direct consequence of the latter.

In fact, even if the need to further explore and to understand metropolitan morphology is widely acknowledged and repeatedly claimed, it seems that the pace at which such understanding advances is infinitely slower than the pace of metropolitan development. The situation is paradoxical: cities (and city-regions) are human artifacts - nothing beyond human agency is responsible for their growth and change; yet, those claiming to have some acquired knowledge on the form of cities, stare at their current state with awe and bafflement - as if, overnight, some outlandish factor had abnormally distorted and augmented their study object.

How come we cannot understand anymore what we build? It is true that cities are complex phenomena, not trivial problems. But they always have been complex; even though today they may be much larger. However, complexity is not a function of size[166]. Urban morphology was born out of the fascination that cities create, exactly for being complex structures. And it was able to devise analytical methods that disclosed many of their intrinsic characteristics and formation processes. Thus, if that was possible regarding historical cities, why not regarding metropolitan regions?

These were the issues driving this work. We started by proposing that the main factor hindering the understanding of metropolitan form is the methodological and analytical fragmentation of urban morphology as a discipline. That problem has been addressed previously by Karl Kropf (2009), who tried to systematize and classify the concepts underlying the several analytical approaches to urban form, and to devise common criteria for their possible future integration under a common conceptual framework. This unifying endeavor was also one of the drivers of this work.

Chapters 1 and 2 have identified a series of *necessary conditions*, underpinning a possible integrated analytical framework for metropolitan morphology. These were related to (or resulting from) general characteristics of metropolitan regions previously indentified in the literature review, namely:

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[166] Unicellular organisms are quite complex and we are far from understanding their intimate functioning. However, 560.000 bacteria can easily fit on a pinhead.

a) their very large territorial scope and complex polycentric spatial structure, demanding analytical methods capable of assessing urban form not only at the regional scale but also at all spatial scales below that (i.e. from the region to the neighbourhood, or even below);
b) the fact that such vast territorial scope entailed a choice on which of the elements of urban form to assess, because it would make impossible the simultaneous study of them all (i.e. street, plot and building systems), and that that choice should be based on their different structural relevancies;
c) the need to incorporate the temporal dimension on analysis, because cities are dynamic objects that may only be understood through the observation of their formation (or morphogenetic) processes at the local scale, and through the emergent outcomes of such processes at the global scale;
d) the fact that all analytical methods to be chosen should fulfill the previous conditions while being mutually compatible, objectively defined, with quantitative outputs and capable of producing operational results.

The assessment of the existing methods of morphological analysis and of their advantages and drawbacks regarding the conditions above, led to the following methodological choices:

a) selecting *streets and street-systems* as the sole objects of analysis (because of their morphological structural importance; because of the availability and empirical proven value of the available techniques for their analysis; and because of the constancy and reliability of their depiction on old cartographic elements);
b) selecting *space syntax* as the main analytical tool to study the global, macro-morphology of metropolitan street systems (because syntactic analysis is scale-independent, thus capable of covering all possible metropolitan scales; because of its previous empirically validated results and well articulated theoretical contributions); and the choice of *classical typomorphological* and *street pattern analysis* for studying the individual, micro-morphology of the incremental development operations constructing metropolitan street systems through time (because of the relevance that typomorphologies, if well-defined, may have both for research and for urban planning and design practices; because of the quantification of street patterns that Marshall's (2005) techniques allow; because the latter technique may help to understand how the former may be quantified);
c) using the traditional *map regression technique* to integrate time into the analysis, in order to overcome the fact that both space syntax and street pattern analysis are static techniques (i.e. not integrating time as analytical dimension), but with several improvements enabled by its implementation in GIS.

But besides specific urban morphology methods, we also identified the potential advantages of two other analytical technologies, namely GIS and data mining. GIS had already been noticed in the literature review as a technology that could greatly enhance some of the existing methods of morphological analysis, and even mitigate some of their drawbacks; data mining was introduced as a package of statistical techniques used today in many scientific fields to overcome the problem of processing the huge data masses generated by current research methods. Its application in urban morphology, even if not unprecedented (Gil et al. 2012), has been highly developed in this work and may be seen as one of its original outputs.

The fact that time is of crucial importance in morphological analysis and that it would need to be previously integrated in street network data (because of the static nature of both space syntax and street pattern analysis) and the fact that both global (i.e. macro) and individual (i.e. micro) metropolitan morphologies would need to be assessed (in order to make available the study of potential causal relationships between micro and macro levels of urban form), led to the definition of *three fundamental analytical modules*, each one integrating different methods and fulfilling different and interdependent tasks. These modules, together with their functional relationships, make up the basis of the proposed *integrated analytical framework for metropolitan morphology*.

Each of these modules was subsequently developed in Chapters 3,5 and 6, whose findings we will discuss below. Chapter 4 constituted a fundamental methodological step, namely the empirical validation of the contemporary version of the spatial network model, without which further investigations would be undermined by doubt. But its subject is not part of this work's main objective; therefore, its results will be discussed in section 7.3, describing the outputs of this work to the specific field of space syntax.

7.1.1. DIACHRONIC AXIAL MODELLING IN GIS

Chapter 3 described the processes included in the first analytical module, namely the construction of the axial model and a new method for the generation of diachronic axial databases, developed for the model's subsequent temporal deconstruction. The main function of this module within the proposed analytical framework, is to encode the temporal dimension into the network data that will be explored by the macro and micro-structural analytical modules (described in Chapters 5 and 6, respectively). But besides this function, the method has several additional advantages.

Firstly, all diachronic information is stored into a single database and not in individual datasets. This allows for the simultaneous visualization, querying and analysis of all transformations made to the street network, while greatly simplifying the storing and management of diachronic information. Furthermore, it can serve as data source for any GIS spatial analysis, and not solely for the purposes concerned in the proposed analytical framework.

Secondly, as it recedes in time, the method creates and accumulates information, instead of discarding it. Diachronic axial modelling is usually conducted through the definitive erasing or altering of axial lines, without any record of the individual changes made to each line. By taking advantage of GIS capability of storing information both in spatial and tabular formats, the proposed method is able to record all additions and transformations that street networks suffer over time, without entailing any information loss. This makes available a wealth of diachronic information usually not studied as, for example: the isolated sub-sets of transformed axial lines by time, type and scope of transformation; or the spatial distributions of each type of transformation, their temporal frequencies and the kind of urban interventions that give rise to them. Besides, the method is not limited to the attributes used here (i.e. types of axial line transformation), but may include any attributes encoding other possible types of information (e.g. the land-uses or building typologies associated with each intervention, the type of promoter, etc).

Thirdly, the method includes the further disaggregation of the sub-sets of axial lines created or transformed between each observation moment, into the individual interventions made to the street network during that time. Such information will constitute the raw material to be processed by the third analytical module.

Fourthly, and finally, the method is not restricted to diachronic axial modelling, but is generalisable to any kind of street network representation, as standard road-centre lines. Such generalization would greatly reduce the time of the process (because, unlike axial maps, such datasets are readily available) and could lead to large comparative studies on the evolution of metropolitan street networks.

7.1.2. MACRO-STRUCTURAL ANALYSIS

Chapter 5 developed the second analytical module, dedicated to the study of the global morphology of metropolitan street networks. Its purpose is to analyze the evolution of metropolitan spatial centrality patterns across time, using the several temporal versions of the street network produced by the module described in Chapter 3. Space syntax was the technique chosen for this type of analysis. In fact, its main analytical theme is centrality in urban spatial networks, which may be assessed for each node (i.e. for each street segment) according to a very large range of radii, or graph neighborhoods (which may be interpreted as the centrality of each street-segment over a large range of spatial scales). In other words, syntactic centrality analysis is scale-independent. Therefore, instead of the rather simple image of a few urban centres within a metropolitan region, space syntax is able to disclose very detailed centrality patterns at the level of the street-segment, ranging from the local scale up to the scale of the entire region.

When spatial centrality is assessed in this way, it becomes obvious that each space in the metropolitan network is actually a ‘multi-centrality’ entity. A space may be central only at the local scale (e.g. an accessible neighborhood street), or only at the regional scale (e.g. a highway stretch between interchanges); but it may also be central at *several* scales (e.g. the neighborhood high street, which is important at the local scale but also as a main urban thoroughfare). Therefore a bold hypothesis becomes evident: that, in very large spatial networks (as metropolitan street systems), each individual space may in fact have a multitude of centrality roles, varying under all possible combinations across the entire spectrum of metropolitan scales. Moreover, spatial centrality may be equated under different types of metrics, describing different types of network properties (as closeness and betweenness), making the issue even more complicated, but also more promising in terms of potential outputs.

Chapter 5 started by acknowledging the very complex and variegated centrality structures that metropolitan street networks can contain, enclosed in the variable centrality values of each of its individual spaces across all scales; something that space syntax’s segment analysis is able to capture. We have called to this representational concept the ‘metropolitan centrality palimpsest’, which can be imagined as a cube made of many layers, each one corresponding to the centrality pattern of the metropolitan street network at each spatial scale (Figure 160, next page). In this mental image, the cube has three dimensions: two axes representing geographical space (i.e. x and y), and another axis representing the variables ranges at which centrality is assessed for every space in the network (or radii). From the shortest walking distances of the neighbourhood, to tens of kilometers in which distances are measured within urban-regions.

But if we had *time* to this ‘cubic’ representation of metropolitan spatial centrality, then it becomes a four-dimensional hyper-cube, which is no longer representable (either graphically or mentally). That is the situation that we have encountered while exploring this idea: that, in order to take full advantage of space syntax’s capability of thoroughly describing metropolitan spatial centrality, we also find a hyper-dimensionality problem that needs to be resolved.

Figure 160 summarizes the method developed in Chapter 5, for the second analytical module of the integrated framework. In a first step, the several temporal versions of the spatial network are processed using syntactic centrality analysis (top image). At this stage, each space (black dot) is only entirely described, when *all its centrality states* at each of the several spatial scales are taken into account. This raw centrality data is then explored with principal component analysis (PCA), in order to find *latent dimensions* among the range of spatial scales (or radii), previously selected for describing the entire metropolitan spatial continuum (bottom left image). In the specific case of centrality radii, these latent dimensions correspond to *natural centrality scales*, induced only by the structure of the metropolitan street network itself. Now each space may be described *only* by its centrality states on each of these natural scales. Finally, using the new centrality variables produced by PCA, the spaces of the metropolitan street network are explored with k-means clustering, in order to find *centrality regularities* among them; i.e. clusters of spaces sharing the same type of variability in the previously defined natural centrality scales (the black dots with varying images, on the bottom left image).

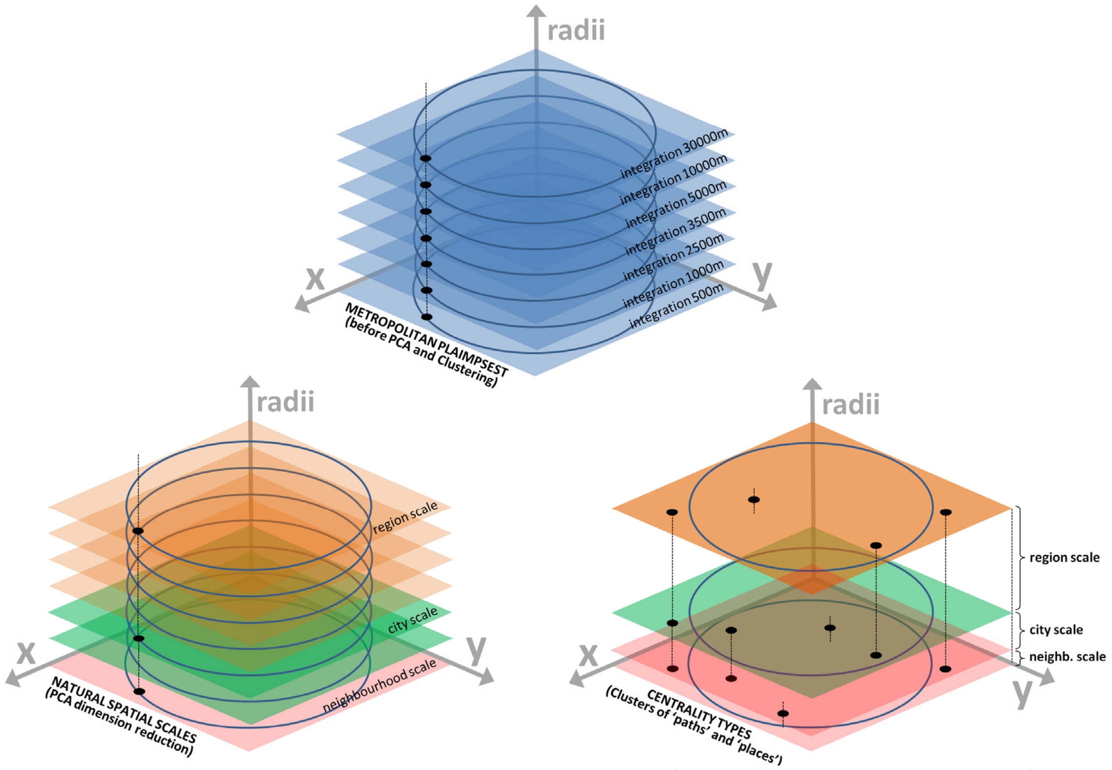

Fig.160 – Unpacking the metropolitan centrality palimpsest. Top: after space syntax analysis, but before data mining; bottom left: reducing the dimensionality of the metropolitan spatial continuum with PCA; bottom right: discovering centrality structures with k-means clustering.

The natural centrality scales found by PCA may be used and visualized as the original centrality variables, but they encapsulate *several* of those initial variables into a *single centrality pattern*. Therefore, not only do they make the manipulation and visualization of all centrality scales much easier, as they can be seen as the *only* scales at which *centrality operates with a certain metropolitan region*. In the present case, we have identified three natural scales: that of the neighbourhood, the city and the region; being notably stable through time, and therefore unquestionably factual.

The interest that this discovering of natural centrality scales may have to urban planning seems evident. In the present case any planning exercise taking the entire metropolitan region as object, would need to address (or to think on) only three scales, or spatial scopes: the *neighborhood*, the *city* and the *region*. Informed by these methods, a planning team can become aware that those are the *natural scopes* to which their options should be directed. This is not the same than to *intuit* that there *may be* three scopes for planning within Oporto's metropolitan region; this actually means *to know* that the street network - and indirectly all that is linked to it, or that flows through it - is factually structured that way.

However, one thing is to know that metropolitan spatial centrality operates that way; another is to know *where the strong structures* of each centrality level (or of any combination of those levels) *are located*. That is the purpose of the third step of this analytical module, namely the *classification* of all spaces in the network according to their *centrality behaviour* on the three natural scales. The two types of centrality metric used in syntactic analysis, integration (or closeness) and choice (or betweenness), describe quite different network properties which we have equated with the concepts of urban 'place' and 'path', respectively. Therefore, the centrality classes discovered with k-means may be seen as describing *types of metropolitan places and paths*: some are important locally, others regionally, others at varying spatial ranges. Two things are worth noting, regarding these metropolitan centrality typologies. The first is that the discovered types correspond to identifiable existing structures, albeit otherwise difficult to classify; the second is that they were also remarkably stable through time (i.e. they were not only present at some observation periods and not on others, albeit each class showed increases or decreases in size through time). Both these aspects strongly indicate that also these classes of *metropolitan places and paths* are reliable structures, and thus may be seen as empirical findings capable of informing metropolitan planning strategies. Their discovery led to the definition of *hierarchically structured taxonomies* of metropolitan centrality structures, constituting very concise but fertile spatial descriptions of the metropolitan region studied in this work.

Like the natural centrality scales discussed above, also these taxonomies of metropolitan places and paths may have a clear application in urban planning exercises. Some of the structures they describe are obvious, but analysis indicates their precise centrality roles. But they also reveal much less obvious centrality phenomena, like the classes representing small local centres (difficult to identify otherwise). Planning options and actions could be directed at these taxonomic classes of metropolitan places and paths (e.g. seeing them as location opportunities for public equipments, or as objects of structural improvement or maintenance). Also, they correspond to a limited set of centrality occurrences, clearly defined in space and in time. Thus, they may also be seen as the few 'pieces' of an otherwise very complicated metropolitan physical planning 'puzzle', something quite useful when addressing such vast and fuzzy territories, where clear targets are difficult to define.

7.1.3. Micro-structural analysis

Chapter 6 developed the last analytical module of the proposed integrated framework for urban morphology, dedicated to the typomorphological analysis of individual street network interventions. Recalling lessons learned in Chapter 1, we started by recognizing the important role that the definition of metropolitan typomorphologies may have, both to understanding of metropolitan form and to urban planning in general. However, the common subjectivity of criteria and of methodologies behind the definition of urban typomorphologies was also recognized as a hindrance to their direct and secure application in urban planning exercises. Stephen Marshall's (2005) work on the establishment of numerical parameters for the definition of street layout typologies was used as a central reference, on how to possibly obtain more consistent, reproducible and well-defined (i.e. numerical described) typomorphologies.

The raw material for this exercise is also provided by the diachronic modelling module, as datasets containing the sub-networks of each individual intervention made to the street network over time. A series of numeric morphological parameters was defined according to criteria discussed below, and the individual morphologies of all interventions were quantified in GIS, using simple semi-automatic techniques, described in detail on Chapter 6.

The choosing of these parameters is open to discussion, however. Unlike the data used in the macro-structural analysis module, which stems only from the centrality analysis of the entire metropolitan street network, the data used here implies certain choices on which morphological attributes to use, which may be questionable on other contexts. Moreover, these choices will always influence the end result of the classification. However, one thing seems clear: the distinction proposed by Marshall (2005) between *configurational* and *compositional* attributes of street patterns is well-defined enough to serve as a basic rule on any context. In this work it has particular importance, because it ensures the compatibility with the results produced by the second analytical module, as the these properties are very akin to those taken in account by syntactic analysis.

After morphological measuring and quantification, the following step of the process involves a series of descriptive statistics, in order to study the distributions of the chosen parameters. This has revealed basic cleavages among the sample of network interventions.

The first cleavage pertains to the identification of *non-incremental* and *incremental* interventions. By non-incremental interventions, we mean long, planned operations of infrastructure construction, whose purpose is clearly collective (e.g. high-ways or other regional roads). By incremental interventions, we mean much smaller private developments, whose purpose is commercial and non-collective. This distinction is very important, because our aim is to identify typomorphological regularities among the latter type. But their differences are so significative, that a simple outlier analysis (based mainly on their road-lengths) was enough to distinguish between these two types of interventions.

Once that distinction made, the remaining sample still showed extreme values in some variables. Further analysis revealed still another basic cleavage, this time between interventions with and without internal blocks, to which we have called *linear* and *cellular* interventions, respectively. The simple division of the sample according to this criterion was again enough to remove the remaining statistic irregularities. But more significative than that, is the fact that cellular interventions seem to be an absolute exception, at least in the context studied in this work. Such disparity is difficult to explain and further comparative studies would be needed, in order to understand if that is indeed a local specificity or something more constant.

Once the sample scanned and cleaned of extreme values, we could proceed to the final step of classifying the set of incremental interventions using several unsupervised methods. This resulted in the identification of four classes of cellular interventions and four other classes of linear interventions. In both groups, a similar set of regularities was found. Size was the most discriminant factor in both groups, but the second most discriminant factor was their external connectivities. We were able to identify a basic distinction between interventions creating strong connections with the existing grid, and interventions that used the external grid only for access purposes, being otherwise inwardly structured. The former type sub-divides the existing grid, creating new connections between previously separated streets; therefore we termed this type *conjunctive* interventions. The latter type simply clings to the existing grid and their street layouts seldom create new connections between existing streets; by opposition, we termed this type *disjunctive* interventions.

All classes were organized into a *single hierarchical typomorphology*, constructed according to the criteria of *size*, *ciclicity* and *connectivity*. We showed how this typomorphology was robust enough to clearly distinguish interventions with variable layouts, but also with a strong morphological resemblance, assessed not only in visual but also in numerical terms.

Next, the temporal frequencies and spatial distributions of the discovered types were explored, in order to check for potential variations across time and space. We found that all incremental interventions tended to become larger in more recent periods, that the disparity between cellular and linear interventions was stable over time, but that conjunctive and disjunctive interventions showed significative and unexpected temporal variations. Conjunctive interventions prevailed between the first two periods of observation, then were surpassed by the disjunctive type, becoming again prevalent in the last and more recent period. This clearly suggests fluctuations in the way incremental interventions are conceived, which are of course non-coordinated but nevertheless measurable.

The testing of this last analytical module showed that the proposed methods were indeed capable of creating objective and meaningful typomorphological descriptions, making understandable an otherwise intractable morphological diversity. Indeed, underlying the overwhelming variability of metropolitan incremental developments there are deep morphological regularities which may be studied and exposed, in a way that leaves little doubt on their actual occurrence and substantiality.

7.2 FINAL CONCLUSION AND FUTURE RESEARCH

As final conclusion, we may say that all the proposed analytical modules were capable of individually providing original findings on metropolitan form. Diachronic axial modelling is adaptable to other network representations and constitutes a solid basis for recording metropolitan morphological evolution. The methods proposed for macro-structural analysis are capable of disassemble the very complex centrality structure of metropolitan regions in its fundamental constituent parts, derived only from street networks. And the technique proposed to study metropolitan typomorphologies is capable of discovering solid regularities amongst the seemingly irreconcilable disparity of individual metropolitan developments.

When taken together, these methods constitute an integrated analytical framework, capable of dealing with regional territorial scopes, of probing metropolitan regions at all spatial scales, in global and individual terms, while disclosing otherwise inaccessible aspects of metropolitan form.

As a whole, it seems that the proposed analytical framework for urban morphology is capable of being applied on other geographical contexts and of constituting a systematic package for studying metropolitan regions from the point of view of their formation processes and global structures.

Several potentialities of the proposed techniques have remained unexplored, namely the possibility of studying the relationships between micro metropolitan developments and the global structures resulting from their conjoint properties. That will be undoubtedly a theme for future explorations.

Regarding its operational outputs for urban planning, the proposed analytical framework seems also prolific. All the adopted methods produce results that may be integrated in urban policies with morphological aims, because they are testable, falsifiable or confirmable. Even if the analytical exercises developed in this study were produced more for testing the methods themselves than to obtain definitive results, they can be easily fine-tuned in order to provide robust findings, which may be delivered with statistical certainty.

7.3 OTHER OUTPUTS OF THIS WORK

In Chapter 4 a series of procedures were developed, in order to empirically validate the model of the spatial network of Oporto's metropolitan region. Such validation was essential, because thw model would provide not only the main object of analysis but also the base from which the city's past spatial form would be inferred. It should, therefore, be capable of emulating the present use of the metropolitan spatial network, namely the movement flows occurring therein. Furthermore, every axial map can be translated into more than one structural formalism (i.e. the axial and segment graphs), where several concepts of distance and radius definition are applicable. Thus, Chapter 4 had also the objective of deciding which type of graph and which type of distance/radius definition best described the actual use of the spatial network. But in doing so, it provided some findings and methods with relevance beyond the objective of this study, namely for the space syntax research field.

The empirical validation exercise entailed several methodological steps: firstly, the reconnaissance of the basic structural properties of the two graphs extractable from the model; secondly, the study of the behaviour of the several distance metrics applicable to those graphs; thirdly, the development of a transversal scale relating those metrics, so that their comparative analysis could be consistently carried out; and fourthly, the correlation between the centrality values produced by those metrics at comparable spatial scales, and the actual traffic volumes flowing in the network.

The initial exploration of the structural characteristics of the axial and segment graphs has provided some insights on their intrinsically different structures and some results regarding unexpected similarities between the spatial elements that they represent. Both graphs are extremely sparse when compared to their random counterparts, while possessing strong modularity (which the correspondent random graphs do not). We have noted that these are typical characteristics of geographically constrained networks. Also, we found that the segment graph has a higher average clustering coefficient (i.e. its nodes are locally more interconnected) suggesting a greater potential for describing the local spatial structure, which was later confirmed by the results of the correlations. However, both graphs have diameters and average path lengths that are much longer than those of their random counterparts. Thus, they are very far from being 'small-worlds'[167] (Watts and Strogatz 1998), i.e. networks with much higher modularity than comparable random graphs, but with similarly short average path lengths. In that sense, both the axial and segment graphs seem rather different from other types of street network's dual graphs, where this type of network effect has been found (Jiang, 2004, 2006, 2007).

Regarding their degree distributions, axial and segment graphs show striking differences. In fact, the degree distribution of the segment graph is trivially normal, but the axial graph has a scale-free degree distribution, i.e. a highly structured and strongly hierarchical connection topology. This has led us to note that both graphs are able to encapsulate meaningful (albeit different) structural aspects of urban space. They are complementary instruments describing different things and the morphological information contained in axial maps/graphs should not be neglected, in spite of their lower predictive capability of urban phenomena. Actually, there seems to be a deep relationship between the lengths of axial lines and the lengths of segments, even if these elements represent rather different things, without evident relationship. While corroborating the finds of (Carvalho and Penn 2004) for axial lines, we have shown that also the rank of segments' lengths obeys to a scaling law, similar to the one dictating the length of axial lines. Moreover, the scaling exponent seems to be approximately the same in both size/rank relationships. This opens new research opportunities, not only for verifying if this regularity holds in different geographical contexts, but also if it holds, converges or diverges across time in the same network.

In order to define the necessary common scale between the three possible distance metrics (topological, angular and Euclidean), we developed a method to study the behaviour of such metrics in the axial and segment graphs. The method consists in plotting the ranked distance values (from smallest to largest) from a given node to all the others, in order to observe the variation of the number of nodes found at each distance level; or, in other words, to observe the progression rate (to which we have called 'percolation') of distance through the graph. This method allowed us to determine that the three distance metrics were indeed comparable (at least numerically) in spite of their different natures, which were also made clear. We noted that the number of nodes at each distance level increases initially as a power-law, for all metrics. This finding is in accordance with known properties of spatially constrained networks (Csányi, Szendröi 2004), but it also provides a theoretical ground for the practice of considering a higher density of radii at close distances, which is recurrent (but not theoretically supported) in space syntax studies. The method also served to determine with accuracy the moment from which edge-effect starts, for each of the three distance metrics. Edge-effect reveals itself as an abnormal decrease in the number of nodes found at each distance level, which entails an exponential increase in the slope of the progression curve. This is useful, not only in what concerns this work but also in general configurational analysis, for edge-effect is a permanent concern in space syntax studies. The similar behaviour of the three distance metrics allowed us then to define three sets of 17 different radii (one for each type of distance), which we have shown to be equivalent. Without these equivalent radii we could never compare the results of the centrality analysis provided by each

[167] The 'small-world' effect refers to networks where just a few (but very far-reaching) connections, bring close nodes that may belong to completely different parts of the graph. Social networks are a frequent example, where one may find a link from a friend-of-friend of ours to an unexpected and unlikely personality. Many natural networks share this effect, namely biological neural networks. However, such far-reaching links are very improbable in geographically constrained networks, unless entire roads are modeled as single nodes.

distance/radii combination, simply because it would be impossible to determine if the correlations obtained by different distance metrics were referring to the same (or to different) spatial scales.

Finally, we were able to correlate the centrality values produced by the three (equally constrained) distance/radii combinations, with observations of the actual volumes of vehicular traffic flowing in the network. In spite of the small number of observations (given the size of the study area), the results were conclusive regarding the capability of the model to reflect the actual use of the spatial network. We obtained very high correlations (max. r=0.931) for traffic flowing in the top hierarchical level of the network (i.e. the highway/motorway super-structure), high correlations (max. r=0.732) for meso-scale traffic (i.e. flowing in the regional and local networks) and significative correlations (max. r=0.671) for traffic flowing in the local street network of central Oporto. These traffic distinctions are not entirely rigorous of course, but reasonably accurate nonetheless, given the sources and the points of observation of the three datasets.

We have also found that, from all the three distance metrics, Euclidian distance is undoubtedly the worst postdictor of urban vehicular movement. Its results are consistently lower and less significative than those of topological and angular distances. This corroborates many claims from the space syntax field in this sense, but still Euclidian distance seems to be blindly considered the only possible distance concept for the large majority of urban planners and researchers. Topological distance behaves much better, especially at large spatial scales, but is clearly outperformed by angular distance. And when constrained by Euclidian radius, angular distance produces not only the best results (regarding the value of correlations) but also the most plausible (regarding the significance level and the radii at which maximum correlations are attained).

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