UNIVERSIDADE DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Modelling urban form and energy performance across urban typologies in Lisbon, Portugal

João Filipe Mota Guedes Fumega

Supervisor: Doctor Paulo Manuel Cadete Ferrão
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Thesis approved in public session to obtain the PhD Degree in
Climate Change and Sustainable Development Policies
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Jury

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2017

"Cities happen to be problems in organized complexity, like the life sciences. […] *They can be analyzed into many such problems or segments which, as in the case of the life sciences, are also related with one another. The variables are many, but they are not helter-skelter; they are ´interrelated into an organic whole´"*

"*In the case of understanding cities, I think the most important habits of thought are these: 1) To think about processes; 2) To work inductively, reasoning from particulars to the general, rather than the reverse; 3) To seek for ´unaverage´ clues involving very small quantities, which reveal the way larger and more ´average´ quantities are operating*"

Jane Jacobs in "*The Death and Life of Great American Cities*"

(1961:564;574)

Resumo

A crescente concentração de população em áreas urbanas, (cerca de 60% da população mundial em 2030); a contribuição das áreas urbanas para o consumo mundial de energia (60-80% do consumo total de energia) e gases de efeito de estufa (30-40% do total das emissões); assim como a sua localização em zonas com alta ou muito alta vulnerabilidade a eventos extremos relacionados com as alterações climáticas, coloca as áreas urbanas no centro da problemática em torno da sustentabilidade. No presente existe uma quantidade crescente de investigação sobre forma urbana e a sua relação com energia, contudo, esta tende a focar-se em aspectos específicos da forma urbana ou energia, assim como em diferentes escalas de análise, não abordando esta problemática de uma forma integrada, e a uma escala de bairro. A hipótese de investigação desta tese é baseada na assumpção que a forma urbana tem um impacto nas necessidades energéticas, nomeadamente nas necessidades de aquecimento e arrefecimento de uma área urbana dependendo da sua forma urbana específica.

É assim proposto um novo método integrado que tem como objectivo partir de ferramentas existentes, integrando-as num novo modelo que possa ser extrapolado para outras áreas urbanas um pouco por todo o mundo, e que permita uma quantificação detalhada de vários parâmetros de forma urbana, assim como criando um modelo operacional de relação destes parâmetros com os de radiação solar e necessidades energéticas. No que concerne à análise da forma urbana foi analisada a cidade de Lisboa e 25 tipologias urbanas. Os passos metodológicos na análise desta dimensão prendem-se com: a) análise morfológica da cidade de Lisboa; b) métodos de cálculo para as 10 métricas de forma urbana e 4 dimensões propostas; c) método de identificação de tipologias urbanas; d) correlações e análise de clusters, para perceber a relação que existe entre métricas, e como as tipologias urbanas se agrupariam tendo em conta as métricas de forma urbana, o que resultou em 5 casos de estudo. A segunda dimensão, a da análise energética em áreas urbanas, é caracterizada pelos seguintes passos: a) caracterização do perfil energético de Lisboa; b) cálculo do rácio de volume passivo, autonomia solar, radiação solar, e também as necessidas energéticas em termos de aquecimento e arrefecimento; c) análise da robustez dos valores calculados, através da comparação das necessidades energéticas estimadas com literatura relevante e também com certificados energéticos que se inseriam nos 5 casos de estudo.

A análise de clusters permitiu a identificação de 5 tipologias como previamente indicado: áreas urbanas complexas, áreas urbanas heterógeneas, áreas urbanas alongadas, áreas urbanas compactas, áreas urbanas modernas. Analisado estas tipologias e tendo em conta as métricas de forma urbana e radiação solar, e necessidades energéticas, é possível concluir de forma geral que:

- O acesso a radiação solar é importante para perceber as necessidades energéticas, de forma directa no que respeita à radiação solar recebida por área de fachada e também no que diz respeito ao rácio de volume passivo; e de forma indirecta no que respeita à autonomia solar;
- Tipologias que apresentaram um rácio de volume passivo elevado têm necessidades energéticas mais baixas (GWh), mas mais altas se este valor for analisado por m^2, pois outros factores como a área do edifício, rácio de volume por área e radiação solar recebida por área contribuem activamente para este aumento;
- Tipologias com formas urbanas muito complexas tendem a apresentar necessidades energéticas maiores, o que pode ser relacionado com o acesso à radiação solar, que tende a ser menor;
- Tipologias que têm uma forma mais heterógenea, permitem uma maior exposição solar e consequentemente uma radiação solar por área de fachada maior e também maior autonomia solar; contrariamente, tipologias compactas e densas tendem a apresentar níveis de autonomia solar mais baixos;
- Existe uma diferença de mais de 70% nas necessidades energéticas de aquecimento e arrefecimento (kWh/m^2) da tipologia que apresenta menores necessidades (áreas urbanas modernas), para a que apresenta maiores necessidades (áreas urbana complexas), só considerando variáveis relacionadas com a forma urbana;
- Desta forma, as tipologias que apresentaram as melhores performances foram aquelas com níveis médios a baixos de complexidade e heterogeneidade, e médios a elevados de compactação e densidade.

Analisando a robustez dos valores, de notar que os valores obtidos para as tipologias analisadas estão dentro da magnitude da investigação desenvolvida para Lisboa. Comparando com a investigação realizada para outros contextos internacionais, a tendência de formas urbanas mais complexas apresentarem valores mais elevados de necessidades energéticas, e formas urbanas mais compactas e densas valores mais baixos é também registada. No que respeita à análise dos certificados energéticos os valores obtidos apresentaram algumas diferenças em termos de magnitude, contudo, a distribuição das necessidades energéticas pelas 5 tipologias é similar o que indica que os cálculos efectuados oferecem robustez à análise efectuada.

Palavras-chave: forma urbana, tipologias urbanas, métricas espaciais, necessidades energéticas, radiação solar

Abstract

The growing concentration of population in urban areas, that will be up to 60% of the total World population until 2030; the contribution of urban areas to the World energy consumption (60-80% of total energy consumption) and GHG emissions (30-40% of the total GHG emissions), together with the location of major metropolis in zones with high and very high vulnerability to climate change extreme related events, puts urban areas in the center of the world´s sustainability problem. In what regards the research on energy and its relation with urban form, there are already many studies but they tend to focus on specific aspects of urban form or energy, and in different scales of analysis, but don´t tackle the problem from an integrated perspective and at the neighborhood scale.

The PhD thesis research hypothesis is based on the assumption that urban form can have an impact on the energy needs, namely on the heating and cooling energy profile of an urban area depending on its specific urban form.

Therefore, it is proposed a new integrated method that has the objective of building on existing tools, integrating them in a new configuration model that could be extrapolated to different urban forms across the world and that allows a comprehensive quantification of various urban form parameters, while at the same time creates a framework to relate these parameters with energy performance ones. In what regards urban form, both the city as whole, and 25 selected urban typologies were analyzed. Methodological steps in this dimension are: a) morphological analysis of the city of Lisbon; b) calculation methods developed to access 10 urban form metrics through 4 dimensions identified; c) typology identification method; d) and the correlation and cluster analysis that were used to understand the relation between metrics, and also to understand how the urban typologies would group if the urban form metrics were taken into account in a cluster analysis, which resulted in 5 case studies. The urban energy dimension is characterized by the following tasks: a) analysis of Lisbon´s energy profile; b) calculation of passive and non-passive volume ratio, envelope radiation, daylight autonomy, and thermal energy needs; c) validate the calculated metrics, namely the heating and cooling energy needs through comparison with the Portuguese energy certificates for the typologies areas, and also relevant literature.

The cluster ranking analysis allowed the identification of 5 typologies based on the metrics results: complex urban areas, heterogeneous urban areas, elongated urban areas, compact urban areas, and modern urban areas. Some general conclusions can be drawn while analyzing the 5 urban typologies that were selected in the city of Lisbon:

- Urban daylight access is important to understand thermal energy needs (directly in what regards envelope radiation and passive volume, and indirectly in what regards daylight autonomy);
- Typologies with a high passive volume ratio have lower energy needs (GWh), but higher energy needs if seen by kWh/m^2, because other factors such as the area of the building, surface to volume ratio and envelope radiation strongly contribute to this increase;
- Typologies with very complex urban forms tend to have higher energy needs, this can also be related with urban daylight access;
- Typologies that have a more heterogeneous urban form, allow more solar exposure and therefore a higher envelope radiation and daylight autonomy;
- On the other hand, compact and dense typologies have lower levels of daylight access;
- There is a more than 70% difference on the heating and cooling energy needs (kWh/m^2) of the typology with the lowest energy needs (modern urban areas) to the one with the highest energy needs (complex urban areas), only taking into account urban form variables;
- This way, the typologies that performed better are the ones that have medium to low levels of complexity and heterogeneity and medium to high levels of compaction and density.

Analyzing the accuracy of the energy needs results, the obtained values for the 5 typologies are in line with recent research for the city of Lisbon. When compared to other research made in other international contexts the same tendency was registered, of complex urban forms presenting higher energy needs than compact and densest urban forms. Regarding the energy certificates analysis, there were differences in the magnitude of the values, however, their distribution throughout the 5 typologies is similar which is an indicator of the validity of the results.

Keywords: urban form, urban typologies, spatial metrics, energy needs, solar radiation

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Acronyms

ADENE Agency for Energy

CO_2 Carbon dioxide

DEM Digital Elevation Model

DGEG General Directorate of Energy and Geology

DHW Domestic Hot Water

EPC Energy Performance Certificate

HVAC Heating, Ventilation and Air-Conditioning

INE Portuguese National Institute for Statistics

INETI National Institute of Engineering, Technology and Innovation (now part of LNEG)

IPMA Portuguese Institute for Sea and Atmosphere

LNEG National Laboratory of Energy and Geology

RCCTE Regulation of the Characteristic of Thermal Behavior of Buildings

RCP Representative Concentration Pathways

TIN Triangular Irregular Network

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SECTION A - Introduction

1. Introduction and Objectives

1.1 Research Problem

The study of urban form is of upmost importance to understand cities - their location, order, structure and character (Mumford, 1961; Lynch, 1981). Even the oldest cities known have a hierarchy and structure in the spatial configuration of their activities. The urban form assumed new configurations according to different historical, cultural, economic and social contexts. If in the pre-classic and classic period its main function was clearly of structure and order, of demonstration of a political and religious ideology, in the medieval period was mainly for defense, and in the industrial period until the present mainly as an economic medium for promoting growth and wealth. The characterization of cities as economic hubs and great centers of consumption is nowadays more clear than ever, together with the high dependence on the automobile as the main transport for daily commute, the growth and dispersion of the urban landscape, the strong increase of the world population living in cities, and a growing tendency for the fragmentation of the urban space.

With the strong growth of the world population living in cities in the 19th century (a process that began with the industrial revolution and that still manifests nowadays but with different expressions depending on the urban areas), the quality of life in cities began to deteriorate, which gave rise to some concerns regarding city planning towards well-being and quality of life, and not only for economic or rational proposes. These first interventions marked the birth of modern urbanism, as a response to the strong levels of pollution, congestion, overcrowding and lack of a space without the minimum conditions for wellbeing. It was the first hygienist interventions that had a special expression in the works of Haussmann in Paris in the 19th century, with linear and broader roads with a geometric organization between them, and with an integration of green elements, boulevards, and water and energy infrastructure. The first very empirical and problem solving interventions of the 19th century gave way to a more ideological and utopian urbanism, that has grown in the 20´s and 30´s of the 20th century, through the Bauhaus school (Gropius, Miles Van Der Rhodes), and also with important documents as the Athens Charter a result of CIAM (1933), and works of Le Corbusier (La Ville Radieuse project). It was the rational city with high density, broad open spaces, strong zoning of activities, and great communication axes. In the second half of the 20th century, especially in the 60´s and 70´s another movement began to take expression in opposition to the "rational city" and the propagation of the suburbs with "endless" size and mono-functionality, the decline of the historical centers, but also as a response to the oil crisis and the strong increase in the oil prices. This new movement arose from the social sciences in opposition to a more positivist thinking, and advocated the return to the walkable city, the importance of the historical context, culture, mix of functions, and other ideals, as a way to keep the character of the urban spaces and revitalize the life of cities. It was the opposition to the dominant tendency at the time of thinking cities as purely spaces of economic transaction and circulation, and a response to the decay of historical centers and loss of identity of the European and American cities. Authors like Jacobs (1961), were important in introducing the fundamental contribution that diversity, singularity and the cultural background of each city has on urban diversity, economic productivity, innovation and wellbeing.

With the end of the century and with the increasing consumption of fossil fuels (specially in cities with all the resulting impacts that were registered in the environment and at the city scale with increased levels of congestions and pollution), an integrated approach to tackle the complexity of the problem began to take form with the introduction of the sustainable development concept with the Brundtland Report in 1987 and the 2nd Conference of the United Nations on Environment and Human Developed in 1992, a concept that later became mainstream and today highly used in various domains. For better or worse the concept stayed, and its relation with cities through the incorporation of its values in the urbanism and planning theory, developed what is called nowadays the sustainable urbanism (Farr, 2008). The connection of the environment, the economy, and the social spheres, is even more evident if we take in consideration cities, due to their strong concentration of capital, people and their heavy dependence on natural resources. The problems of resource equilibrium, agglomeration, scale and access are well defined by Daly (1992), the problems of identity and fragmentation of urban centers are addressed by Jacobs (1961), and the problems of urban dispersion and strong dependence of a single transportation type are well addressed by Kunstler (1993).

Presently, the majority of population already lives in cities, being that until 2030 60% of the world population will be urban (UN-Habitat, 2011). Besides this aspect, cities are located in the majority of the zones with a higher vulnerability to climate change as are the coastal zones (UN-Habitat, 2011). Urban areas contribute to climate change through two vectors: emissions related with aerosols, greenhouse gases and solid waste; and changes in land use. They are responsible for 60-80% of the world energy consumption (IEA, 2008), as well as of 30-40% of Green House Gas (GHG) emissions (UN-Habitat, 2011).

It is therefore clear that there is an urgent necessity to intervene in cities in order to implement sustainable development strategies to adapt and mitigate the effect of climate change. In order to address this objective it is very important to understand the relation between the structure and functioning of cities and its energy and emissions profile, to better intervene in a context of growing uncertainty. This way it is fundamental to deepen the knowledge that exists about urban morphology – the structure, fluxes and function of cities. Various authors have pointed the importance of a better understanding of urban morphology as a key element for urban sustainability (Farr, 2008; Haughton et Hunter, 2003; Kärrholms, 2008; Jabareen, 2006; Jenks et Dempsey, 2005; Frey, 1999; Mindali et al., 2004; Song and Knaap, 2004; Seto et al., 2010; Seto et al. 2011). In the academic field the discussion around urban form and its relation with sustainability has shifted to the duality between compact and disperse urban form, and the relation with multiple domains as are social cohesion, mobility, ecology, transportation, economy, among others (Moudon et al. 1997; Frey, 1999; Camagni et al. 2002; Song and Knaap, 2004; Soltani and Bosman, 2005; Jabareen, 2006; Bramley et al. 2009; Kärrholm, 2008; Silva, 2008; Guerra, 2010). Existing studies focus on the question of density and its relation with the energy profile and emissions (Ishii, 2010; Liu et Sweeney 2012; Mindali, 2004; Norman, 2006); density, transportation patterns and energy consumption (Reiter et Marique, 2012); spatial indicators of urban morphology and energy consumption (Chen et al. 2011); urban typologies of growth and emissions (Ewing et al. 2007); statistical analysis of the GHG emissions that are attributed to urban areas (Dodman, 2009); development of urban energy models (Ratti, 2005; Salat, 2009); but what really lacks is an integrated approach on urban form and energy that could help to understand both the complexity of urban form in a detailed way, and its impact on energy needs and GHG emissions of buildings.

To approach the problem of the sustainability of urban form in an integrated way, this thesis characterizes the current research on urban models, urban typologies, and indicators that is being developed. It does also describes the contribution of cities for climate change, their levels of vulnerability and main trends for the future. There is also a reference to the growing contribution of the complex systems theory to the study of cities (Batty, 2007a; Batty, 2007b; Moreira, 2010; Rakha et Reiinhart, 2012; Portugalli et al. 2012; Salat et al. 2010; Salingaros, 2000, Simon, 1962), and late approaches on studying the relation between urban form and energy (Ratti 2005, Salat 2011, LSE 2014). Therefore the main focus of this thesis will be on the understanding of the relation between urban form and energy.

To understand this relation, the methodology will be divided into 2 parts: urban form characterization and typological definition through urban form metrics analysis; and an urban energy analysis to understand the impact of urban form on energy needs and daylight availability. The result of the thesis is expected to be a model for the analysis of the relation between urban form and energy consumption at the neighborhood scale in order to assess the impacts that different urban typologies may have in the energy profile of cities and consequently their GHG emissions.

1.2 Hypothesis, research question and objectives

The research question of this PhD will be: What is the influence of urban form in the energy profile of urban areas?

The PhD thesis research hypothesis is based on the assumption that urban form – in the sense of the buildings individual geometric characteristics and the way they configure as a whole – can have an impact on the energy needs, namely on the heating and cooling energy profile of an urban area depending on their different configurations. While taking into consideration that other variables such as building materials, source of energy, households equipment's, socio-economic variables, among others, are fundamental in assessing the energy profile of urban areas, this research aims to understand and quantify specifically the contribution of urban form to the energy profile of urban areas. What is proposed is the development of an integrated methodology that could be replicated in other contexts and that integrates a comprehensible set of urban form metrics, that characterize in detail the physical dimension of urban areas – their urban form – and relate them with an urban energy modelling analysis, that integrates both the individual geometric properties of the buildings and also the influence of their context in the urban daylight potential and energy needs at the neighborhood scale. Different urban typologies in the city of Lisbon will be analyzed to understand the impact of various urban configurations on the energy needs.

This way, the main objectives of this PhD will be:

- Develop a methodology to identify and measure different urban typologies through urban form metrics;
- Develop a methodology to implement an urban energy analysis that could analyze both urban daylight potential and heating and cooling energy needs in previously defined urban typologies;
- Understand what is the contribution of urban form to the heating and cooling energy profile of different typologies

SECTION B - Literature Review

2. Urban morphology as a framework for an integrated analysis on urban performance

The importance of urban morphology as a field of academic research and practice began mainly in 20th century, with the development of an urban analysis not limited to the physical elements, but also to their context and the social and cultural aspects that characterize the urban space and its connections (Larkham, 2006:118). There are mainly three schools or urban morphology which have known a great development in the 50´s and 60´s: the British, French and Italian schools. The British school is greatly influenced by M.R.G Conzen, one of the firsts to identify the tripartite division of landscape into town plan (comprising streets, plots and buildings), building fabric and building utilization; the development of the fringe belt idea together with building cycles, land values and innovation adoption; the concept of morphological frame (the way forms created on the ground have an influence on the large scale development); and the idea of morphological regions (identification of different parts of the city based on their physical characteristics) (Whitehand, 2001:104-106). The Italian school is greatly influenced by Savario Muratori. Its work considered spatial structures to be concrete material forms (as opposed to modernists which indicated that were abstract); that the rules that govern the transformations of these forms are autonomous systems that can be studied separately; that the form is more than its functionality in the sense that it signifies the culture where is grounded; and the creation of the typological method that groups forms into types (Rutgers, 2012:11). The typological method is centered on the idea that for urban analysis there are 4 scale levels (building, district, city and territory), and that each of those levels have four common aspects: elements of design, internal structure of the elements, relation between form and use, and the formal aspect. The objective of this method was, in opposition to Modernism, to create a coherent and place-specific analysis. Finally, The French school is more focused on the social aspects of urban life, namely in the social involvement (empowerment), the city as producer of social and economic relations, the study of how people interact with the environment, and the importance of the historical city as a way to continue cultural identity and resist fashionable structures (Rutgers, 2012:56).

Apart from the schools of urban morphology, there are also prominent authors who contributed to the development of the urban morphology science, mainly in the 60´s, and those were Mumford (1961) with its historical view of the city evolution; Lynch (1960) with its study of the elements of urban design that constitute the image of the city and thus its structure; Jacobs (1961) that pointed the importance of diversity and mixed uses as well as the importance of the history of the city in explaining the complex order and the intricacy of city life; and Alexander (1965) with his analytical attempt to describe the complexity of urban areas, that he perceived as having a semi-lattice in opposition of the tree organization made by urban planners in the zoning fashion, and with his contribution in developing a language to cope with this understanding ("*a detailed system of design rules – which could be used to design semi-lattice structures without simply creating chaos*" (O'Sullivan, 2000:72)) that later evolved into the book a "Pattern Language" (1977).

Urban morphology known a substantial decay in the 70´s-80´s with the growing importance of the quantitative methods that "exploded" in the urban research agenda, which were more positivist and less focused on the urban context and the importance of space. Urban morphology regained a new momentum in the 90´s and until the present with the development of the geographical information systems (GIS), the growing concern of understanding the complexity of the urban environment through an integrated perspective (the question of sustainable development) and, according to Larkham (2006:132), to the renewed interest in the study of place in geography and the rise of urban design in both in practice and as an academic discipline. According to Larkham (2006:120) three of the most important lines of research of urban morphology are concerned with "[…] *the nature and amounts of urban landscape change, especially viewed over long time spans, and thus generally focused on historic towns; the agents involved in the process of change; and the management of that change*".

The concepts of urban morphology and urban form are often used in the academic literature to express the same meaning, since their definition is not consensual. Lynch (1981:52-53) indicates that his perspective of urban form is the one that encompasses the spatial disposition of people developing their activities, the spatial movements that result from these activities, products and information, and the physical characteristics that modify significantly the space for those actions. Lynch´s definition of urban form is by far the broadest one, while the other authors tend to associate urban form to the city´s physical structure. Moudon (1997:7) for instance, indicates that urban form is defined by three fundamental physical elements – buildings and their related open spaces, plots or lots and streets. The author also indicates that it can be analyzed at different levels of resolution, typically building, street, city and region, and it can only be understood historically since the elements of which it is comprised undergo continuous transformation and replacement. Levy (1999:79) also indicates that in most research on urban form there are common elements that are analyzed separately or in relation to each other and they are the plot, street, constructed space and the open space. Marshall (2005:15) indicates that urban form "[…] *can imply either design or emergence of form, in two or three dimensions, from the scale of courtyards to conurbations*.", and that it can "[…] *refer to the overall size or shape of the urban area (e.g., a linear or star-shaped form), or its degree or articulation into discrete settlement units*".

On the other hand, Moudon (1997:1) indicates that urban morphology, and urban morphologists in particular, analyze "[…] *a city´s evolution from its formative years to its subsequent transformations, identifying and dissecting its various components; focus on the tangible results of social and economic forces; study city´s elements as are buildings, streets, parks, gardens and monuments; and the dynamics that tie together all those elements*". Rutgers (2012) also stresses the importance of not only analyzing the built form: "*Important for morphology as a tool of analysis is that it is not just about form. In serious urban design form may never be seen without its context: the meaning attached to it, its relation to use, the processes of transformations that characterize it, and its relation to urban processes (for instance social and political processes)*". ISUF (2013) defines urban morphology as "*the study of the physical (or built) fabric of urban form, and the people and processes shaping it*". Sanders (2008:3) quoting Bentley and Butina (1990:67), also indicates the more encompassing nature of the concept or urban morphology: "[…] *it is an approach to studying and designing urban form which considers both the physical and spatial components of the urban structure of plots, blocks, streets, buildings and open spaces, all of which are considered as part of the history/ evolutionary process of development of the particular part of the city under consideration*". Levy (1999:79) indicates that urban morphology tries to identify laws that orient the organization and development of the urban fabric, and that a common hypothesis is that there exists a systemic organization, with organic attributes, where there is an "[…] *interdependence between part and whole, that is between building type and fabric*", indicating also that "*Some studies envisage a non-causal, dialectical relationship between building types and urban forms*". What Levy said, and summarizing, is that urban morphology is about the study of the great rules that govern the city, and that there are two main approaches to this study the more "synchronic" approach, namely the typomorphological analysis (already stressed before), of the study of the relation between building and street, and a more diachronic approach, more related to the morphogenetic analysis, focused on the study of the evolution of the urban form through time (constants analysis or relationship between building and urban fabric over time). The author leaves also an important conclusion, since in his opinion both urban morphology perspectives are only viable when studying the historical fabrics. The modern urban fabric represents a whole new challenge to the urban morphology school since it represented a shift "[…] *from a closed fabric, including a central business district and outlying suburbs in which the links between the different elements […] formed a system […], to a peri-urban fabric which is open and fragmented, with autonomous and atomized elements which do not relate to each other*".

2.1. From ideal cities to urban models: main theories on urban growth

In order to understand the current complexity of cities patterns and dynamics, it is crucial to make an analysis on the main theories and models of city growth. These models have an influence on today´s thinking about urban areas, and are key in framing the more advanced urban modeling techniques that are being developed by researchers, including some that will be applied in the present work.

The end of the 19th century and until the 1930´s was a fertile age for utopian city models. The strong and rapid economic development, associated with the belief in technology, gave rise to city models that corresponded to a desired city that should be developed everywhere, regardless of the context. The objective was to express in all its power and beauty the modern technology and the most enlightened ideas of social justice (Fishman, 2012:27). Three urban planners have known a relevant status and dissemination due to their city models: Ebenezer Howard, Frank Lloyd Wright and Le Corbusier, each one different from the other. Their works showed above all a necessity for society to depart from the old cities and embrace a new future with a total different set of scale, and with a strong faith in the virtues of urban design as a tool to solve social problems, that were very significant in that time, due to the rapid industrialization and urban growth. Howard was the first urbanist to propose his model – the "Garden City" (Figure 1) – a plan for moderate decentralization and cooperative socialism, built on unspoiled countryside, on land that would remain the property of the community as a whole (Fishman, 2012:30). The city would be limited in size to 30.000 inhabitants, surrounded by a greenbelt, compact, efficient, healthful and beautiful, with the objective of attracting people from the polluted cities. On the other hand, Wright proposed the "Broadacre City" (Figure 2), which took the decentralization beyond the small community (which was a Howard´s ideal) to the individual family home (Fishman, 2012:30). In this vision all large cities disappear; the center of society moved to the thousands of homesteads that cover the countryside; people work on both their farms and small factories, offices or shops; a network of superhighways joins the scattered elements of society (Fishman, 2012:31). The main belief of Wright is that society must be founded on individual ownership and that the decentralization of its city model would allow that each person could have its own lifestyle. Le Corbusier idea about the city was like the organization of a factory, where each element was perfectly coordinated with the other, in perfect organization and disposal, and a clear identification and separation of the uses, and a strong relevance of the communication channels (Figure 3). He favored strongly dense environments, with geometrical skyscrapers that would stand between parks, gardens and superhighways. According to Fishman (2012:46), "In the Radiant City every aspect of productive life is administered from above according to one plan".

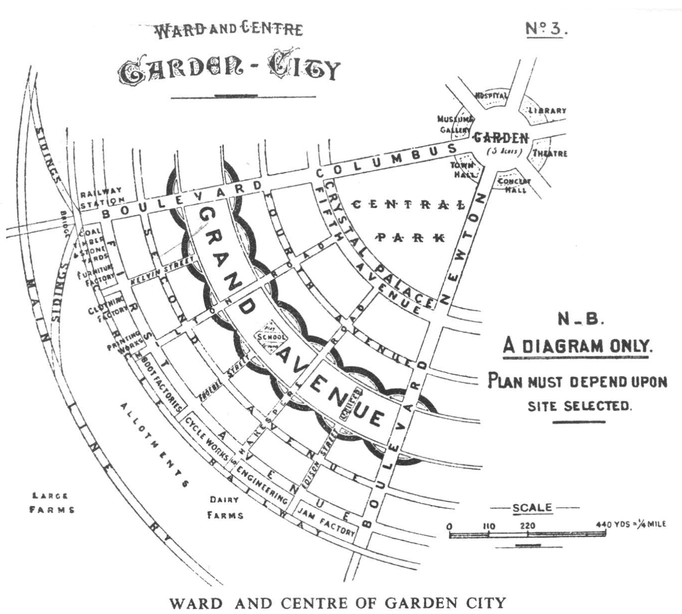


Figure 1: Howard´s "Garden City"
Source: Archdaily (2014a)

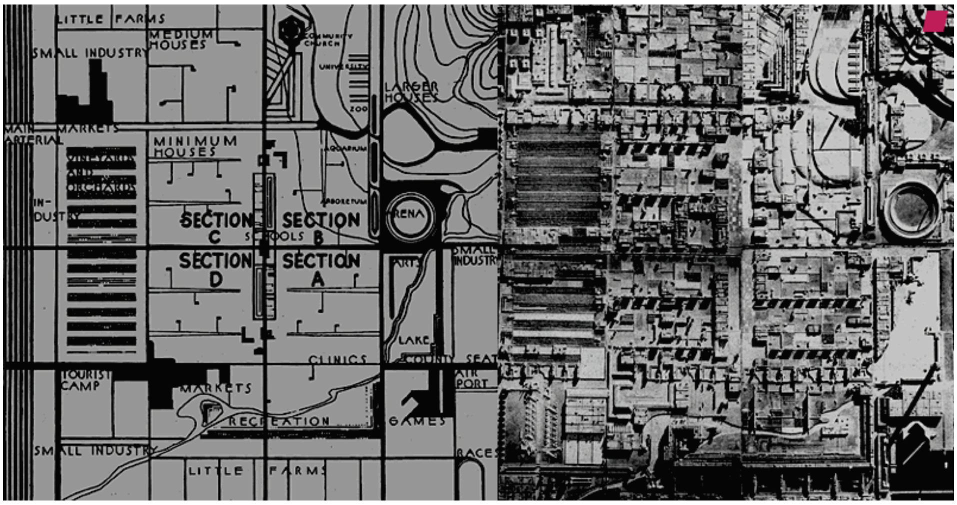


Figure 2: Wright´s "Broadacre city"
Source: Mediaarchitecture (2014)

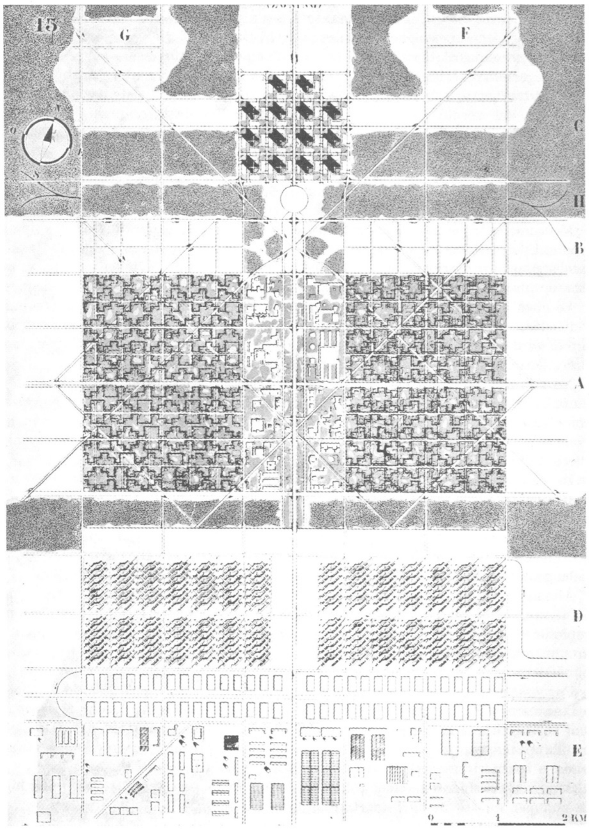
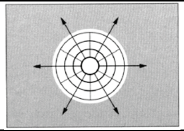
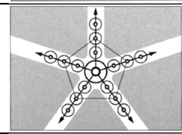
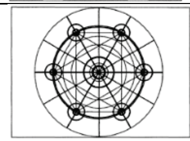
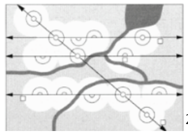
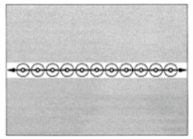
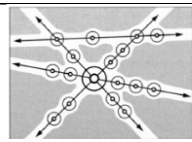


Figure 3 Corbusier´s "Ville Radieuse": A – Housing, B – Hotels and embassies, C - Business center, D – Industry, E – Heavy industry, F and G – Satellite core for specialized activities (government, education, etc), H – Train station and airport
Source: Archdaily (2014b)

Frey (1999:71) building upon the identification and description of different city forms and structures made by authors like Lynch, Minnery and Calthorpe identifies a set of city models (Table 1). The author indicates that the models assume to accommodate a similar total population of 250.000-500.000 inhabitants, being excluded models of extreme low density that according to the author, are not desirable in a sustainable city form. He also indicates that the objective of these models is to focus on the macro-scale characteristics of cities, thus, on the general description of spatial patterns of the city.

More than a practice framework for intervention, these models represent both interpretations of parts of current urban forms and also possible urban forms and their respective characteristics. They indicate above all “possible futures” and respective consequences, and thus represent different schools of tough and visions on urban growth.

Table 1: Different city models / Source: Frey (1999)

Model	Description	Spatial configuration
The core city	- All the city's functions are packed into one continuous body with very high density and an intense peak of activities at the center (Lynch, 1985: 373–374); Green spaces generally small, housing in multi-storey apartments; 350 persons per hectare; Second residence in the countryside; Public transport with high quality; Strong sense of community; Problems of pollution, congestion, overcrowding.	
Star city	- Single dominant center of high density and mixed uses; Transportation routes radiate out of the center containing public transport systems and the main vehicular traffic routes; Secondary centres and other uses of high to medium density are located along the public transport routes with the more intensive uses around the sub centers which form at transport stops; Less intensive use may occupy space outside either side of the denser development along the routes, towards the green wedges.	
Satellite city	- A central city is surrounded, at some distance, by a set of satellite communities of limited size; The limitation of the growth of satellites is essential for maintaining the efficiency; Satellites are separated from the central city by rural land and are themselves surrounded by greenbelts.	 [1]
Galaxy of settlements – TOD (Transit Oriented Development)	- Approximate size of 80 hectares; Distance from edge to center of 10 min. walk (600m); Fine grain of different land uses: 2/3 housing, 1/3 commercial or workplaces; Density of 44,5 dwellings/hectare with 3,000 persons; A central area operates as the focus of the community's activities; Residential development in the central area would be in the form of high density low-rise apartments or town houses; An area of up to 1,600 m from the central public transport stop would provide lower-density single-family housing, public recreation space, parks with ponds, and countryside.	 [2]
Linear city	- Grows along a continuous transportation line, ideally public transport, or a parallel series of lines; Intensive uses of production, residence, commerce and services are located along and on either side of the line(s) and, specifically, form dense nodes at transport stops; Less intensive uses are located in parallel bands of space outside the compact strips of development; Variety of housing (high density to single family houses); Growth would be possible by linear extension at either end of the line; - Adaptability inside the linear city would be by replacement as in all other denser city models.	
Polycentric Net or the Regional City	- It's a combination of different models; Wide range of different densities, with intensive peaks at junctions of the transport network and with high linear concentrations along the major channels between the peaks; Regions of low density inside the grid or between high-density nodes and linear development; Green belts and wedges would form another kind of grid; Central city activities would be decentralized over the net and concentrated in nodes at junctions of the circulation system with different densities and degrees of specialization; There would be a large range of different housing forms and a large choice of access to services and open land.	

[1] Howard´s model (1898 *in* Frey, 1999)
[2] Calthorpe (1993 *in* Frey, 1999)

There was a decay in the importance of the ideal or utopian cities in urban planning mainly after the 2nd world war, since the implementation of those models would be too controversial and economically impossible. Either way, portions of those visions were applied on different cities and even today can be seen all around the world (e.g. Brasilia by Oscar Niemeyer). The second half of the 20th century saw the appearance of numerous urban models and theories that no longer advocated a new city that would completely obliterate the "old" city, instead they tried to cope with the city that already existed. Lynch in its work "Good City Form" identified the main theories about cities through six main themes that he labeled with metaphorical titles (Lynch, 1981:307-321):

1) **Cities are singular historical processes**: the city is analyzed as a singular entity in which each city has a specific process that is cumulative and historical, influenced by cultural, climate, political and economic events. No generalizations are allowed, with the exception of minor elements with repetitive roles such as specific local growth patterns, the influence of the localization of the center of power, or the influence of public transportation stops. Lynch (1981:307) indicates that this theory is important in understanding the evolutionary processes in history but, in avoiding the systemic point of view, it's not useful for predicting future events since it does not establish causal relations. It is a useful theory to study specific local cases when immediate decisions, concrete patterns, and a modification of the constant forces are referred.

2) **Cities as a conflict arena**: It is more a Marxist theory about cities in which the city is seen as the arena where the social classes struggle and social cohesion is more fragmented. The city is therefore seen as the unconscious results of the control that is made by the capitalist class through the land market and the construction of housing. It attributes the problems of overcrowding, pollution, and diseases to the rapid growth that was the result of the industrialization and the capitalist expansion that sees the utilization of space as an asset and not as a common good. It centered its main analysis on the work conditions in industry, and neglected the housing and services, which had severe consequences in the design of socialist cities, that saw a predominance of high density buildings with a low quality and lack of diversity in their activities.

3) **Cities as ecosystems of human groups**: Based on an ecological perspective it had its beginning in the works of Robert Park and Ernest Burgess in Chicago in 1925 in what latter became known as the "Chicago School". It was a theory that departed from the sociological point of view that saw people as systems of groups that are relatively stable, together with notions from the environmental ecology and land use patterns developed by planners, being its main theme the North American and European cities. In its framework there is an agglomeration with a unique center and the spatial measurements and patterns are established taking that center as a

reference. Human groups are analyzed from an external point of view, regarding their living and work places and the way they change those places. A simple dynamic was created based on a successive growth towards the outwards of the city, the historical age of a certain area, and in principles of social attraction and repulse (progressive substitution of a group by other group is an analogy to the plants succession). It contributed to important pattern analysis as are the sectorial growth, ethnic succession and density waves. It has known a special relevance as factorial ecology, an area that uses sophisticated statistical techniques to analyze the changes in correlations in the complex mix of the social groups in space. It is a theory that doesn´t use the historical analysis, takes the space as a neutral medium, and the city is seen as a quantitative distribution of workplaces and homes. Other aspects of environmental quality like the tridimensional form, design and social meaning are more neglected.

4) **Cities are spaces destined for the production and distribution of materials**: Mainly an economic perspective, in which cities are seen as patterns of activities in space that facilitate production, distribution and the consumption of materials. Space is seen as an element that creates an additional cost, due to the time and resources that are necessary to move people and materials. In other way, this perspective sees also space as a resource, because it is the place where consumption and production takes place, and where a strong competition of this element between the activities exists. Space is therefore presented as a transportation cost and a place to occupy, in which the basic notion is the equilibrium – men through multiple decisions (and with purely economic intensions) tend to balance the spatial pattern, and that balance allows a more efficient production and consumption of the products with the available resources. This theory subdivides into two fields: industrial location theory and the central place theory. This first studies the best location for an industry taking into consideration the spatial dispersion of its various resources, markets, workforce, and support industries. The second, developed by Walter Christaller in 1933, has as main focus the distribution of products. Taking into account a neutral space, uniform costs of transportation, producers and consumers distributed in the same way, scale economies and specific principles for different types of traders with liberty of movements, demonstrates that central places of distribution should have a stronger role. The typical hexagonal patterns and triangular network of movements that characterize this theory allow a maximum efficiency in the distribution and economic relation. Lynch (1981:313) indicates that this theory has some advantages and is above all useful in a more regional analysis, however, it is not able to address the spatial complexity of the city, because it is a static perspective, based on an equilibrium in which space is an empty container. The values of the theory are mainly liberal, and the justice and distribution of resources don´t have a fundamental role.

5) **Cities as a force field**: This theory understand cities as electromagnetic or gravitational fields, in which distinct particles (human beings) - that are distributed and move across space - communicate between them and attract and repulse. These points in movement attract or repulse mutually depending on their mass and relative load, divided by the square of the distance between them, since influence decreases at the same time that irradiates to space and that the area of the spherical bubble expands from that point, an area that in itself is proportional to the square of its radius. This analysis is useful to predict future changes like tendencies of agglomeration and distribution of growth rates, and also to explain the fluxes between different areas (e.g. by using mobile data). The influence of the initial barriers and inequalities can be addressed by attributing different "masses" to each person in accordance to the income, or other factors. Models in this fashion are used mainly in transportation studies to predict the changes in traffic due to the construction of a new highway for example. The graphs theory and the chaos theory are two examples of theories associated with this perspective. Lynch (1981:314) indicates that in this theory, people are considered as static units without a rational thinking that only respond to the dynamic forces around them, and the best city is the one with the highest interactions (communication). It also indicates, as weak points, that the model is very limited due to the centralization in communication, in the valorization of the maximum interchange, and ignores the capacity of learning of human beings, however, as strong points, it contributed to the development of important mathematical models on cities and on the acknowledgement of communication as a crucial element for cities existence.

6) **Cities as a system of connected decisions**: takes into account that a city is the product of various decisions made by people and institutions, actors that have diverse goals and resources, and that are constantly influenced by the decisions of all. This analysis can be framed as a complex system: a set of defined elements or states that can be quantified (e.g. location patterns, housing data, transports capacity, etc), and a set of interactions that connect those elements and introduce change. The most significant elements and connections, their states and relations, have to be mathematically defined. A great set of assumptions must be developed in order to define the elements, connections and inter relations and time sequence. After developed, models in this fashion should be able to explain the current form of a city and predict future changes. In particular, they should allow the identification of possible changes if implemented the policy A or B, or if an extreme event takes place. Lynch (1981:318) indicates that some limitations can be seen in these models: if applied for long periods of time they tend to reach an eternal state, or explode since the rules endure; new policies can be drawn in the model, but those will take very long to create real and significant changes in the model; these models are more recommended for the short term forecasts since they do not predict how the motives and decision rules change depending of the situation. Despite those limitations, Lynch (1981:318) indicates that these models in its essence have a correct approach, since they

analyze the city as a series of flows that are the result of the interaction of multiple agents and their decisions.

2.2. Urban design and the search for the "good city form"

2.2.1. The immaterial qualities: Identity, structure and meaning

Urban form can be characterized as the structure of a city, its DNA. Being in its essence a physical element, it is of upmost importance to associate to its study the social and cultural characteristics of the society that inhabits the urban space. Lynch (1960) indicates that the non-static elements of a city, specially people and its activities, are as important as their physical and static parts. The study of urban morphology is above all a study about the great tendencies of the evolution of cities, but also about the small details of urban development, that slowly are changing the image of the city. Even when there is a control of the city´s development by the agents that manage it, it's impossible to exactly predict how it will be the structure of the city: "*it's only partially possible to control its growth and form. There isn´t a final result, but only a continuous succession of phases*" (Adapted Lynch, 1960). Frey (1999) indicates that on the traditional city the structure and form evolved in slow and incremental processes without formal planning and design (thou on basis of commonly understood and accepted patterns), and in the modern city there are many non-local forces that are shaping its development, which frequently don´t even know the specific reality of a city. It's therefore essential to maintain above all the legibility of the urban structure, so it can be understandable and coherent to its inhabitants.

Apart from its main objective of organization of people and activities, urban form can be a "*structure of reference, and an activity, belief or knowledge organizer*", being that "*a physical structure alive and integral, able to produce a clear image, also performs a social role supplying the raw material for the symbols and collective memories of the communication between groups*" (Lynch, 1960). Apart from the importance of legibility in the organization of urban form, there should be also qualities of non-repetition and heterogeneity that could break the monotony and create a reference quality.

Therefore it is of upmost importance the promotion of quality design in order to ensure an urban form coherent to the cities identity. According to Frey (1999:22) urban design can be understood as a process and as a product. As a process urban design "[…] *should set, the* *framework, the rules and guidelines for the form and orchestration of the city's physical parts and by doing so it creates the city's physical form and structure*". It can be applied on the scale of individual public spaces through the city itself and the relation with the hinterland. As a product, urban design is a series of guidelines and frameworks that ensure that the city has two important characteristics: to be both *imageable* and adaptable, so create a long lasting image of the city clearly identifiable and also to enhance the process of adaptation to the changing needs and aspirations of its citizens. There isn´t a unified theory about urban design, and its principals and fundamentals are in most times based not in a strong theoretical background, but more on architectural and planning practice in the form of manuals, for example. According to Sternberg (2000:266) the existence of a theory of urban design faces a number of challenges: it should not simply advocate one set of design approaches but should rather reveal the principles that underlie them; it should be a substantive (not just procedural) theory; it should make us aware of the constituents of the human experience of built form; it should recognize the sources of urban form in both markets and plans; it should answer both to the economic and architectural streams of planning thought and should be able to direct our attention to pertinent features of reality (experiential features of space and built form) and thereby help guide practice. This way, what is important in characterizing urban design is more than enumerate a series of procedures, is to indicate integrative principles that could constitute a framework for urban design theory.

Lynch (1960) in its book "The image of city", develops a very important set of principles for urban design, more specifically for understanding the image of the city. He says that the image of the city can be analyzed through 3 components: identity, structure and meaning. Identity in the sense that it should have unique characteristics; structure due to the relation between subject and object; and meaning because of the importance of the city to the subject both in practical, but also emotional terms. The author also states that "*the image should, preferably, allow an open end, adaptable to change, and allow the subject to continue the investigation and organization of its reality: there should be open spaces where he could propagate the image of himself*". In its study of the cities of Boston, New Jersey and Los Angeles, Lynch (1960) defined the elements that are critical for the inhabitants in their construction of the image of those cities. The first conclusion is that people build a structure and identity of the space where they live, and that there are elements that are common throughout the analysis: space and the openness of the field of vision, places as squares, elevated points, among others, are fundamental in the perception of the individual; there is an emotional pleasure derived from an extended view; spaces with a coherent form tend to have a stronger impact on the individuals; importance of the natural elements as vegetation or water for well-being; the importance of streets as elements of connections, social contact and meaning of the city itself; and the notion of historical evolution through the constant reminder from the presence of various physical elements of different periods.

Jacobs and Appleyard (1987) in the article "Toward an Urban Design Manifesto" establish five physical characteristics in order to provide a high quality urban life: livable streets and neighborhoods; some minimum density of residential development as well as intensity of land use; integration of activities – living, working, shopping – in some reasonable proximity to each other; a manmade environment, particularly buildings, that defines public space; and many separate, distinct buildings with complex arrangements and relationships . According to the authors all five characteristics must be present, and other important qualities of a city are not addressed deliberately as are transportation, environment, etc. It is important to stress that a minimum density is necessary for a city to exist and for cities activities and transportation be viable, and that is of 15 dwelling units (30-60 people) per acre (=0,40 hectares or a square with 40mx40m) (Jacobs and Appleyard, 1987:118). Apart density, it is also important to exist intensity, e.g. a minimum number of people using an area for it to be considered "urban". Together with these characteristics there should be an integration of activities – mixture of uses – that should respond "[...] *to the values of publicness and diversity that encourage local community identity*" (Jacobs and Appleyard, 1987:118) that are easily accessible (preferably by foot), which does not mean that all the city should be highly mixed, but there should be areas more residential (to rest), and others more diverse. The location of buildings in the urban space is also of upmost importance, since they define the configuration of the public space in their relation to the street and of themselves. The distance between buildings, their size and geometric properties, and their design should take always the characteristics of the public space that surrounds them as well as the other buildings, design elements, activities and people. The importance of the public space, as the stage for the social interactions and existence of the community is also focused by the authors. They indicate that "*The most important public places must be for pedestrians, for no public life can take place between people in automobiles*" (Jacobs and Appleyard, 1987:119), and the essential value of public spaces as places where people meet, observe and communicate, and the importance of public transportation to allow the development of these spaces. Space complexity, with many building types and spaces with complex arrangements and relationships, are also encouraged by the authors as a way to foster spaces that are not monotonous, have intimacy, confrontation with the unexpected, and that are stimulant.

Sternberg (2000:267-268) also underlines the importance, as elements of good urban design, of some of the characteristics identified by Lynch (1960) and Jacobs and Appleyard (1987). He starts its analysis by indicating that market theory cannot extend to realms of human experience that are non-commodifiable (non-tradable and commensurable on markets), being that "*it is in creating, protecting and restoring cohesive experiences of built form that urban design acquires it distinctive social role*"; and the importance of integration of natural elements with artificial elements in order to create collective benefits for urban populations – an organics point of view. The author indicates four integrative principles for urban design theory: good form, legibility, vitality and meaning. In what regards good form the author refers to Camillo Sitte´s work around the opposition of planning in the mid-20th century that had turned public spaces into impersonal and mechanical places, in opposition to the formerly "organic" city. He proposes the integration of buildings in the public space, in the surroundings and between them, and the importance of cohesion, giving as examples numerous plazas. He also names the work of Bacon (1974) namely that good design should interlock and interrelate buildings across space, and the importance of the axis of movement – the articulation between street, building types and forms, and public space elements in the framework of a space that is owned by different owners and interests. In what regards the principle of legibility, it is the city whose constituent parts "*are easily identifiable and are easily grouped into an over-all pattern*" (Lynch, 1960:3). As already stressed by Frey´s (1999) analysis on the product of urban design, Lynch also stresses that a city with a great capacity of legibility is a city with a very easy degree of knowledge by its inhabitants but with a complex meaning, which can be understood through time and will leave a tendency of continuity, like a reflection of a future that would come. Fundamental for the legibility of a city is the connection of its various elements – axes, limits, neighborhoods, connections and symbolic landscape. In what regards the principle of vitality, it has a special expression in the work "The Death and Life of Great American Cities" (1961) by Jane Jacobs, which was a manifest against the planning practice done so far, based on strong zoning policy and an aggressive renewal planning that changed substantially the historical centers. The main idea of Jane Jacobs argument is that diversity is the key to the success of an urban area and that streets and neighborhoods need "[…] *a most intricate and close grained density of uses that give each other constant mutual support […]*" (Jacobs, 1961:19). The key component of diversity is the mixture, so according to Jane Jacobs there should be a mixture of uses (residential, work, leisure), and proportion in that mixture. Density is also very important in the sense that it allows a greater diversity and vitality, but also the design of buildings that should connect with the street, public spaces where people would want to spend time, and businesses that have a ground connection. Finally the last principle that Sternberg (2000) enumerates is meaning. It is greatly connected with the "[…] *capacity of the city to exhibit history, tradition, nature, nationality or other themes that heighten meaning and solidify identity*" (2000:274). It is a very difficult task for the urban planner to keep in mind and stress in urban policy the importance of meaning, since it is a concept that is fairly different from place to place and from people to people. It is therefore of upmost importance to have the community to participate in the planning process and to develop detailed studies of the reality that is being analyzed in order to take the relevant meaning for the whole community. The Homes and Communities Agency in the UK in the publication "Fundamentals of urban design" (2013:12), also enumerates key aspects of the discipline but in a more operational way (Figure 4).

Places for People
For places to be well-used and well-loved, they must be safe, comfortable, varied and attractive. They also need to be distinctive, and offer variety, choice and fun. Vibrant places offer opportunities for meeting people, playing in the street and watching the world go by.
Enrich the Existing
New development should enrich the qualities of existing urban places. This means encouraging a distinctive response that arises from and complements its setting. This applies at every scale - the region, the city, the town, the neigbourhood, and the street.
Make Connections
Places need to be easy to get to and be integrated physically and visually with their surroundings. This requires attention to how to get around by foot, bicycle, public transport and the car - and in that order.
Work with the Landscape
Places that strike a balance between the natural and man made environment and utilise each site's intrinsic resources - the climate, landform, landscape and ecology - to maximise energy conservation and amenity.
Mix Uses and Forms
Stimulating, enjoyable and convenient places meet a variety of demands from the widest possible range of users, amenities and social groups. They also weave together different building forms, uses, tenures and densities.
Manage the Investment
For projects to be developable and well cared for they must be economically viable, well managed and maintained. This means understanding the market considerations of developers, ensuring long term commitment from the community and the local authority, defining appropriate delivery mechanisms and seeing this as part of the design process.
Design for Change
New development needs to be flexible enough to respond to future changes in use, lifestyle and demography. This means designing for energy and resource efficiency; creating flexibility in the use of property, public spaces and the service infrastructure and introducing new approaches to transportation, traffic management and parking.

Figure 4: Key Aspects of Urban Design
HCA (2013:12)

2.2.2 The material qualities: the physical elements that define the urban space

Apart from the non-physical characteristics of the urban space identified before, there are a set of physical elements that contribute to the definition of the urban space and actively contribute to its performance. Salat (2011:30) in his work "Cities and Forms – on sustainable urbanism" defines three hypothesis that frame his work, and that are also well applied to the analysis that is pretended and the understanding of the importance of the physical elements for the performance of the urban form: 1) On the city scale, a relationship of reciprocity exists between the typology of blocks and the taxonomy of street patterns; 2) On the scale of urban fabrics, a relationship of reciprocity exists between building typologies and urban morphology; 3) The two relationships of reciprocity are fundamental to elucidating the structure of urban facts.

In physical terms the urban space has its reflection in the urban structure. According to HCA (2013:33) "*The term urban structure refers to the pattern or arrangement of development blocks, streets, buildings, open space and landscape which make up urban areas. It is the interrelationship between all these elements, rather than their particular characteristics that bond together to make a place.*" The term urban structure doesn´t refer to a particular trend in urbanism but solely to the current characteristics of a certain urban form, being that form the suburbs or the city center for instance. By its encompassing nature, the concept of urban structure provides "*coherent framework, which forms the basis of the design of individual developments – quite possibly by different actors*" (HCA, 2013:33). It exists with the following objectives (HCA, 2013:33): integration (connection with other areas); functional efficiency (individual elements working together as part of an efficient whole); environmental harmony (forms that are energy efficient and ecologically sensitive); sense of place (a place that is recognizably distinct); commercial viability (responding to the realities of market influence).

Carmona et al. (2010:136) referring to the organization of the urban structure refers that there are essentially two types of urban space system: one where buildings define space and the other where buildings are objects-in-space. The author continues saying that the former usually consists of "*[…] buildings as constituent parts of urban blocks, with urban blocks defining and enclosing external urban space*" – the traditional urban space, and the latter *"[…] typically consists of freestanding buildings in landscape settings*" – usually referred to as the Modernist urban space.

Morphologists vary in their identification of the crucial elements that constitute the key factors for understanding a city´s urban form. In what regards the identification of the elements of urban form, Lynch (1960), in its approach through the concept of “the image of the city” and what people identified as important elements in a city, indicated 4 types: 1) *axes*, namely streets, paths, sidewalks, and other channels through which people move; 2) *limits* - barriers like walls, buildings and bank rivers; 3) *neighborhoods*, areas that are relatively large and that are distinguished by their identity and character; 4) *connections*, namely intersections, squares, focal points and landmarks. Conzen (1960 in Carmona et al. 2010:137), for instance, indicated that the key elements of the city where the street pattern, the plot pattern, building structures and land uses, emphasizing the difference in the stability of these elements (being the land uses that buildings accommodate the least resilient elements).

- *Streets and junctions*

The street pattern is the layout of urban blocks and the public space and movement channels between those blocks (Carmona, 2010:140). It is of upmost importance to have a network of streets that is both easily understandable and accessible to the population that uses them. Apart from its main function of transportation, streets should also allow the residents to spend time on them, offering a space for relaxation, shelter, meeting and gather. Since they are the connection between the building and the city, they should be designed in order to ease the access to buildings, thus allowing a greater variety of services and commerce to develop. This way it is important to stress the sidewalk as a fundamental characteristic of a good street. Carmona (2010:142) indicates the importance of a characteristic that he called permeability, that is “(…) *the extent to which an environment allows people a choice of routes through and within it* (…)”, indicating that a network of streets with high permeability tend to have streets that are more used and by consequence, a richer life in the activities and services that characterize that area (Figure 5).

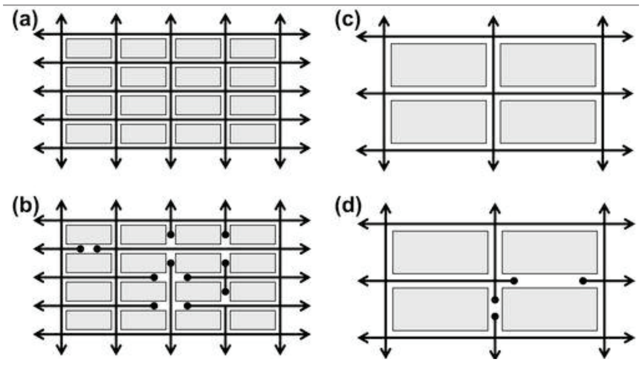


Figure 5: Different street patterns and their effect on possible routes
Carmona (2010:142)

HCA (2013:38) referring to the street grid, indicates that a grid spacing of 80-100 m provides an optimum network for pedestrian and vehicular needs in most circumstances. It also refers that the size of the development blocks should be checked against proposed uses and buildings types. Salat (2009:7) indicates the importance of the composition, configuration and constitution of the street network for the urban form. Composition in the sense of the connection between people and its environment, namely in how does the space physically or visually impact people; configuration in the sense of the analysis of the form and topologies in where ratios and indicators are calculated; and constitution through the structure of links and nodes, where hierarchy and constraints are the two main topics.

The work of Marshall (2005) is very important in what regards the characterization of the composition, configuration and constitution characteristics of streets. In his book "Streets and Patterns", he studies the fundamental importance of streets as elements of definition of urban form. He indicates the main types of street configurations (Table 2): a) the core area of old cities where "(…) *The angularity of routes, oriented in a variety of directions, generates a rudimentary radiality, where such a pattern is located at the core of a settlement*" (Marshall, 2005:84); b) planned extensions or newly founded settlements, with bilateral directionality; c) perhaps the most general type which may be found at various positions in a settlement, but mainly astride an arterial route, according to Marshall (2005:84); d) the modern hierarchical layout "(…) *often associated with curvilinear layouts of distributor roads, forming looping or branching patterns*".

Table 2: Different types of street grids
Marshall (2005:85)

Type	Example pattern	Typical location	Frontages	Transport era
A-type *Altstadt*		Historic core	Built frontages	Era of pedestrian and horseback
B-type Bilateral		Gridiron (central, or extension, or citywide)	Built frontages	Era of horse and carriage
C-type Characteristic/ Conjoint		Anywhere; including individual villages or suburban extensions: often astride arterial routes	Built frontages or buildings set back in space ('pavilions')	Any Era of public transport; car
D-type Distributory		Peripheral development: off-line pods or superblock infill	Buildings set back in space, access only to minor roads	Era of the car

Marshall (2005:86) also details the meaning of composition and configuration, being composition the absolute geometric layout, as represented in a scale plan, featuring absolute position, lengths, areas, orientation; and configuration as refers to topology, as represented on an abstract diagram, featuring links and nodes, their ordering (relative position), adjacency and connectivity (Figure 6).

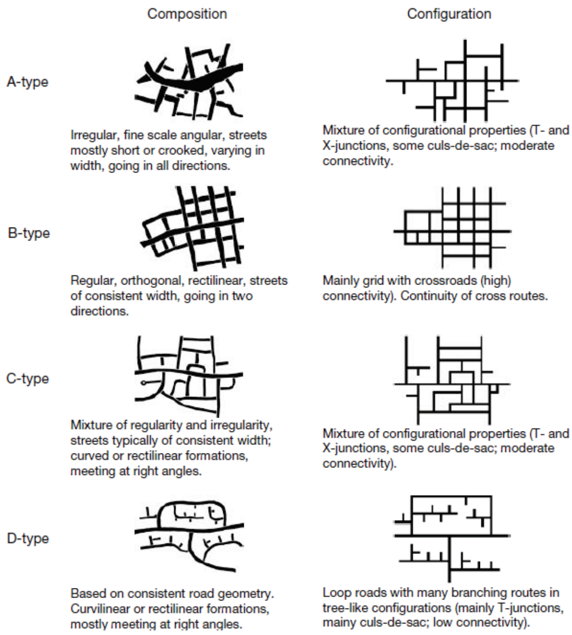


Figure 6: Composition and configuration of different street grids
Marshall (2005:89)

Other crucial element that is related to the urban network and that ties together the street and road network are the junctions or nodes. Junction or nodes, apart from their function of distributing the urban flows, are important points of confluence due to their geometric characteristics. Sometimes these elements due to their capacity to concentrate various activities, to gather people, to accommodate green spaces, have the form of squares or other similar public spaces. According to Chapman (2005:142) squares have two main characteristics: function and shape. In what regards function they can vary from private, central garden, to open public spaces with open-air markets, settings for ceremonial occasions, architectural elements such as fountains, and activities like cafés. The shapes can also vary "(...) *from large and monumental, to small and intimate, from irregular in plan form, to formal and geometric*" (Chapman, 2005:142).

- *Buildings and the urban blocks*

Buildings are essential elements for the understanding of the urban form since they represent the content of an urban area, can have a private or/and public use, contribute significantly to the character of an urban area through its architecture, in a way they represent the 3rd dimension of the city and therefore its density. Carmona (2010:138) referring to Conzen (1960), identifies the importance on what became known as the "burgage cycle" (Figure 7), in order to understand buildings displacement in the urban area, more precisely in the plots. This analysis was first introduced to understand the development of medieval towns but was also applied to 19th century towns and even 20th century suburbs, meaning the word "burgage" a type of property in the medieval era. What is really important in this process is that it shows the pattern of spatial displacement of buildings depending on the process of evolution of the urban form, and reinforces the importance of street hierarchy design to the spatial configuration of buildings.

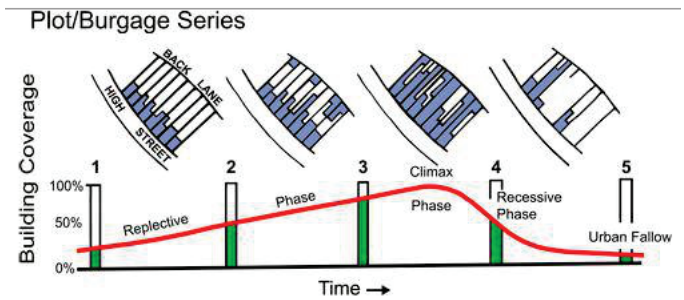


Figure 7: The "Burgage Cycle"
Carmona (2010:139 in Larkham, 1996:175)

If the burgage cycle applies to the common buildings, other buildings with historical or symbolic importance (public buildings, churches, etc.) have a longer duration. This is due usually to the investment that was made in the construction of those buildings and of their design and meaning to the residents. Carmona (2010:139) indicates that "*With the exception of major buildings and in the absence of conservation controls, other buildings will only tend to survive if able to adapt to new uses or the contemporary demands of existing uses – a quality known as robustness*", and that buildings over time will tend to accommodate different uses or intensity of uses during their lifetime.

Buildings may be constructed as a single entity or in group as part of an urban block. Typically urban blocks are subdivided into plots: ´back-to-back´ plots (with a frontage onto a main street or circulation route and a shared common plot boundary at the rear); front onto main street with service alleys at the rear; and less common the ´through´ plots with a frontage at each end onto a main street (Carmona, 2010:139).

Only more recently the urban block approach has known more attention, in the growing necessity of promoting a more integrated planning, that could take into consideration not only the architecture of a single building, but the articulation of that architecture with the street network and with the surrounding buildings in order to create a common urban framework. This perspective, in opposition to the Modernist movement, which promoted the high density single buildings, had roots in the typomorphological analysis, developed by Aldo Rossi. Carmona (2010:165) indicates the main advantage of the urban block: "[it] *is important in determining the pattern of movement, setting the parameters for subsequent development and in contributing to an area's character*". In order to build a "good" urban block it is important to design a network of streets accordingly, so to have the necessary dimensions allowing to accommodate future growth, while in terms of buildings, a balance must be made between buildings providing sufficient area (to be commercially viable for instance), for efficient circulation and for social space. Carmona (2010:166) also indicates that: microclimate and issues of wind and sun penetration need to be considered (e.g. tall narrow streets in northerly or southerly climates will influence sunlight penetration); street blocks typically feature buildings of 2-7 floors; a balance needs to be made between smaller blocks (with pedestrian permeability, walkability, and social use of space) and larger blocks (with a more optimal distribution of built form and open space). HCA (2013:64) indicate that blocks should face the street, in order to make a clear distinction between the public fronts and private backs. The distinction between the public front of a building and the private back is made when the primary access is from the street principal frontage, and the private accesses are relegated to side streets. There should be the basic conditions for people privacy, orienting the private parts of the building to more enclosed views and separating the back of the building with a minimum distance (app. 20 meters). HCA (2013:64) also refers to the importance of lining the perimeter of blocks in order to accommodate a diversity of building types and uses at medium-high densities, while ensuring a positive relation to the public realm, and of the importance of the continuity of the street frontage in order to assist commercial viability and street vitality (Table 3).

Table 3: Characteristics of block, parcel and plot
Adapted from HCA (2013:65-67). For HCA blocks are groups of parcels, parcels groups of plots, and plots the smallest subdivisions of land

Characteristics	Block	Parcel	Plot
Size	- Ease of access; - Ability to sustain a variety of building types and uses; - Ability to change and adapt over time; - 80-90 m outside center/ 60-80 m center.	- Keep the grain fine – enabling a range of developers to participate is usually desirable to generate a richer mix of building types, tenures and uses; - Parcels of 1-2 hectares avoid mono-function and they should decrease in size towards the center.	- Keep plots small and narrow; - Small plots encourages a diversity of forms, uses and tenures and allows a rich variety of buildings. Generates more active frontage, encourages human scale, high densities, flexible basis for amalgamation and enables future incremental growth, minimizes costly and wasteful leftover space; - Larger plots used for commercial, industrial or civic buildings (15x20m wide and 30-40 m deep).
Shape	- Square block usually recommended for commercial and residential buildings; - Rectangular blocks (110m) recommended for factories, warehouses on the fringes; - Rectangular blocks (100x200m) with the short side onto de street can increase connectivity with surroundings, more crossings and junctions; - Irregular blocks can be molded to respond to topography and creation of focal points (green areas, squares).		
Constitution	- Perimeter block structure enables many interior uses: car parks, service yards, private gardens, mews houses, offices, a park or civic square, others.		

- *Limits*

In what regards the limits or barriers, those are according to Lynch (1960:62) "*the linear elements not considered as paths: they are usually but not quite always, the boundaries between two kinds of areas. They act as lateral references [...] Those edges seem strongest* *which are not only visually prominent, but also continuous in form and impenetrable to cross movement*" (Lynch, 1960: 62). MacDougall (2011:47) also details the meaning of barriers: "[…] *urban infrastructure, as well as other urban and/or natural elements, which impede pedestrian movement and disrupt urban tissue patterns within the built landscape*". Jacobs (1960) also refers to the importance of barriers: "*Some of these borders halt cross-use from both sides… such is the case with railroad tracks or expressways or water barriers (i.e. canals, rivers, lakes, etc.) are common examples*" (1960:261). One important characteristic is that borders or edges are not necessarily linear, as Jacobs (1960:261) also pointed out, and given parks as examples. MacDougall (2011:8) stresses the importance of Jacobs's analysis in defining mono-functional zones, since according to the author, they constitute barriers by not incorporating other uses, not being friendly to walk and to the scale of the human being. Despite the negative connotation of the word "barriers", MacDougall (2011:8) refers to the work of Alexander et al. (1977) to indicate the importance of barriers in defining a concrete geographical space that separate physically urban subcultures that otherwise would not "survive". Other qualities of edges are defined in the "Urban design compendium", namely "*The linear elements that define the boundaries of a place - the edges – may be used to define the limits of a development site or regeneration area. Rivers, canals, parklands, busy roads or viaducts, may provide the definition that contributes to a sense of place*" (English Partnerships, 2000: 36).

MacDougall (2011:48) identified a series of criteria in order to define a taxonomy of barriers. Criteria used focused on morphology (dimension, configuration and relative position), nature (natural or human-made barriers), level of spatial resolution (region, city, urban tissue and building), configuration (linear or non-linear), permeability (degree of crossing facility), connection type (with other infrastructures and adjacent tissues), relative position (element´s location within the urban organism). In terms of barriers of natural origin MacDougall (2011:187-188) identified rivers, lakes and slopes, as elements of high impermeability with linear configuration (exception slopes). As artificial elements the author identified at the regional scale railroads, highways, high tension power lines, large mono functional specialized zones, and mono functional zones which correspond to parks. From those both railroad and highways are highly impermeable and linear, and tension lines are also linear but moderately permeable. In what regards the mono functional zones both are non-linear, but in terms of permeability the specialized ones have a variable permeability (dependent on presence and type of internal street network), and the green areas highly impermeable to frequent crossing.

- *Neighborhood*

Song and Knaap (2004) indicate that "*The neighborhood has long been regarded as the basic building block of urban form*" but that "*What constitutes a neighborhood is disputed*". Cervero and Gorham (1995:212) tried to define neighborhood through their mobility component and with two different types: the traditional neighborhood or the "transit neighborhood" (which stands for public transit), which was initially built along a streetcar line or rail station, primarily gridded (over 50% intersections four-way or "X"), laid out and largely built up before 1945; and the "auto neighborhood" (which stands for automobile neighborhood) which were defined by a laid out without regard to transit and without public transit, primarily random street patterns (over 50% intersections either 3-way, "T", or cul-de-sacs), and laid out and built up after 1945. What they concluded when analyzing two different neighborhoods is that those definitions where indeed accurate, and specifically that "[…] *neighborhood design seems to affect the degree to which people drive alone to work, and the degree to which they walk or bicycle*" (Cervero and Gorham, 1995:222).

Song et al (2013:73) indicates that "*The continuing efforts in creating alternative types of neighborhoods have brought increasing attention to the need for understanding neighborhood form attributes in order to describe patterns of development at the neighborhood scale*". In their work of defining a set of metrics to understand the neighborhood´s form, Song et al (2013:75) defined dimensions that encompassed: permeability, or the connectiveness of places; vitality and accessibility, the vibrancy and convenience of places; and variety, or the mix of an appropriate land uses which generates greater opportunities for social interaction (Figure 8).

Figure 8: Examples of permeability, variety and vitality
Source: Song et al (2013:76)

Frey (1999:66) stresses the importance of the neighborhood as the morphological unit in which takes place the essential relations of a city. Besides being the spatial element by definition where city life happens, it has also the function of articulating the urban structure physical elements that were identified before: the streets and squares, buildings and blocks, and the limits – all contribute in its relations and complexity to the identity and performance of a neighborhood. The streets provide the grid or the form of the neighborhood and respective types of fluxes; the buildings and blocks its identity through their architecture, activities and relation to the network; and the limits in contributing to a strong identity - a delimitation that is essential in maintaining a neighborhood´s characteristics and to transmit a “coherent” image to both its residents and visitors. According to Frey (1999:66) the proximity of activities and residential areas constitute a key characteristic of the neighborhood along with other desired characteristics: a distance of 600 m between the edge of a neighborhood and its central area, the catchment area with a size of 110-120 ha. of built-up area, average gross population density of 60 persons per hectare with 7,000 persons, services and facilities located at the center of neighborhood and transport nodes contributing to the creation of a meaningful central place. Frey (1999:66) continues saying that the neighborhood should have "*population large enough to support local services and facilities which provide for daily needs. (It is important that this population should be mixed, as regards income levels)*".

2.3 Urban patterns and sustainability: the development of metrics to assess urban design and diversity

2.3.1 The debate between the compact and disperse urban form

Seto (2010:170) quoting Kates et al. (1990) indicated that two great transformations occurred in the last decades: "(…) *one where the scales, rates, and kinds of environmental changes have been fundamentally altered as humanity has passed through an era of rapid population growth*" and other where "*Humanity crossed a milestone in 2008 when the global urban population exceeded the rural population for the first time in history*". Five main changes have been identified by the author: changes in scale, changes in rate, changes in location, changes in form and changes in urban life and urban function.

Concerning scale and rate Seto (2010:170) indicates the rate at which cities with more than 1 million inhabitants have appeared, indicating that in 1800´s there was only one city with 1 million inhabitants (Beijing), 100 years later there were 16 cities, and another 100 years later there was an impressive number of 378 cities (in China alone there are more than 100 and in India more than 40). Not only cities are increasing in terms of population, but they are becoming larger, which has a significant impact in the ecosystems that surround them.

In terms of location Seto (2010:173) analyzes the shift in the location of the biggest world cities, from Europe and North America to Asia and South America. This is positively correlated with the growth rates in each country, which are considerably higher in Africa and Asia, and considerably lower in Europe and North America. In the next two decades, and only in China and India, the urban population is expected to increase 400 million and around 300 million respectively, which corresponds to an increase of 700 million urban inhabitants worldwide.

Seto (2010:178) also refers to the changes in urban function and life, namely in three factors: the primacy of a city (degree to which a city's population and economic function dominates other cities in a country) that is being seen more commonly; the importance of cities as regional hubs of development; and the intraurban level of dynamic interactions of economic, social, cultural processes that influence the scale, rate and patterns of urbanization. What is important in this analysis is that Seto indicates that despite being traditional sources of wealth, cities worldwide are presenting increasing levels of segregation, poverty, health and pollution problems, specifically cities who present strong levels of growth.

Less studied, but very important, is the urban form. Seto (2010:176) indicates that "(…) *urban form—or urban morphology— is central to the impact of urbanization on the environment*". She stresses that the urban spatial configuration is seen as the interaction between processes (social, economic, political, etc) and landscape, and thus the result of this interaction will be the shape of the form. The author continues stating the increasing use of spatial metrics to quantify and spatially describe the evolution of the urban form, spatial metrics that originate from the field of landscape ecology. An analysis on urban form made by various authors indicated, according to Seto (2010:177), that "(…) *contemporary urbanization is increasingly disperse and expansive*", in what became expressed in the automobile dependent and mono functional low density urban structures – the suburbs. Peri-urbanization is also another result from the rapid growth of cities, which originated a fragmented growth, with the loss of connection in ecosystems and increased segregation of the space.

The image created by Duany et al (2000 in Carmona, 2010:155) shows very well (in an abstract way) the differences between the urban forms that where the result of the changes in urban growth identified before (Figure 9). The urban form became less connected, less coherent, more fragmented, dependent on a single transportation type, segregated in its activities and population location.

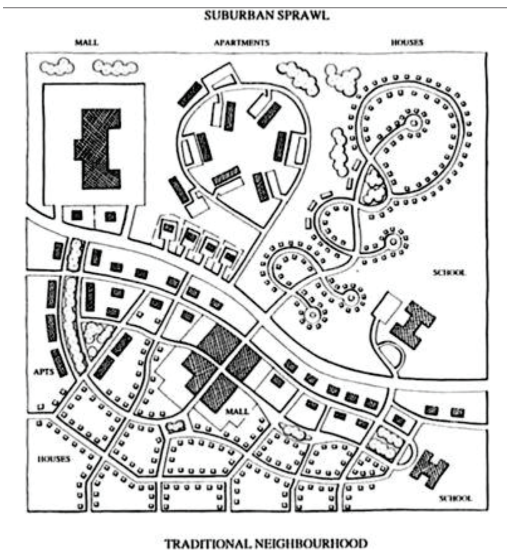


Figure 9: Traditional neighborhood vs. suburban sprawl
Duany et al (2000 in Carmona, 2010:155)

In the searching for a more "sustainable urban form", a rich set of definitions have been suggested by various authors. Jabareen (2006:48) summarizes the main notions around this concept. It indicates that sustainable urban form (in terms of design) is *"(…) that which has a high density and adequate diversity, compact with mixed land uses, and its design is based on sustainable transportation, greening, and passive solar energy*", and establishes as objectives of sustainable urban form: "(…) *decreased energy use, reduced waste and pollution, reduced automobile use, preservation of open space and sensitive ecosystems, and livable and community-oriented human environments*".

In the academic community, the discussion around urban form and its relation with sustainability, has been framed by a duality between the compact and disperse urban form, and its relation with multiple domains, like ecology, mobility, economy, social cohesion, among others (Moudon et al. 1997; Frey, 1999; Camagni et al. 2002; Song and Knaap, 2004; Soltani and Bosman, 2005; Jabareen, 2006; Bramley et al. 2009; Kärrholm, 2008; Silva, 2008; Guerra, 2010). Haughton and Hunter (1994 *in* Moreira, 2010:13-14) indicate that this academic debate has 3 main perspectives: the centrists, the decentrists and the "peacemakers". In this vision, the centrists defend the city that has a human scale, built to walk, served by efficient public transport, with the necessary compaction for social interaction; the decentrists defend a strategy of promotion of concentration but not necessarily centralization, being this the case of the polycentric city; and in the end, the "peacemakers" that argue for the decomposition of the city in minor elements, thus strengthening the identity of each one of those elements, supporting transportation and a common economic strategy at the regional level (Figure 10).

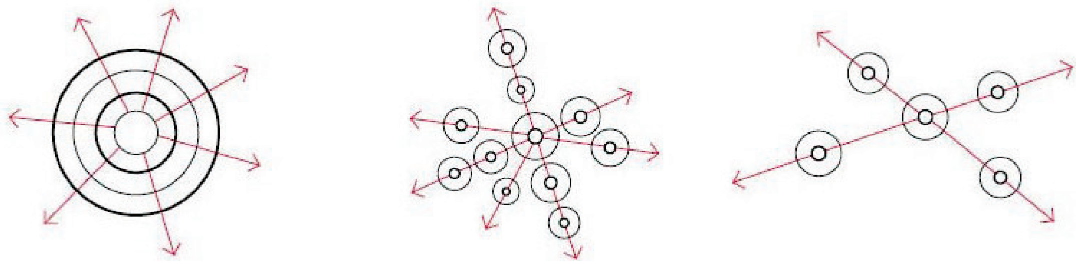


Figure 10: Compact centers; compact agglomerations distributed in a decentralized way through transportation routes; self-sufficient dispersed communities.
Source: Moreira (2010:14, adapted from Frey, 1999)

In a sustainability perspective the compact city gained a great expression mainly due to policy initiatives, like the Green paper on the Urban Environment (CEC, 1990), where the compact city was described as the model for sustainable urban growth, due to the fact that in Europe many cities have dense historical centers, where there is a strong interaction and social mix (Frey, 1999). According to Moreira (2010:14 quoting Burton et al. 1996) the concept of compact city has its fundamentals on density, programmatic diversity and intensity, and in a city which do not need to expand to grow. However, this is a city model that requires a very high quality public transportation system, can present congestion problems, and does not give a solution for many disperse forms that characterize cities nowadays. The polycentric model in its turn, is an intermediate response to both the compact city model and the decentralized model. It is characterized by two complementary aspects: morphology, mainly the distribution of urban areas in a territory (number of cities, hierarchy and localization); and the relation between urban areas, based on cooperation and interdependency.

Frey (1999:108-109) builds on the identification made before of different city models, and establishes a relation between city models characteristics and sustainable dimensions or criteria (Table 4).

Table 4: Comparison of the expected performances of six city models
Source: Frey (1999:108-109)

Criteria	Core city	star city	Sat. city	TODs, TNDs	Lin. city	Reg. city
Degree of containment of development	+	+/–	+/–	–	–	+/–
Population density relative to land needed	+	+/–	+	+	+	+
Viability of public transport	+	+/–	+	–	+	+
Dispersal of vehicular transport	–	+/–	+/–	+	–	+/–
Viability of mixed uses	+	+/–	+	–	+/–	+/–
Access to services and facilities	+/–	+/–	+/–	–	+/–	+/–
Access to green open spaces (parks, countryside)	–	+	+	+	+	+
Environmental conditions (noise, pollution, congestion)	–	+/–	+/–	+	+	+/–
Potential for social mix through variety of housing	–	+/–	+/–	+	+/–	+/–
Potential for local autonomy	–	+/–	+/–	+	+/–	+/–
Potential for self-sufficiency	+	+	+	+	+	+
Degree of adaptability of city to changing conditions/needs	–	+/–	+/–	–	+/–	+
Imageability of the city (the physical entity) as a whole	+/–	+/–	+/–	–		+/–
Imageability of parts of the city (neighbourhoods, districts, towns)	+/–	+/–	+/–	+	+/–	+/–
Sense of place and centrality	+/–	+/–	+	–	–	+
Equal weights	–1	+2	+6	+1	+1	+6
Weighted (bold)	–4	+1	+2	0	0	+3

Note: Sat.= satellite; TOD= transit-oriented development; TND= traditional neighbourhood development; lin.= linear; reg.= regional

The main conclusions that can be taken from Frey analysis are that, when taking into account the equal weights score, the core city is the model who scores worst, and both the Satellite City and the Regional City the models who score higher. If a high priority is given to the degree of containment (policies to stop the growth via dispersion), access to services and facilities, access to the countryside, environmental conditions and the potential for social mix, local autonomy and adaptability, the core city maintains its negative performance and the Regional City appears as the solution with more positive aspects.

Jabareen (2006:47) develops a similar analysis, in which he created a matrix with the main types of cities and urban development's according to his understanding, and their relation with design criteria (Figure 11). The neotraditional development is inspired in the traditional built environments, namely in the integration of their urban forms in the present architecture, in a clear opposition to the suburban urban forms, and a strong emphasis in the neighborhood, sense of community, small scale developments. An example of this development is the New Urbanism movement[3]. The urban containment development is intended to be also a response to extensive urbanization, through the prevention of the outward expansion of the urban field and forcing the development market to look inward. According to Jabareen (2006:44) "*It seeks to employ an array of public policy tools to manipulate "push" and "pull" factors so that the metropolitan area will take a particular and desirable geographical form*". The compact city was already described earlier in its characteristics. Jabareen (2006:45) illustrates some advantages of this model: efficient for more sustainable modes of transportation; preservation of land from the countryside; promote diversity, social cohesion and cultural development; and a more effective use of infrastructure. Finally the Eco-City, is a model that encompasses a wide range of urban-ecological proposals, more precisely the notion presented by the author that is a type that promotes the ecological agenda, and emphasizes environmental management through a set of institutional and policy tools (Jabareen, 2006:47).

Design Concepts (Criteria)	*Neotraditional Development*	*Compact City*	*Urban Containment*	*Eco-City*
Density	1. Low **2. Moderate** 3. High	1. Low 2. Moderate **3. High**	1. Low **2. Moderate** 3. High	1. Low **2. Moderate** 3. High
Diversity	1. Low 2. Moderate **3. High**	1. Low 2. Moderate **3. High**	1. Low **2. Moderate** 3. High	1. Low **2. Moderate** 3. High
Mixed land use	1. Low 2. Moderate **3. High**	1. Low 2. Moderate **3. High**	1. Low **2. Moderate** 3. High	1. Low **2. Moderate** 3. High
Compactness	1. Low **2. Moderate** 3. High	1. Low 2. Moderate **3. High**	1. Low **2. Moderate** 3. High	**1. Low** 2. Moderate 3. High
Sustainable transportation	1. Low **2. Moderate** 3. High	1. Low 2. Moderate **3. High**	1. Low **2. Moderate** 3. High	1. Low 2. Moderate **3. High**
Passive solar design	**1. Low** 2. Moderate 3. High	**1. Low** 2. Moderate 3. High	**1. Low** 2. Moderate 3. High	1. Low 2. Moderate **3. High**
Greening—Ecological design	1. Low **2. Moderate** 3. High	**1. Low** 2. Moderate 3. High	**1. Low** 2. Moderate 3. High	1. Low 2. Moderate **3. High**
Total score	15 points	17 points	12 points	16 points

Note: Scores of the urban forms are highlighted in bold.

Figure 11: Sustainable urban form matrix: assessing the sustainability of urban form
Source: Jabareen (2006:47)

In what regards the quantification of the performance of each city under a set of design principles, a scale from 1-3 (being 1 low and 3 high) provided the method which consisted in the sum of the absolute values given to each design concept. The urban form with the best

[3] It is an urban design movement that arose in the USA in the beginning of the 1980´s which promotes environmentally friendly habits by creating walkable neighborhoods containing a wide range of housing and job types (Boeing et al. 2014)

classification, or more in line with the sustainability principles, was the compact city, followed by the Eco-City, neotraditional development, and finally urban containment.

From the analysis presented, it is clear that there isn´t a common agreement on what is the "best city" in terms of sustainability. In fact, the debate around sustainability is, more than a search for the perfect urban form, a search for the characteristics that have a stronger contribution to a city´s sustainability, and what is the desired performance of each characteristic keeping in mind the context that is being studied.

2.3.2 Measuring urban form: contributes from the complexity science and examples of urban form metrics

Kärrholm (2008:4) indicates that in many studies on sustainable urban form, and from the morphological perspective of the spatial scale, 3 important factors need to be addressed:

1) *There isn´t a differentiation in what concerns the specific aspect of the urban form*, in that there isn´t a connection to the parameters of urban form (patterns and design), being that many times the studies end up in the analysis of statistical indicators without a spatial expression;
2) *Scale is often not taken into account*, and when it is, is often in a rigid way, being that in the opinion of the author a more flexible approach, adaptable to the context, should be taken into consideration;
3) *There is an excessive emphasis in the same indicators*, like density or the mix uses, being that other indicators should be produced in order to better explain the complexity of the urban development and its relation to the sustainability.

The use of quantitative data and methods do understand the urban phenomena is relatively recent. The growth of the complexity science, mainly in the last 30 years, strongly contributed both to the systemic view of cities and also to new methodologies and models that are interdisciplinary and try to measure and explain reality with increasing detail. The vision that dominated the world with a complete separation of the mechanical and social structures changed into a more integrated perspective, of cause and effect, and extremely complex logics of relations between the built environment and activities. Batty (2007:3) indicates that the way we think of cities is changing from a rigid structure to one which is the consequence of various behaviors and processes with the focus on the social processes. The beginning of the "systems approach" (Churchman, 1968) was marked by the "general systems theory" formulated using biological analogies by von Bertalanffy (1968) and "cybernetics" based on communication and control as articulated in engineering (Weiner, 1948) (Batty, 2007:5). In the 1950´s and 1960´s the idea of system with various subsystems tied together by interaction (idea of network and of hierarchy), was developed by the social sciences, namely in management and urban planning, as a basis for underpinning their structure and practice. According to Batty (2007:6) "*Cities were extremely suggestive artefacts for such a theory* […] (since) *its components were individuals or groups tied together spatially and economically through transportation and socially through various friendship networks*". Naturally, the systems approach began to be developed in cities with the transportation research (Lowry, 1968 in Batty, 2007:6), but since its perspective was too narrow regarding the way systems behave, it didn´t responded as expected. It was Jane Jacobs (1961) who really approached the problematic indicating that cities " […] *should not be treated like machines but like living systems with the implication that life, hence city form, emerges from the bottom up following the Darwinian paradigm*", being that a new paradigm was created: "*as soon as the systems approach was articulated, its limits became evident in that thinking of cities as systems in equilibrium with planning aimed at restoring this equilibrium, clearly conflicted with innovation, competition, conflict, diversity and heterogeneity, all hallmarks of successful city life*" (Batty, 2007:8).

Above all the contribution of the complexity sciences to the urban agenda, is on the focus of the importance of the "local" in the performance and structure of the "whole", this way it changes the scale of action from a top-down perspective to a bottom up perspective. Thus it strongly influenced urban research in four ways: 1) *scale* – in developing methodologies that analyzed with increasing detail the city namely through typological and neighborhood analysis; 2) *integration* – in connecting the various scales of analysis, not taking into account a specific scale but the types of connections that exist between them, but also on integrating different dimensions of the urban areas; 3) *measurement* – developing of increasingly complex metrics to assess urban performance, in order to better quantify it and reduce uncertainty; 4) *time* – importance of scenario making, namely integration of backcasting, current data and forecasting.

Chapter 2.3.2 will therefore focus on the analysis of metrics and indicators for assessing urban form, that were influenced by the complexity science but also from other areas of urban research.

- *Urban form metrics*

One of the most used metrics to understand urban complexity is the fractal. According to Thomas et al. (2008:100) a fractal is "*a rough or fragmented geometric shape that can be subdivided into parts, each of which is (at least approximately) a smaller copy of the whole. Fractals are generally self-similar and independent of scale*". The use of fractals appeared in the 1990´s mainly in landscape analysis (McGarigal and Marks, 1995), however soon they began to be applied to cities, since cities can be conceptualized as fractals at several interrelated scales. Fractals have the advantage of providing a synthetic measure of complexity, thereby allowing a numerical characterization of places (Thomas et al., 2008:100). The fractal behavior is associated with a scaling principle that governs how the constituent elements of a structure are distributed in space (Figure 12). Thomas et al (2008:100) explains that in the case of the figure below the initiator is a square of length l0 (a), that is reduced by a factor r=1/4 into N=8 elements. These elements are smaller replicates of the initiator with base length l1= rl0, and they organize within the area of the initial figure which is now called a generator (b). The first iteration is obtained by repeating the process – cluster hierarchy emerges with main lanes in the first iteration and secondary lanes in the second (c), also demonstrating the hierarchy between forms. The closer the Fractal Dimension (D) is to 2 the more homogeneous the structure is (the more similar the width of the lanes separating the clusters).

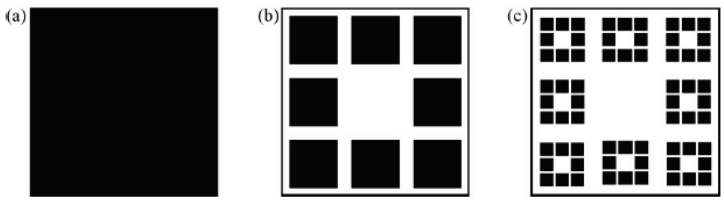


Figure 12: First steps in generating a Fournier dust
Source: Thomas et al (2008:100)

Applying the same principle to cities, Encarnação (2011:146) indicates that fractal dimensions more close to 2 correspond to areas that are heavily compact, while areas closer to 1 are areas with a linear growth, for instance along communication axes, and areas with values that are below 1 correspond to highly dispersed areas. The same principal was applied in one of the seminal works on complexity and cities developed by Batty and Longley – "Fractal Cities", in 1994 (Figure 13).

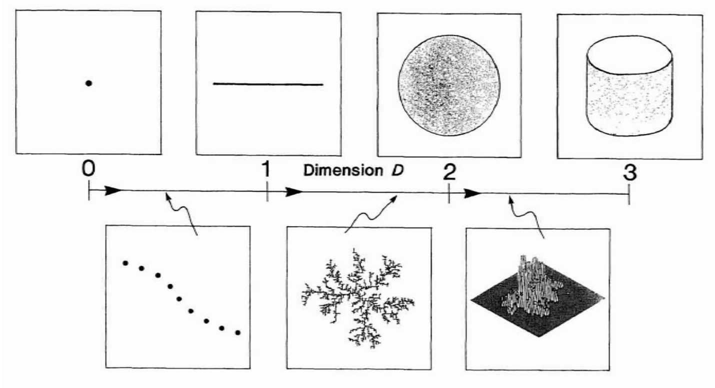


Figure 13: Fractal Dimension
Source: Batty and Longley (1994:76)

Encarnação (2011:146, quoting Batty and Longley, 1994:242) also indicates that it is not accurate to extrapolate a concrete analysis based on the values given for other analyzed cities, however, some conclusions can be drawn and be generalized for an analysis of the fractal dimension: i) all fractal dimensions for urban areas vary between 1 and 2 as what was expected theoretically, ii) the majority of the values for whole cities are situated between 1,6 and 1,8 (with an average of 1,7) which suggests common tendencies between different cities around the world. Other important factor is that, according to Shen (2002 in Encarnação, 2011:148), the values indicate above all the degree of fulfillment of space by the urbanized areas, which means for instance, that it could not be appropriate to extrapolate solely from a Fractal Dimension value a conclusion about a city dispersed, fragmented or compact pattern.

Thomas et al. (2012) analyzed 18 cities and 97 neighborhoods from European Countries (Italy, Finland, France, Belgium, Germany and Switzerland) and have identified 4 types of neighborhood clusters to explain the fractal dimension of cities (Figure 14): cluster 1 with very high fractal dimension values (1.90) typically corresponds to city centers (very high concentration of buildings constructed in a continuous way along the streets); cluster 2, that corresponds to built-up neighborhoods composed of upper-middle class detached houses, which can be found in the first and second level peri-central areas of the cities studied by the authors, and have low to medium density of urbanization with a regular morphology (1.86); cluster 3 has a mix of dwellings and non-residential buildings, often built from 1950-1970, with an arrangement of buildings that not always follows the street pattern, and contains modern industrial areas, housing and located in the periphery of city, thus explains the low fractal dimension (1.64); finally cluster 4 (1.58), is composed by low Fractal Dimension values, corresponding to neighborhoods mainly built in the 1960´s often with a "Charter of Athens style" – the street design disappears, the spatial arrangement of buildings and their forms is varied, lots of green areas, and the center is not clearly recognizable.

Figure 14: Examples for each of the 4 clusters that were identified. D_{aDc} –Fractal Dimension according to the fractal law with a parameter a, and D_{Dc} where the Fractal Dimension is calculated according to the constrained law, where *a* is fixed to 1.0 a priori. Parameter *a* is the form factor or prefactor of shape: a given parameter to address the question of the scale that is being analyzed and thus the size of the objects (buildings) regarding the case study area
Source: Thomas et al. (2012)

Thomas et al. (2012:204) indicate that overall two kinds of urban design emerge from this analysis: a) traditional urban designs (of smaller and irregular buildings and compact configuration of urban form) tend to have high fractal dimensions, and b) modern functional designs (larger and less irregular buildings that display in a more fragmented pattern) represent a low fractal dimension.

Frankhauser (2004:3 in Encarnação, 2011:153) indicates the importance of fractals for the identification of different urban patterns according to their spatial configuration, namely in what concerns the different processes that defined their initial function, being that the case of organic versus heavily planned areas. Frankhauser (2012) identified the following scales for fractal dimension according to urban form: City centers $1.8 < D < 1.95$; Individual housing $1.75 < D < 1.89$; New towns $1.63 < D < 1.77$; Pericentre $1.61 < D < 1.87$ (Figure 15).

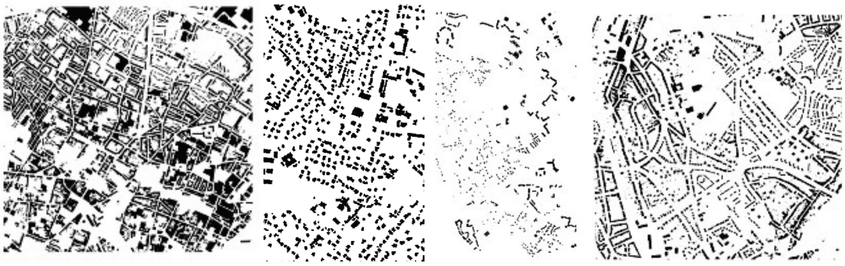


Figure 15: Different fractal patterns - From left to right – city centers, individual housing, new towns, pericenters
Source: Frankhauser (2012)

The author also indicates that the factors that seem to influence the most urban form patterns are: the context of urbanization, local policy, national legislation context and less important but relevant, topography because it acts on the scale of agglomeration.

Other intra-urban analysis on the fractal dimension of urban form was conducted by De Keersmaecker et al. (2003), in which the authors analyzed the city of Brussels, dividing the city in cells and analyzed 26 of them (Table 5). Overall the case study area had *D* values that ranged from 1,338 to 1,961, being the average 1,822. The authors then applied a Ward hierarchical cluster to the 26 cells on three criterions of *D*, which allowed the grouping of *D* values into urban forms.

Table 5: Ward classifications of 26 windows according to *Dsurf-Cor* , *Dsurf-Dil* and *Dper-Cor* . *Dsurf-Cor* , *Dsurf-Dil* and *Dper-Cor* are the notations used respectively for fractal dimensions computed on surfaces (*Surf*) or borders (*Per*), with the correlation (*Cor*) or dilation technique (*Dil*).
Source: Keersmaecker et al. (2003:12)

Group	Sub-group	Mean *D*			Content	Description
		Surf-Dil	*Surf-Cor*	*Per-Cor*		
Urban	**U1**	1.70	1.92	1.69	*B2, D2, C3, E3, C4, D4*	City center and mixed wards of the 19th century
	U2	1.75	1.89	1.65	*C2, B3, D3*	CBD with buildings and offices + some residential and old industrial wards
	U3	1.52	1.79	1.73	*C1, D1, B4, E4, B6, B1, E5*	Mixed residential parts of the 20th century and industrial
Suburban	**S1**	1.46	1.82	1.78	*A2, E2, A3, F3, F4, C5, D5, C6*	Urban with gardens, 20th century
	S2	1.42	1.44	1.68	*E1, A4*	Rural, large industrial surfaces and public equipment

Once again traditional and compact urban forms have the highest *D* values, while rural (in this case suburbs) or residential and industrial mixed zones tend to have lower *D* values. To note that all suburban urban form has a low *D* value, and that is illustrated by the above mentioned example of a planned urban area with green space.

Other work from Thomas et al. (2008) analyzed 262 communes in Wallonia (Belgium) and categorized the results into 6 clusters: Peri-urban I and small cities, Rural I compact isolated hamlets, Peri-urban II and eastern part (Hainaut), rural II hamlets with linear structure, Urban (homogeneous, fully urbanized communes), Rural III – rural communes with hamlets and one (small) city centre (Figure 16 and Table 6).

Figure 16: 6 fractal clusters identified in Wallonia (Belgium)
Source: Thomas et al (2008:112)

Table 6: Average results of $D_{Surf(-d)}$ (fractal dimension of surfaces and $D_{bord\text{-}d3}$ (fractal dimension of borders) for the 6 clusters of Wallonia communes
Source: Thomas et al (2008:112)

Cluster	$D_{Surf\text{-}d0}$	$D_{bord\text{-}d3}$	*n*	Three most representative communes	Typology
1	1.37	1.65	44	Brugelette, *Heron*, Nandrin	Peri-urban I and small cities
2	0.92	1.50	40	*Lierneux*, Havelange, Merbes-le-C	Rural I: compact isolated hamlets
3	1.50	1.76	49	Pepinster, Saint-Georges, *Blegny*	Peri-urban II and eastern part (Hainaut)
4	1.11	1.59	47	Erquelinnes, Baelen, *Rendeux*	Rural II: hamlets with a linear structure
5	1.68	1.70	40	Ottignies, Châtelet, *Chaudfontaine*	Urban (homogeneous, fully urbanised communes)
6	1.25	1.63	42	Gesves, Jalhay, *Ciney*	Rural III: rural communes with hamlets and one (small) city centre

n, number of communes in the class; names in italics indicate the communes illustrated in Fig. 14.

The same tendency of dichotomy in the *D* values between urban and rural areas was observed. A rural area is no supposed to have a strong homogeneous and compact urban form, however, the problem that may exist is that there is a very dispersed urbanization pattern throughout rural land, which can have a strong negative impact on the ecosystems, but also on the transportation system.

The table below (Table 7) summarizes the values of Fractal Dimension (D) for each typology, according to the studies conducted on inner city scale analysis of urban form.

Table 7: Fractal Dimension values for different urban form types according to various authors
Source: Thomas et al. (2008), Thomas et al. (2012), Frankhauser et al. (2004), Frankhauser (2012), Keersmaecker et al. (2003)

Urban form type	Thomas et al. (2008)	Thomas et al. (2012)	Frankhauser et al. (2004) and Frankhauser (2012)	Keersmaecker et al. (2003)
City center (historical)	-	1,88	1,8-1,95	1,92
Consolidated urban form	1,68	1,86	1,75-1,89	1,89
1st Periphery	1,50	1,64	1,61-1,87	1,79
New towns, Le Corbusier developments, periurban areas	1,37	1,58	1,63-1,77	1,82
Suburban and industrial areas	1,25	-	-	1,44

While characterizing the current urban form is important, it is also essential to track its evolution through time. Herold et al (2005) also combined remote sensing and spatial metrics, with the objective of modeling urban growth and land use change during an almost 100 year period. They identified that the major problems in the application of urban metrics are related with the spatial accuracy of the remote sensing data that is used as inputs to the spatial metrics analysis; the thematic accuracy, namely that there is a wide range of different classes when it comes to remote sensing depending on the source and tools used, which does not contribute to the quality of the information and to a broader analysis; selection of metrics, which also relates to a dispersion on the types of metrics that is not useful for comparative analysis and for the definition of a standard of metrics for assessing urban form; definition of the spatial domain, in which the author indicates the multiple approaches in defining the case study area and the fact that these approaches strongly depend on the type of analysis, also saying that "*The spatial discrimination and thematic definition of the spatial units must consider the characteristics of the landscape, the objectives of the study, and the use of the metrics in further analysis that may require a specific spatial subdivision of the urban area*". Herold et al (2005:382) applied 4 spatial metrics for nine types of land uses found within urban areas from an IKONOS image mosaic of the Santa Barbara South Coast region, USA, and obtained with the Fragstat software (McGarigal et al. 2002) (Figure 17).

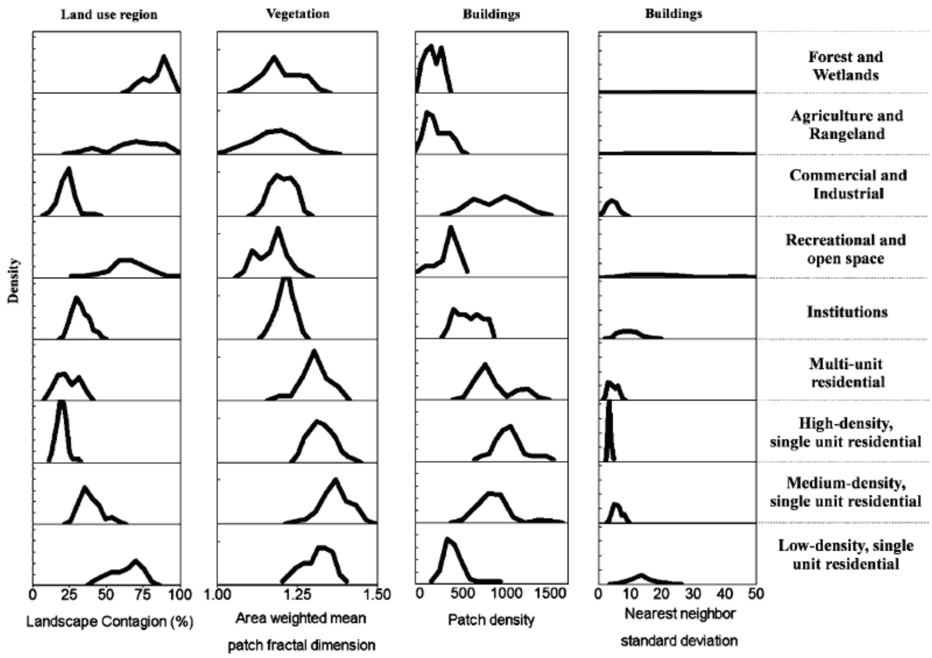


Figure 17: Density graphs of four spatial metrics for nine types of land uses found within urban areas from IKONOS data. The metrics represent different spatial features noted on top of each graph
Herold et al (2005:382)

Four different metrics were analyzed taking into account their density in the environment where they are being measured and respective land uses. The land contagion measures the level of fragmentation of a certain area, being that for high levels of contagion are land uses that have less fragmented types of landscape like forests, wetlands, agricultural areas, etc. In these cases there are low values of contagion for single unit high-density residential, multi-unit residential and commercial/industrial areas. In what regards the metric area weighted mean patch fractal dimension for vegetation, there is a high fragmentation for all residential land uses (vegetation structures typically become more fragmented in urban tissue), and commercial and public institutions present more compact green areas. For the metric patch density there is a strong correlation of the density of patches and land uses density. In what regards the regularity of the building pattern (explained by the metric nearest neighbor standard deviation), the natural or semi-natural areas have a tendency of low levels of regularity, and in contrast, the high density single unit residential area have the highest levels of regularity.

Herold et al (2005:387) also focus their analysis in the use of spatial metrics to represent spatial heterogeneity in urban areas, namely in assessing change and patterns of urban form at more local scales. They indicate that "*The structures and patterns identified with spatial metrics may constitute critical independent measures of the urban socioeconomic landscape and can be used for an improved representation of a variety of urban spatial characteristics*" and that "*Beyond socioeconomic functions, spatial metrics can also help highlight the relationships between urban spatial form (including its three-dimensional building structure) and various dimensions of urban environmental quality and performance*". One of their focus in this specific analysis, is that there should be developed new metrics tailored to the urban space, that could capture important urban characteristics, and that the development of urban metrics should focus on describing spatial characteristics of the built environment and the patterns formed by buildings. Finally, Herold et al. (2005:391) also focus on the importance of metrics as an approach to analyze the spatio-temporal urban growth patterns. When looking at the urban change in Santa Barbara, CA region (USA), and comparing both the metrics evolution and satellite images through time, it is possible to understand the main dynamics in the urban form that have occurred (Figure 18). Those pointed out to a dispersion and fragmentation of urban form until 1997, a result of a strong urban growth that can be explained by the decrease in density (patch density), decrease in fractal dimension, % largest patch, and near neighbor distance.

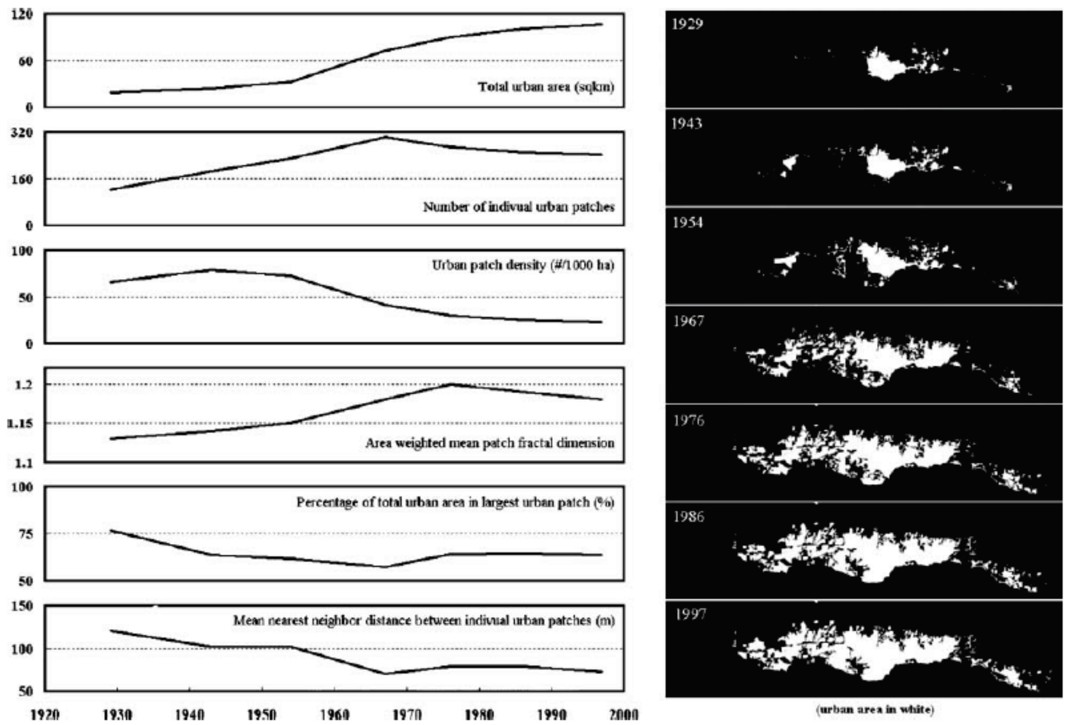


Figure 18: Spatial metrics describing the spatial and temporal growth dynamics mapped from multi-temporal air photos in the Santa Barbara, CA region 1929-1997
Source: Herold et al (2005:391)

Huang and Sellers (2007) made a comparative analysis of different urban forms through the application of spatial metrics and remote sensing. They utilized and processed satellite images of 77 cities from metropolitan areas all around the world, to calculate seven spatial metrics that could capture 5 distinct dimensions of urban form: complexity, centrality, compactness, porosity and density (Figure 19). Then they grouped the cities into developed and developing countries and applied a T test to understand the differences between these two groups; made a comparison of the metrics performance by region; made a correlation analysis between metrics to understand their relation; and made a cluster analysis to understand how the cities would group according to their performance.

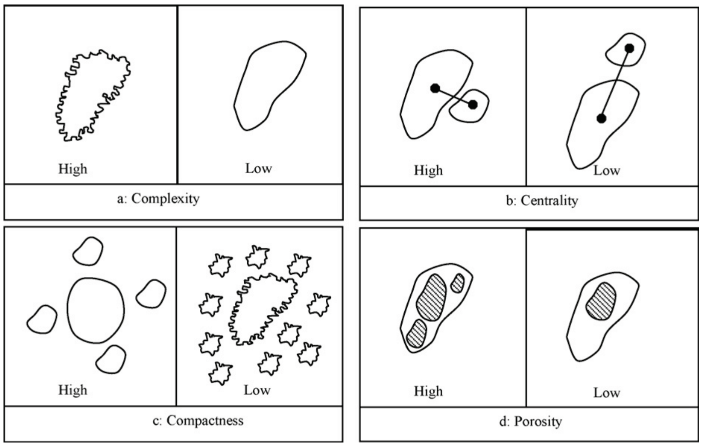


Figure 19: Urban form metrics dimensions
Huang and Sellers (2007:187)

Complexity analyzes the level of the shape´s regularity of each urban area: areas with high levels of complexity tend to be irregular in their shape and areas that have low levels of complexity tend to have a regular form – it is a principle similar to the fractal dimension. Centrality is about the size of the main shape (e.g. urban form) and the average distance from the centroid of that shape (city center), and the centroids of the other smaller shapes (sub-centers), signifying "(…) *the degree to which the urban development is close to the central business district (CBD)*" (Huang and Sellers, 2007:186 quoting Galster et al., 2001). Compactness measures simultaneously the irregularity of each shape but also the fragmentation of the overall urban landscape (the more regular the patch shape and the smaller the patch number, the bigger the *CI* value). Finally, porosity measures the ration of open space when compared to the total urban area. The authors also used socio-economic indicators to strengthen the analysis. A detail explanation of each metric used can be seen in Table 8.

Table 8: Characterization of the urban form metrics used
Source: Huang and Sellers (2007:187)

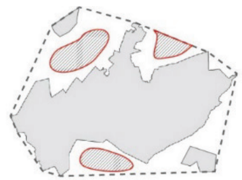
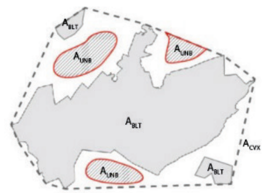
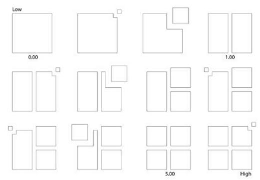
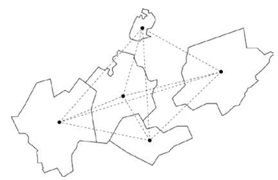
Indicators	Abbreviation	Formula	Description
Area weighted mean shape index	AWMSI	$\text{AWMSI} = \frac{\sum_{i=1}^{i=N} p_i/4\sqrt{s_i}}{N} \times \frac{s_i}{\sum_{i=1}^{i=N} s_i}$	Where s_i and p_i are the area and perimeter of patch i, and N is the total number of patches
Area weighted mean patch fractal dimension	AWMPFD	$\text{AWMPFD} = \frac{\sum_{i=1}^{i=N} 2 \ln 0.25 p_i / \ln s_i}{N} \times \frac{s_i}{\sum_{i=1}^{i=N} s_i}$	Where s_i and p_i are the area and perimeter of patch i, and N is the total number of patches
Centrality	Centrality	$\text{Centrality} = \frac{\sum_{i=1}^{N-1} D_i/N-1}{R} = \frac{\sum_{i=1}^{n-1} D_i/N-1}{\sqrt{S/\pi}}$	Where D_i is the distance of centroid of patch i to centroid of the largest patch, N is the total number of patches, R is the radius of a circle with area of s, and s is summarization area of all patches
Compactness index	CI	$\text{CI} = \frac{\sum_i P_i/p_i}{N^2} = \frac{\sum_i 2\pi\sqrt{s_i/\pi}/p_i}{N^2}$	s_i and p_i are the area and perimeter of patch i, P_i is the perimeter of a circle with the area of s_i and N is the total number of patches
Compactness index of the largest patch	CILP	$\text{CILP} = \frac{2\pi\sqrt{s/\pi}}{p}$	Where s and p are the area and perimeter of largest patch
Ratio of open space	ROS	$\text{ROS} = \frac{S'}{S} \times 100\%$	Where s is the summarization area of all "holes" inside the extracted urban area, s is summarization area of all the patches
Density	Density	$\text{Density} = \frac{T}{S}$	Where T is the city's total population, S is summarization area of all the patches
Purchasing power parity	PPP	Definition from (UNDP, 2001)	Gross domestic product per capita
Telephone lines/1000 people	TELP	Definition from (World Bank, 2000)	National telephone lines ownership
Vehicles/1000 population	VEHPOP	Definition from (World Bank, 2000)	National vehicles ownership

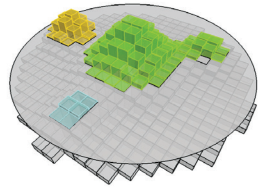
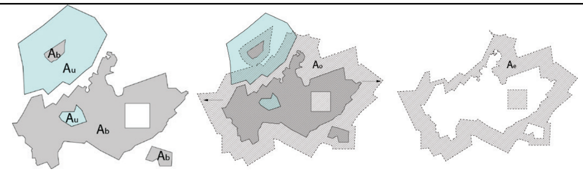
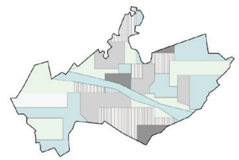
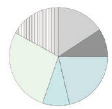
The main conclusions of Huang and Sellers (2007:194) are that "*The compactness, density and regularity of urban areas in developing regions generally exceed the levels throughout developed countries*" and that "*Although European and Japanese cities display more centralized, more compact, denser, and less irregular forms than US counterparts, developed regions in general feature higher levels of sprawl than the developing areas of either Asia or Latin America*". The authors also concluded through the cluster analysis, that Australian and New Zeland cities are starting to have urban forms very similar to the US ones; that the European cities urban form is closer to the US and Australian cities; that Chinese and Indian cities cannot be framed in the group of typical Asian cities; and that the Latin American cities are starting to resemble the Chinese cities in their growth patterns.

Amindarbari and Sevtsuk (2013) proposed the development of a metropolitan form analysis toolbox[4], in order "*to track growth and change in cities around the world*" through 7 metrics: size, coverage, polycentricity, compactness, discontiguity, expandability and land-use mix (Table 9).

[4] http://cityform.mit.edu/projects/metropolitan-form-analysis-toolbox-for-arcgis

Table 9: Characterization of size, coverage, polycentricity, compactness, discontiguity, expandability and land-use mix metrics
Source: Adapted from Amindarbari and Sevtsuk (2013b)

Metric	Description	Spatial representation
Size	Estimates the area of a land use category. Takes into account: the build-up area (grey), the area of the Convex hull around all developed polygons, the unbuidable area within the Convex Hull (circled with red).	
Coverage	Estimates the ground cover of a land-use type within a total area. If the area of the convex hull around the developed polygons is ACVX, the unbuildable area of the convex hull is AUNB, and the total area of all builtup polygons is ABLT, then the built-up coverage CBLT is estimated as follows: $C_{BLT} = \frac{A_{BLT}}{(A_{CVX} - A_{UNB})}$	
Discontiguity	Quantifies the degree to which a city is fragmented into 52omplexity52n52 built-up areas. The metric jointly increases by the number of discontinuous developments and the size inbalance between the developments. $DC = \sum_{n=1}^{N} (\frac{\sum_{i=n+1}^{N} A_i}{A_n})(\frac{\sum_{i=n}^{N} A_i}{A_{total}})$ where *DC* is the discontiguity of the built-up area, *N* the number of urbanized clusters, *An* the area of cluster *n*, and *Atotal* the joint area of the urban extent. Note that *An*≥ *An+1*, so that the denominator in the first part of the index always compares other areas to the largest continuous area	
Compactness	Indicates the average spatial accessibility between separate built up areas – the higher these accessibilities, the more compact a city is. A compactness index should capture the degree to which the resources of a city (e.g. people, buildings, jobs, etc.) are spread out. *Gravity index:* $G_i = \sum_{j \in G-\{i\}} \frac{W[j]}{e^{\beta \cdot d[i,j]}}$ where Gi is the gravity index for location façade, W[j] the size or attractiveness of the destination j, and d[façade,j] the distance between locations façade and j, and beta is the exponent that controls the effect	

	of distance decay between façade and j. Distance d[façade,j] can be measured from the centroid of polygon façade to the centroid of polygon j.	
Policentricity	Estimates the degree to which a city's employment (or other activity) is concentrated in centers. Polycentricity depends simultaneously on three factors: a) the number of centers; b) the size-balance between centers and c) the share of total employment that is located in centers. *PC*=HixNxRc where *PC* is the polycentricity index, *HI* the homogeneity index, *N* the number of centers, and *Rc* the ratio of the total amount of jobs found in all centers to the total amount of jobs in the city.	
Expandability	Illustrates how much space is available for development beyond the city's current borders in a given distance threshold. a) Current situation where Ab is currently build-up areas, Au unbuildable areas. b) Desired scenario for urban expansion where Ao represents the expansion c) All unbuildable areas (Au) are subtracted from Ao to find Ae the area actually available for expansion	
Land-use-mix	Captures the degree to which the observed distribution of land uses corresponds to an expected distribution. The final land use mix index Mxi around location façade is given by multiplying the observed share of all land uses of interest around I (Si) with the product of all individual matching indices Mn:façade around i: $MX_i = S_i \cdot \left(\prod_{n=1}^{N} M_{n:i}\right)$ This land use metric tells us how closely the distribution of all land uses of interest around location façade correspond to their expected distribution. Mxi always ranges between 0 and 1. Mxi is at its maximum value when the land uses in the immediate square kilometer around façade perfectly match the expected distribution. Mxi is zero when none of the expected uses are found in the area of i.	 

Song and Knaap (2004) proposed a series of metrics to measure the urban form, in order to compare a “New Urbanism” form and a “typical” form in Washington County (Portland), Oregon. They divided the metrics onto 5 dimensions and characterized in detail what each metric would measure as it can be seen in Table 10.

Table 10: Metrics proposed by Song and Knaap to compare a “New Urbanism” and “typical” urban forms
Source: Song and Knaap (2004:214-215)

Dimension	Metric	Description
Street Design and Circulation Systems	*Int_Connectivity*	Number of street intersections divided by sum of the number of intersections and the number of cul-de-sacs; the higher the ratio, the greater the internal connectivity.
	Blocks_Peri	Median perimeter of blocks; the smaller the perimeter, the greater the internal connectivity
	Blocks	Number of blocks divided by number of housing units; the fewer the blocks the greater the internal connectivity
	Length_Cul-De-Sac	Median length of cul-de-sacs; the shorter the cul-de-sacs, the greater the internal connectivity
	Ext_Connectivity	Median distance between Ingress/ Egress (access) points in feet; the shorter the distance, the greater the external connectivity
Density	*Lot_Size*	Median lot size of SFDUs in the neighborhood; the smaller the lot size, the higher the density.
	SFDU_Density	Single-family dwelling units divided by the residential area of the neighborhood; the higher the ratio, the higher the density.
	Floor_Space	Median floor space of SFDUs in the neighborhood; the smaller the floor space, the higher the density
Land Use Mix	*Mix_Actual*	Acres of commercial, industrial, and public land uses in the neighborhood divided by the number of housing units; the higher the ratio, the greater the land use mix
	Mix_Zoned	Acres of land zoned for central commercial, general commercial, neighborhood commercial, office commercial, industrial, and mixed land uses in the neighborhood divided by the number of housing units; the higher the ratio, the greater the mix.
Accessibility	*Com_Dis*	Median distance to the nearest commercial use; the shorter the distance, the greater the accessibility.
	Bus_Dis	Median distance to the nearest bus stop; the shorter the distance, the greater the accessibility
	Park_Dis	Median distance to the nearest park; the shorter the distance, the greater the accessibility
Pedestrian Access	*Ped_Com*	% of SFDUs within ¼ mile of all existing commercial uses; the higher the percentage, the greater the pedestrian access
	Ped_Transit	% of SFDUs within ¼ mile of all existing bus stops; the higher the percentage, the greater the pedestrian access

To compare the two neighborhoods concerning the metrics of urban form, plots of data were presented together with the results of regressions that have measures of urban form as the dependent variable, and the age of neighborhood as the only independent variable. Song and Knaap (2004:223) discuss that in their assessment of the performance of the two neighborhoods through time they “*found systematic changes over time in most measures of urban form, excluding measures of land use mix and distance to parks*”, and that many of the measures improved in the early 1990´s, specifically in terms of connectivity, pedestrian access and density, however they remain relatively homogeneous in land uses. They indicate that recent developed neighborhoods have relatively higher internal street connectivity and pedestrian access due to specific local policies, however, New Urbanist neighborhoods remain inconclusive in their overall effect on urban form, because besides local improvements, the overall tendency to create more cohesive urban forms is not taking a strong effect due mainly to the difficulty in changing lifestyles.

Bramley et al. (2009:2130) also proposed metrics of urban form, but more focused on residential neighborhoods (at the sub-area level, which were defined using maps and local knowledge to identify natural subdivisions via major boundary features), to support the analysis of social sustainability indicators in five British cities. The metrics proposed were: Net dwelling density, Gross dwelling density, Distance from CBD (km), Detached dwelling (%), Terraced dwelling (%), Flats (%), Buildings >4 storeys (%), Average garden size (ha), Gardens (% area), Green space (%), Nonresidential and mixed use (%). Then they assessed the values of each of those metrics by the location of each neighborhood (in their inner, middle and outer distances to the center), and also by their gross density. They created another set of social sustainability variables and made a regression analysis which indicated that there were significant relations between the social indicators and the ones of urban form. Next, the authors constructed component measures that represent the value of all the specific variables in each category, and respective coefficient from the model, and plotted that against three variables: neighborhood pride and attachment, social interaction, and use of neighborhood services. The results can be observed in Figure 20.

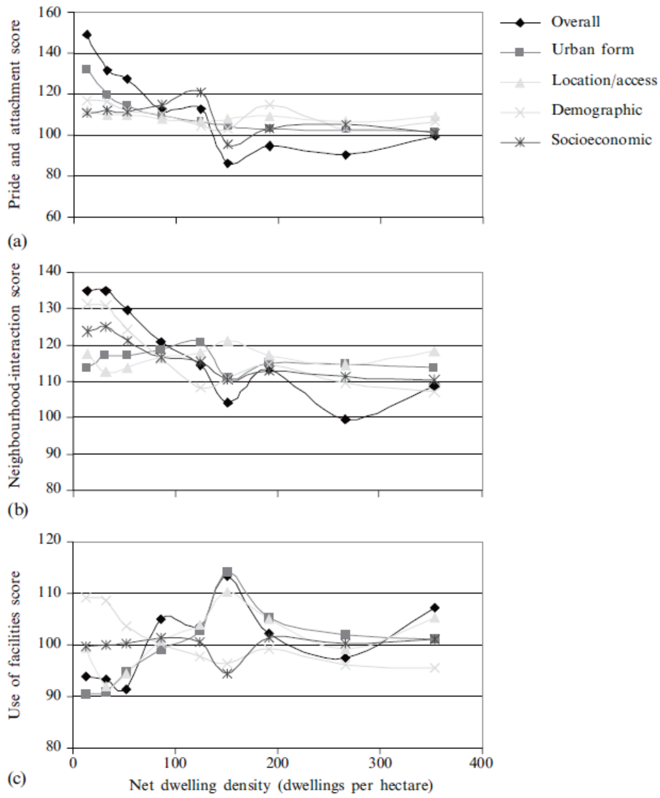


Figure 20: Importance of urban form, together with other dimensions for neighborhood pride and attachment, social interaction, and use of neighborhood services
Source: Bramley et al. (2009:2137)

Bramley et al. (2009:2139) present three main conclusions in their work: 1) outcomes relating to neighborhood pride and attachment, stability, safety, environmental quality, and home satisfaction all display a negative and nonlinear relationship with density; outcomes relating to social interaction and group participation tend to improve as density rises up to a medium level, and then fall off at higher levels; 3) outcomes related to the use of local services are broadly positively related to density.

The work developed by the London School of Economics (LSE, 2014) on "Urban Morphology and Heat Energy Demand" across 4 cities – Berlin, Istanbul, London, and Paris – is a very interesting work on the application of urban form metrics for urban typologies characterization and analysis and relation with an energy model (as it will be seen further ahead). In what regards specifically the urban form analysis, 25 different building configurations were identified, and five different urban morphological types were selected with 500 x 500 samples in order to represent the urban fabric as homogenously as possible: detached housing; high rise apartment/apartment building; slab housing (made with concrete); terraced/regular urban block/row housing/modern apartment; and compact urban block (Figure 21). ´Idealized´ samples were also created for a "[…] *purification of the real samples*" (LSE, 2014:26). The metrics that were calculated were built-up area, land area, coverage ratio, floor area, floor are ratio, % built-up area, land area and road area.

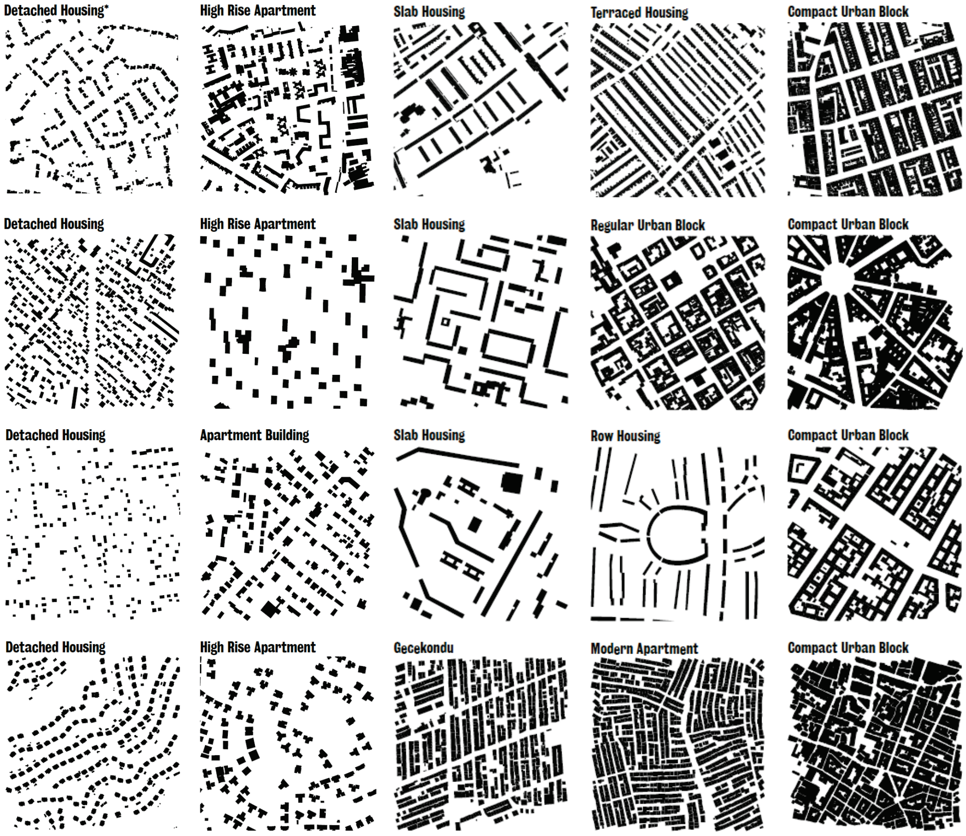


Figure 21: Examples of the typologies analyzed by the LSE study, each row represents on city (from top to bottom): London, Paris, Berlin, Istanbul
Source: LSE (2014:12-13)

According to LSE (2014:86), and in general, a positive correlation was found between surface coverage and density (FAR); building height correlated strongly with density (FAR). Apart from these general remarks that are registered through all typologies there were to different trends: 1) Fast building height increase with increasing density (in the high rise apartments and slabs); 2) very little building height increase with increasing density (regular blocks, modern apartments, compact blocks). The two trends are mutual exclusively: "[…] if one wishes to increase density, one can wither build upwards or increase the surface coverage of buildings" LSE (2014:21). Surface-to-volume ratio and density tend to correlate negatively, mainly until FAR of 1.5, being that no significant increase in surface-to-volume ratio was found beyond this point. According to LSE (2014:86) "*In all cities, detached housing dominated the upper end of the scales of both surface-to-volume ratio and density. The lower end of this scale was occupied by the remaining morphology types, depending on their particular localized architectural styles*". A spacemate diagram (Berghausen and Haupt, 2005) was created in which

4 metrics were combined: FAR, building height, surface coverage and open space ratio[5] (Figure 22).

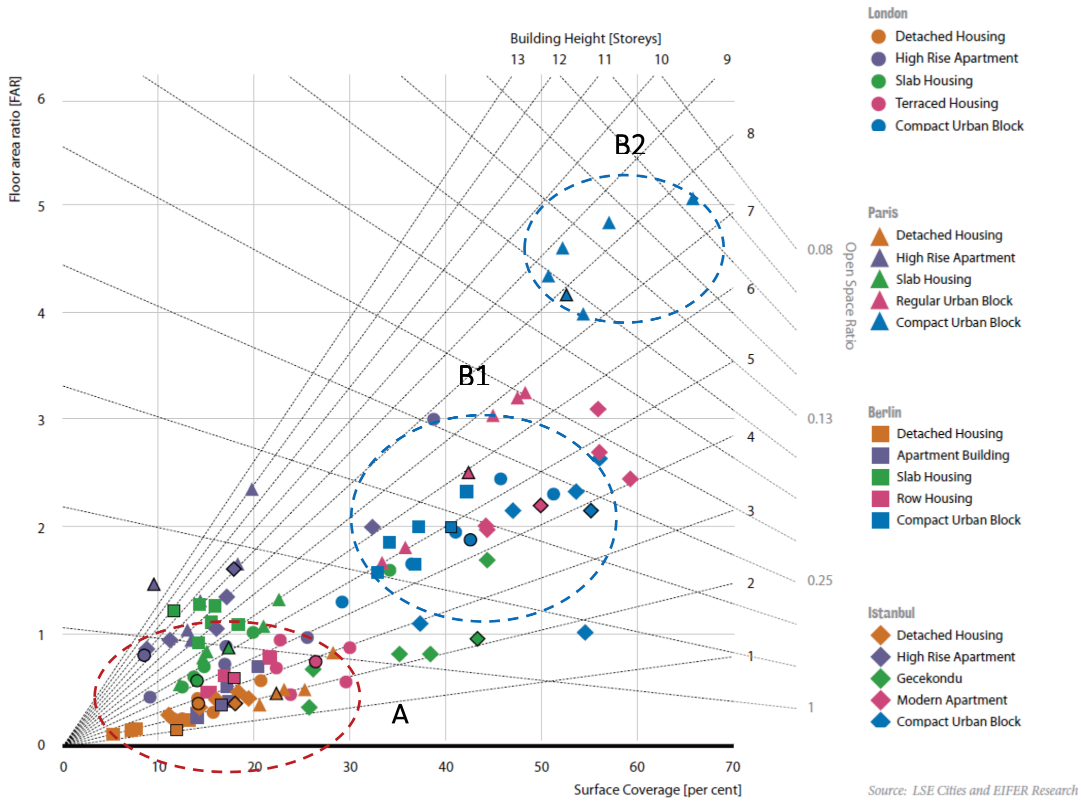


Figure 22: Spacemate diagram showing the key spatial variables used in the LSE study and their relations by urban typology
Source: LSE (2014:52)

The diagram clearly shows 2 main groups – one of detached housing (A) and another with divides in two of compact urban blocks (B1 and B2). Detached housing had value of < FAR 0.5 and surface coverage of < 30%, building height of 2 floors and open space of 1. The B1 group had a FAR of 2.0, surface coverage of 30-60%, building height of 4-6 floors; while group B2 (with only Parisian typologies), presented higher densities, (4-5.2 FAR), average height (7-9 floors), and open space ratios around 6-7.

[5] Ratio between the un-built areas and the gross floor area of any given site

- Key findings of chapter 2

- The "ideal cities" concept is not adequate to today´s urban reality. City interventions are favored at a more local scale and dependent on the specific context;

- Urban design has been studied in two main dimensions: the immaterial and material qualities. In what regards the immaterial qualities, those are identity (the unique character of a specific place); structure (how the space is organized); and meaning (how the citizens that live in that space relate to it). The material qualities are the physical expression of cities, namely, streets and junctions, buildings and urban blocks, limits, and neighborhoods;

- In the debate between compact versus disperse urban form, there isn´t a "one solution fits all", however generally, the compact urban form is preferred due to the more sustainable solutions it allows. However, polycentric urban forms are suggested whenever there is the need to intervene in a fragmented and dispersed urban form;

- Urban form modelling and the development of urban form metrics has known a substantially development in the last years with the introduction of new tools and models, however, there are still limitations: there isn´t a differentiation on specific aspects of urban form; scale is often not taken into account; and there is an emphasis on the same indicators and metrics.

3. Climate change and energy – the importance of urban areas for sustainability

3.1. Contribution of anthropogenic factors to climate change

According to IPCC (2014:2) "*Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history*", also the "*Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen*". In Table 11, some of the main observed changes resulting from climate change from the 5th IPCC Report are summarized.

Table 11: Climate Change Impacts until the present time on temperature, oceans, precipitation and ice snow cover
Source: IPCC AR5 Summary Report (2014)

Observed Changes	Climate Change Impact (IPCC AR5, 2014)
Temperature	The globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] °C over the period 1880 to 2012.
Oceans	Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*), with only about 1% stored in the atmosphere; Since the beginning of the industrial era, oceanic uptake of CO_2 has resulted in acidification of the ocean; Over the period 1901 to 2010, global mean sea level rose by 0.19 [0.17 to 0.21] m. The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*).
Precipitation	Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (*medium confidence before and high confidence after 1951*). For other latitudes, area-averaged long-term positive or negative trends have low confidence.
Ice and snow cover	Over the period 1992 to 2011, the Greenland and Antarctic ice sheets have been losing mass (*high confidence*), likely at a larger rate over 2002 to 2011; Glaciers have continued to shrink almost worldwide (*high confidence*); Northern Hemisphere spring snow cover has continued to decrease in extent (*high confidence*); There is high confidence that permafrost temperatures have increased in most regions since the early 1980´s in response to increased surface temperature and changing snow cover; The annual mean Arctic sea-ice extent decreased over the period 1979 to 2012, with a rate that was very likely in the range 3.5 to 4.1% per decade; It is very likely that the annual mean Antarctic sea-ice extent increased in the range of 1.2 to 1.8% per decade between 1979 and 2012. However, there is high confidence that there are strong regional differences in Antarctica, with extent increasing in some regions and decreasing in others

The main changes in the climate system, and respective anthropogenic greenhouse gas emissions are summarized in the Figure 23.

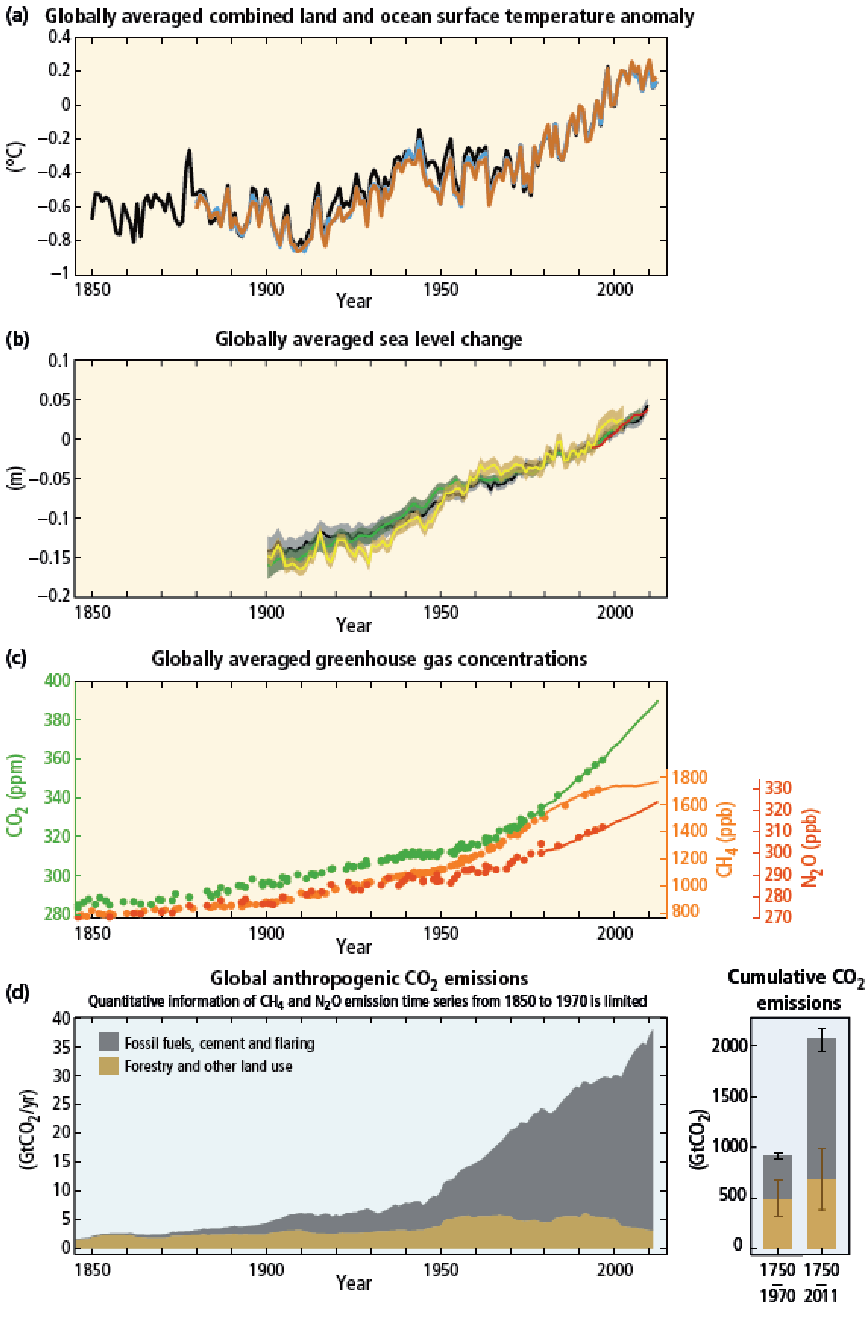


Figure 23: Main changes in the climate system, and respective anthropogenic greenhouse gas emissions. Observations (colours indicate different data sets): (a) Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005; (b) Annually and globally averaged sea level change relative to the average over the period 1986 to 2005 in the longest-running dataset; (c) Atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2, green), methane (CH_4, orange) and nitrous oxide (N_2O, red) determined from ice core data (dots) and from direct atmospheric measurements (lines); (d) Global anthropogenic CO_2 emissions from forestry and other land use as well as from burning of fossil fuel, cement production and flaring. Cumulative emissions of CO_2 from these sources and their uncertainties are shown as bars and whiskers, respectively, on the right hand side. The global effects of the accumulation of CH4 and N2O emissions are shown in panel c.

Source: IPCC AR5 Summary Report (2014:3)

Has it can be seen in this figure, there has been a continued increase in the GHG emissions since the pre-industrial era for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). From 1750 to 2011 40% of the carbon dioxide emissions have remained in the atmosphere, being the remaining removed from the atmosphere and stored on land (plants and soils) and in the ocean (IPCC, 2014:4). From those the ocean has absorbed 30%, causing ocean acidification.

The majority of the GHG emissions were registered in the last 40 years. When we look specifically into this period, and to the contribution of the main greenhouse gases to the total GHG emissions, it is clear that the carbon dioxide (from fossil fuel and industrial processes with 59% and from forestry and other land use [FOLU] with 16%) is the one with the largest contribution, followed by CH_4 (18%) and N_2O (7,4%). F-Gases have a minor contribution with 0,81%. Despite the climate change awareness and policies, the increase on GHG emissions was higher from 2000-2010 (+2,2%/yr) than in 1970-2000 (+1,3%/yr) (Figure 24).

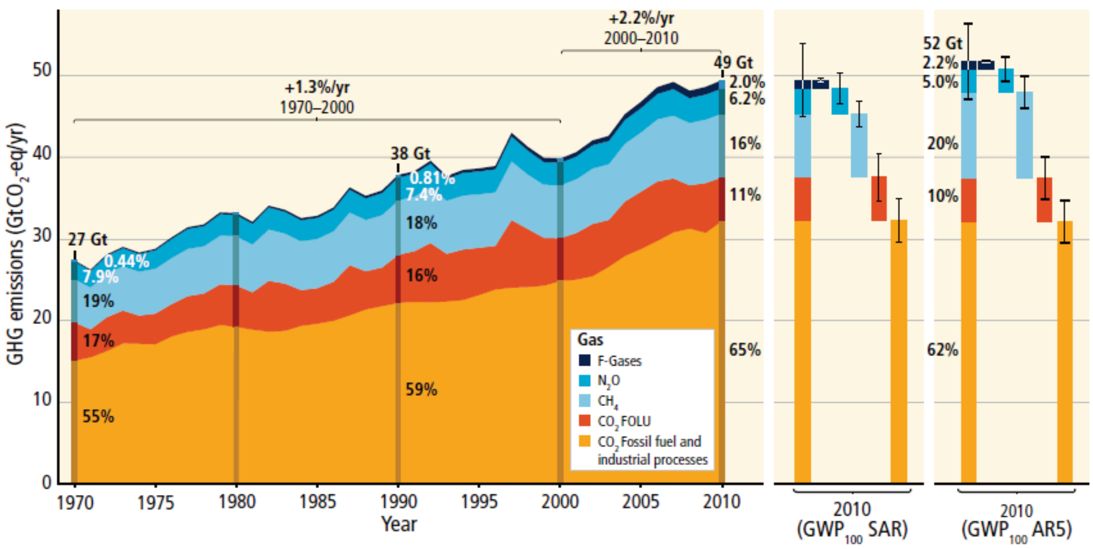


Figure 24: Total annual anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2-equivalent per year, GtCO2-eq/yr.) for the period 1970 to 2010 by pollutant: CO_2 from fossil fuel combustion and industrial processes; CO_2 from Forestry and Other Land Use (FOLU); methane (CH_4); nitrous oxide (N_2O); fluorinated gases covered under the Kyoto Protocol (F-gases). Right hand side shows 2010 emissions, using alternatively CO_2-equivalent emission weightings based on IPCC Second Assessment Report (SAR) and AR5[6] values. Unless otherwise stated, CO_2-equivalent emissions in this report include the basket of Kyoto gases (CO_2, CH_4, N_2O as well as F-gases) calculated based on 100-year Global Warming Potential (GWP100) values from the SAR. Using the most recent GWP100 values from the AR5 (right-hand bars) would result in higher total annual GHG emissions (52 $GtCO_2$-eq/yr.) from an increased contribution of methane, but does not change the long-term trend significantly.
Source: IPCC AR5 Summary Report (2014:5)

[6] IPCC 5th Assessment Report: https://www.ipcc.ch/report/ar5/

The main drivers that contributed to the carbon dioxide increase that was registered from 2000-2010 have been economic and population growth and particularly economic growth, due to the increased use of coal (IPCC, 2014:5). The influence of human activity on the climate system is clear. IPCC (2015:5) indicates that "[…] *more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together*". Also, according to IPCC (2014:8) "*Multiple lines of evidence indicate a strong, consistent, almost linear relationship between cumulative CO_2 emissions and projected global temperature change to the year 2100 in both the RCPs*[7] *and the wider set of mitigation scenarios analyzed in WGIII*[8]" (Figure 25).

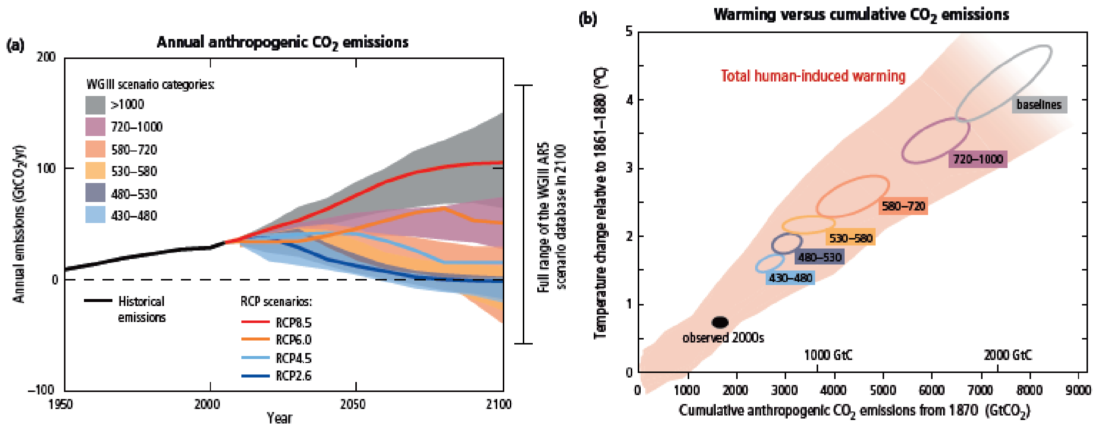


Figure 25: Annual anthropogenic CO_2 emissions until present and projected to 2100, and warming versus cumulative CO_2 emissions. a) Emissions of carbon dioxide (CO_2) according to RCP lines (coloured areas show 5 to 95% range); b) Global mean surface temperature increase at the time global CO_2 emissions reach a given net cumulative total, plotted as a function of that total, from various lines of evidence. Coloured plume shows the spread of past and future projections from a hierarchy of climate carbon cycle models driven by historical emissions and the four RCPs over all times out to 2100, and fades with the decreasing number of available models. Ellipses show total anthropogenic warming in 2100 versus cumulative CO_2 emissions from 1870 to 2100 from a simple climate model (median climate response) under the scenario categories used in WGIII. The width of the ellipses in terms of temperature is caused by the impact of different scenarios for non-CO_2 climate drivers. The filled black ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000–2009 with associated uncertainties.
Source: IPCC AR5 Summary Report (2014:9)

Some of the predicted changes of climate change impacts on temperature, oceans, precipitation and ice snow cover until 2100 are summarized in Table 12.

[7] RCP´s: Representative Concentration Pathways. They have substituted the previous Climate Change Scenarios (SRES) in the IPCC 5th AR and are divided into: RCP 2.6 (optimist scenario) in which temperature will increase 1.0 ºC until 2100; RCP 4.5 with an increase in temperature of 1.8 ºC until 2100; RCP 6.0 with an increase in temperature of 2.2 ºC until 2100; and RCP 8.5 (pessimist scenario) with an increase in temperature of 3.7 ºC until 2100. Most plausible pathways are both RCP 4.5 or RCP 6.0.
[8] WGIII: Working Group III

Table 12: Climate Change Impact until 2100 on temperature, oceans, precipitation and ice and snow cover
Source: IPCC AR5 Summary Report (2014:9)

Observed Changes	Climate Change Impact until 2100 (IPCC AR5, Summary Report)
Temperature	The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is *likely* to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.59; The Arctic region will continue to warm more rapidly than the global mean; It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases; It is *very likely* that heat waves will occur with a higher frequency and longer duration; Occasional cold winter extremes will continue to occur.
Oceans	The global ocean will continue to warm during the 21st century, with the strongest warming projected for the surface in tropical and Northern Hemisphere subtropical regions; Earth System Models project a global increase in ocean acidification for all RCP scenarios by the end of the 21st century, with a slow recovery after mid-century under RCP2.6.
Precipitation	Changes in precipitation will not be uniform; The high latitudes and the equatorial Pacific are *likely* to experience an increase in annual mean precipitation under the RCP8.5 scenario; In many mid-latitude and subtropical dry regions, mean precipitation will *likely* decrease, while in many mid-latitude wet regions, mean precipitation will *likely* increase under the RCP8.5 scenario; Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will *very likely* become more intense and more frequent.
Ice and snow cover	Year-round reductions in Arctic sea ice are projected for all RCP scenarios; A nearly ice-free Arctic Ocean in the summer sea ice minimum in September before mid-century is *likely* for RCP8.5; It is *virtually certain* that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases, with the area of permafrost near the surface (upper 3.5 m) projected to decrease by 37% (RCP2.6) to 81% (RCP8.5) for the multi-model average (*medium confidence*); The global glacier volume, excluding glaciers on the periphery of Antarctica (and excluding the Greenland and Antarctic ice sheets), is projected to decrease by 15 to 55% for RCP2.6 and by 35 to 85% for RCP8.5 (*medium confidence*).

Figure 26 spatially represents projected changes in surface temperature and average precipitation. Mid. to high latitudes, specifically in the North hemisphere, are the ones which will suffer the highest projected temperature increase. In what regards precipitation, there will be a strong increase in the low and high latitudes, and a reverse tendency in the mid latitudes.

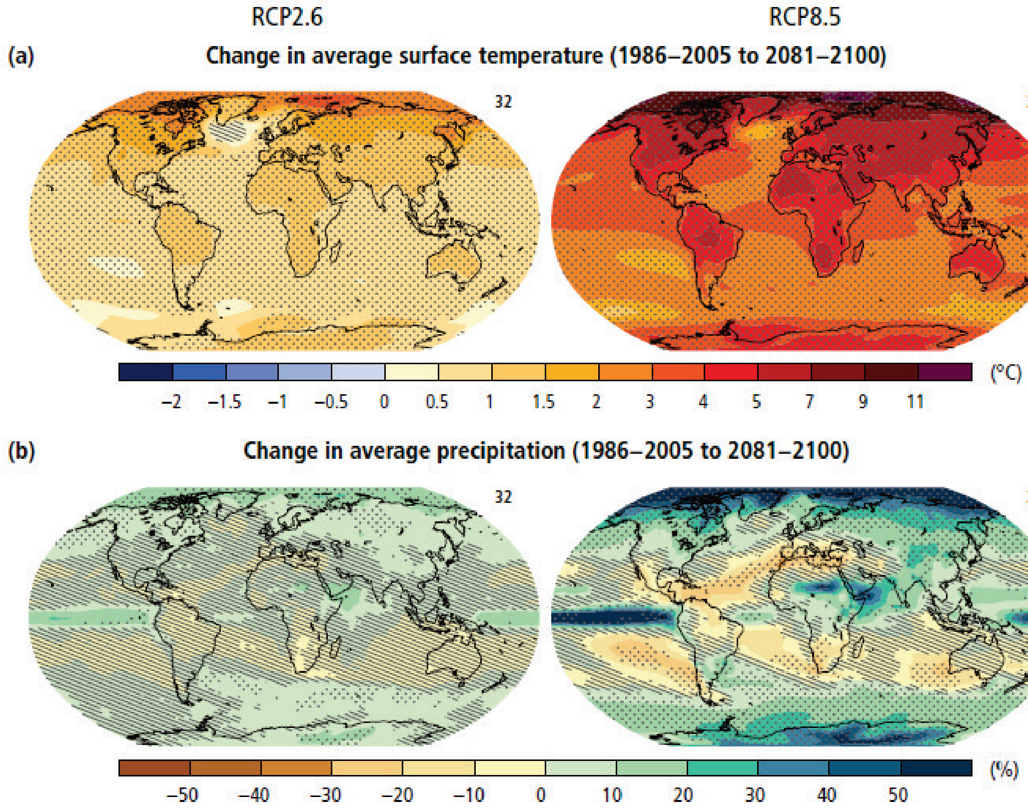


Figure 26: Change in average surface temperature. (a) and change in average precipitation (b) based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the RCP2.6 (left) and RCP8.5 (right) scenarios. The number of models used to calculate the multi-model mean is indicated in the upper right corner of each panel. Stippling (i.e., dots) shows regions where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (i.e., diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability.
Source: IPCC AR5 Summary Report (2014:12)

3.2.1 Urban vulnerability, risk, and resilience

According to IPCC (2014:65) key risks due to climate change that span sectors and regions include the following (*with high confidence*): 1) Risk of severe ill-health and disrupted livelihoods resulting from storm surges, sea level rise and coastal flooding; inland flooding in some urban regions; and periods of extreme heat; 2) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services; 3) Risk of food and water insecurity and loss of rural livelihoods and income, particularly for poorer populations; 4) Risk of loss of ecosystems, biodiversity and ecosystem goods, functions and services. Not only urban areas are major contributors to the GHG emissions, but they will also suffer major impacts from climate change related events, since they are located in many of the world's areas that present the higher risks of climate change impact. As it can be seen in Figure 27, the largest urban areas (in terms of city population size and growth rate), are situated in most of the urban areas which present the highest increase in temperature, both in registered temperature from 1901-2012, but also in projected temperature until 2100.

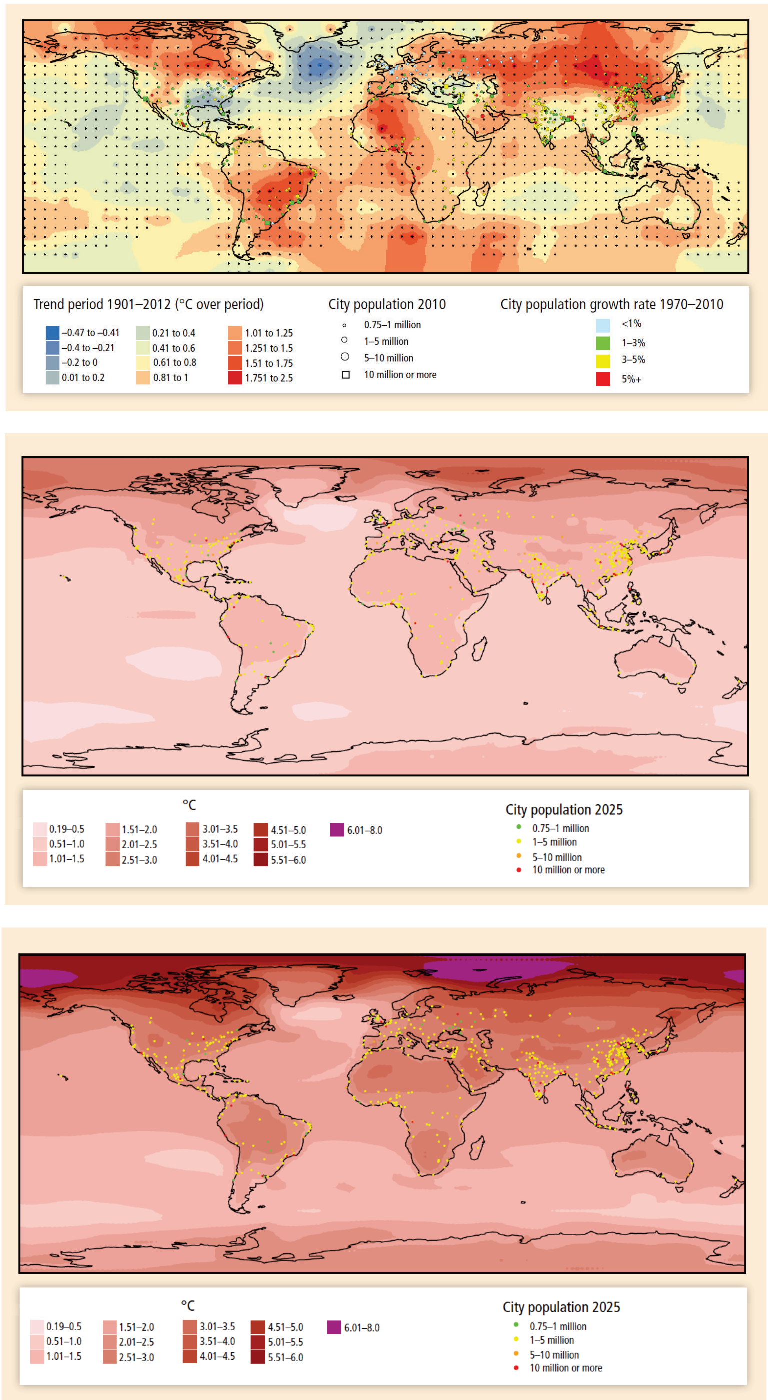


Figure 27: a) Large urban agglomerations and temperature change. a) observed changes from 1901-2012, b) projected temperature change for 2025, taking into account mid-21st century temperature records and the RCP 2.5 pathway, c) projected temperature change for 2025, taking into account mid-21st century temperature records and the RCP 8.5 pathway. Source: IPCC (2014 WGII AR5:553-554)

In Table 13 are summarized the main impacts of climate change on urban areas according to IPCC WGII Report A (IPCC WGII, 2014:552-556)

Table 13: Climate change impacts on urban areas until 2100
Source: IPCC WGII (2014:552-556)

Climate Change Impacts on Urban Areas until 2100	
Impact	Description
Temperature rise	By late-century, under the RCP2.6 scenario, a number of the urban agglomerations that were among the largest in 2025 will be exposed to temperature rise of up to 2.5°C over pre-industrial levels (excluding urban heat island effects), especially in the high latitudes. This implies that mean temperature rise in some cities could be greater than 4°C; Some cities in high latitudes experience a mean 3.5°C rise, or greater than 5°C when combined with UHI[9] effects. Peak seasonal temperatures could be even higher; Temperature increases of 6°C to 8°C in the Arctic and temperature rise in Antarctica would contribute to sea level rise that would impact coastal cities across the world.
Temperature rise – Urban Heat Island	Increased frequency of hot days and warm spells will exacerbate urban heat island effects, causing heat-related health problems (Hajat et al., 2010) and, possibly, increased air pollution (Campbell-Lendrum and Corvalan, 2007; Blake et al., 2011), as well as an increase in energy demand for warm season cooling (Lemonsu et al., 2013).
Drought and water scarcity	Averages across all climate change scenarios, noting the role of demographic growth, suggest a large increase in the already 150 million people which live in cities with perennial water shortage, possibly reaching up to 1 billion by 2050 (McDonald et al., 2011).
Coastal Flooding, Sea Level Rise, and Storm Surge	Estimates for global mean sea level rise are for between 26 and 98 cm by 2100; With a 0.5 m rise in sea level, the population at risk could more than triple while asset exposure is expected to increase more than 10-fold; The “top 20” cities identified for both population and asset exposure to coastal flooding in both the current and 2070 rankings are spread across low-, middle-, and high-income nations, but are concentrated in Asian deltaic cities.
Inland Flooding, hydrological and Geo-Hydrological Hazards at Urban Scale	The review on the world-wide impacts of climate change on rainfall extremes and urban drainage by Willems et al. (2012) has shown that typical increases in rainfall intensity at small urban hydrology scales range from 10% to 60% from control periods in the recent past (typically 1961–1990) up to 2100;
Emerging Human Health, Disease, and Epidemiology Issues in Cities	There is good evidence that temperature extremes (heat and cold) affect health, particularly mortality rates. Increased warming and physiological stress on human comfort level is predicted in a variety of cities in subtropical, semiarid, and temperate sites (Thorsson et al., 2011; Blazejczyk et al., 2012); The impacts on urban air quality in particular urban areas are highly uncertain and may include increases and decreases of certain pollutants (Jacob and Winner, 2009; Weaver et al., 2009);

Overall there is a very-low to medium risk to urban areas in the near term, and medium to very high risk until 2100 if nothing is done. With adaptation measures there is the possibility to revert to a medium risk in the long-term (until 2100). Urban sectors with the higher risk of

[9] UHI: Urban Heat Island

climate change impact until 2100 are the coastal zone systems, terrestrial ecosystems and ecological infrastructure, water supply systems, waste water systems, green built infrastructure, food systems and security, transportation systems, communication systems, housing, human health, human security and emergency response, key economic sectors and services and livelihoods. However, with important adaptation measures, IPCC estimates that the very high risk can be reversed to a medium risk for the coastal zone systems, food systems and security, transportation systems, communication systems, housing, human security and emergency response and livelihoods.

3.2. Contribution of urban areas to the world energy profile and climate change

- *Understanding GHG emissions urban drivers*

According to OECD (2009) cities contribute to climate change through 3 ways: through direct emissions of GHGs that occur within city boundaries; through GHG emissions that originate outside of city boundaries but are related to civil infrastructures and urban energy consumption; and through city-induced changes to the earth´s atmospheric chemistry and surface albedo (Table 14).

Table 14: Contribution of cities to climate change
Source: Adapted from OECD (2009:35)

Type of impact	Description
Direct GHG emissions	- Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions from energy conversion
	- CH_4 emissions from the landfill decomposition of municipal solid waste, CH_4 and N_2O from anaerobic decomposition and nitrification-denitrification of nitrogen during wastewater treatment
	- CO_2 emissions from waste incineration; 69omplexity69n (HFC, PFC) and sulfur hexafluoride (SF_6) emissions from refrigerants, semiconductor manufacturing and insulators
	- CO_2 and N_2O emissions from rural-urban land conversion
Embodied GHG emissions	- GHG emissions embedded in the energy required to produce the concrete, steel, glass, and other materials used in civil infrastructure
	- CH_4 and N_2O emissions used to provide the food consumed by urban residents
	- CO_2, CH_4 and N_2O emissions from rural power plants and refineries that generate energy for urban consumption
Changes to atmospheric chemistry and surface albedo	- Include the direct and indirect GHGs that result from changes in atmospheric composition and surface reflectivity. For instance, the IPCC estimates that tropospheric ozone (O_3), a secondary pollutant commonly found in cities, is the third most important GHG behind CO_2 and CH_4 (Forster *et al*., 2007). Carbon monoxide (CO), an indirect GHG produced predominantly from mobile sources in cities, lengthens the atmospheric residence time of CH_4.

The majority of the GHG emissions in OECD urban areas are increasingly driven by the energy services required for lighting, heating and cooling, appliance use, electronics use, and mobility, while the industrial energy use as becoming less significant (OECD, 2009:35). Energy production and consumption is the major vector for GHG emissions. The impact of energy consumption on the GHG emissions depends not only on the amount of energy consumed, but on the GHG intensity (GHG emissions factor) of all activities that are involved in the process of generation, conversion and consumption of energy. Total life-cycle emissions analysis are thus more reliable since they take into consideration the full energy process (Table 15).

Table 15: Total GHG Emissions, Including End-Use, Life Cycle, and within City Measures, for Ten World Cities
Source: Kennedy et al. (2009:7300)

	emissions within city t e CO_2/cap.	emissions from end-use activities t e CO_2/cap.	end-use emissions including life-cycle emissions for fuels t e CO_2/cap.
Bangkok	4.8	10.7	not determined
Barcelona	2.4	4.2	4.6
Cape Town	not determined	11.6	not determined
Denver	not determined	21.5	24.3
Geneva	7.4	7.8	8.7
London	not determined	9.6	10.5
Los Angeles	not determined	13.0	15.5
New York City	not determined	10.5	12.2
Prague	4.3	9.4	10.1
Toronto	8.2	11.6	14.4

According to Kennedy et al. (2009:7301) GHG emissions are strongly dependent upon the location of cities, urban form, technology, social and economic variables. In terms of climate, the heating degree days is an important variable to explain the amount of energy required to heat a building; the location of a city may determine its key role as a passengers or goods hub; and access to natural resources for renewables production. Urban form, according to the author, has also a strong importance on the GHG emissions as it is explained by the inverse relation between transportation energy use and urban population density. Technology is a key component, since it allows, for instance, as Kennedy et al. (2009:7301) explained, a methane capture system in waste treatment plants, or the use of nuclear power energy to support the energy demand of urban areas. Economic and social contexts also prove to be important in the GHG emissions, since urban areas that are richer and more connected to the world tend to have a higher economic activity and thus higher consumption and necessity of mobility. Jaccard et al. (1997) also indicates the main drivers that impact GHG in urban areas, but above all the fact that some of the most important drivers are not in the scope of urban policy responsibility. This question just shows the complexity of the climate change problem and the necessity of cities in evolving their climate change policy above the administrative boundaries and towards an “urban territory” perspective (Figure 28).

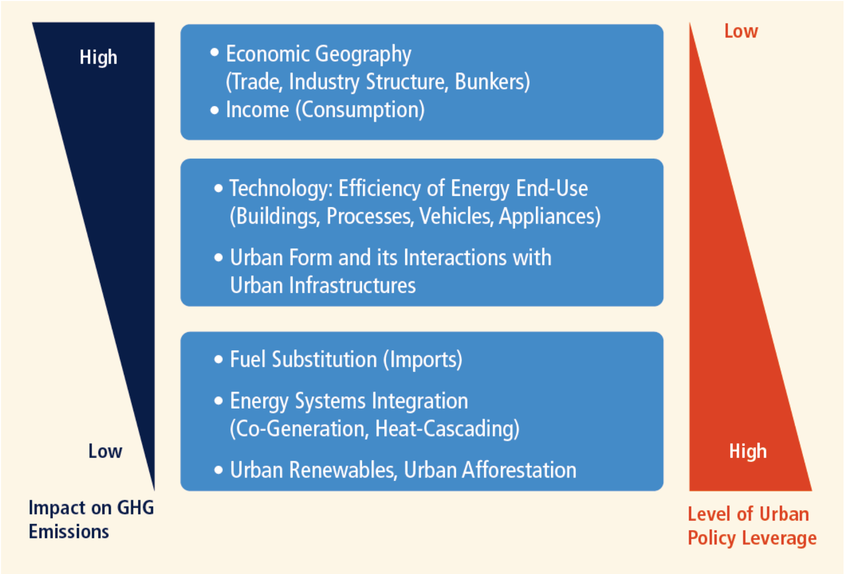


Figure 28: Stylized hierarchy of drivers of urban GHG emissions and policy leverages by urban scale decision making. Cities have little control over some of the most important drivers of GHG emissions and have large control over comparatively smaller drivers of emissions.
Source: Jaccard et al. (1997; Grubler et al., 2012 in IPCC WGIII AR5 2014)

Ferrão and Fernandez (2013:140) also approach the problem of urban intervention on a perspective of sustainability and the need of a more horizontal cooperation between all agents that intervene in cities: "*Achieving real progress toward any kind of predetermined optimal combination of population service, and transportation densities will require an unprecedented level of municipal and regional authority cooperation*". Not only it is crucial to redesign urban policy both vertically and horizontally, it is also important to understand that different policies should be applied to different urban areas, since urban areas present a vast heterogeneity across the world. Salvadir-Sali (2010) developed a methodology that was based on typologies of cities, a grouping of cities based on specific attributes, namely to understand how do cities differ in their resource consumption, and how these differences manifest and what causes differences in resources consumption, in order to achieve urban efficiency and sustainability (Ferrão and Fernandez, 2013:143). Four independent variables were defined as predictor attributes of city resource consumption (affluence, population, population density, and climate), and eight dependent resources types were defined as: total energy, total materials, electricity, water, fossil fuels, industrial minerals and ores, and construction minerals and biomass. Cities from all over the world were analyzed (Figure 29).

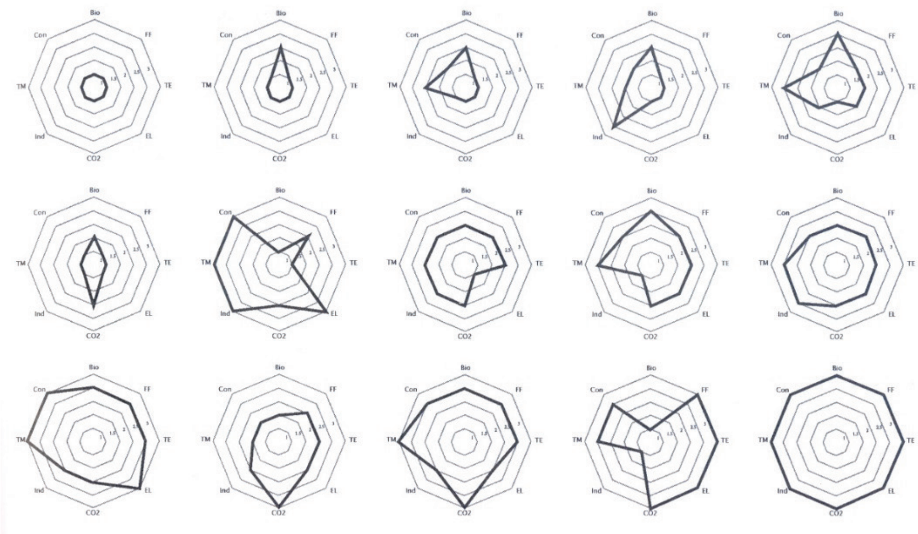


Figure 29: Cities typologies according to predictor attributes for resource consumption and resources type. Type 1 is on the upper left-corner and type right on the bottom-right corner. Bio – Biomass, FF – Fossil Fuels, TE – Total Energy, EL – Electricity, CO2 – Carbon Dioxide Emissions, Ind – Industrial Minerals, TM – Total Materials, Con – Construction Materials
Source: Ferrão and Fernandez (2013:147)

Regarding the results (Saldivar-Sali, 2010), the first row of cities typologies is characterized by cities with relative low resource consumption, usually in under developed of developing countries. They include cities as Jakarta, Kinshasa, Dakar, Lagos, Quito, Mumbai, Manila and Panama City. Consumption on these cities (with exception of the type 5) is mainly based on biomass and water. Type 5 cities (Montevideo, Durban, Curitiba) present already a higher total material consumption and also biomass that is used by industries. Type 6 cities are mainly Indian cities, but also Ho Chi Minh City and Cairo, and is characterized by cities on early stages of industrialization based on carbon-rich energy. Type 7 cities are mostly Japanese cities with very low biomass consumption (due to low agricultural land availability) and a well-developed industrial base together with and energy-efficient economy. Type 8 is composed of cities such as Shenzen, Brasilia, Mexico City and Istanbul, and presents industrializing economies with abundant natural resources, but relatively low quality of living that is demonstrated by the low energy consumption. Types 9 and 10 are mostly European cities (Lisbon, Belgrade, Berlin, London) but also Santiago and Tehran, and is characterized by transitional economies (transiting from a state-controlled economy to a more diverse economy, mainly type 9) and also diverse and industrialized economies (type 10). Type 11 cities (Paris and Dubai) extend the energy consumption levels of type 10, due to a decrease of density and higher affluence. Type 12 typology encompasses cities of countries with a high fossil fuels emissions due to mining and coal-burning. Examples of those cities are the cases of Shangai, Tel Aviv and St. Petersburg. Type 13 cities are located in developed countries that are specialized in the production of coal, cement, food and beverages, textiles, and agricultural and cellulose products. Examples are New York, Los Angeles, Helsinki and Copenhagen. Type 14 cities are a very specific case of cities that have a high export of mineral materials, low biomass consumption, high water consumption, and high energy levels, which are the case of Kuwait City, Doha and Abu Dhabi. Finally type 15 cities are cities that have a very high consumption of almost all resources, which has an intricate connection with their low density patterns, requiring the use of the automobile with high levels of affluence, together with high cooling and heating energy consumption due to their specific climate. Examples are Phoenix, Toronto, Sydney and Melbourne.

Despite the uniqueness of each city, what recent research is demonstrating is that there are patterns, complex ones, in urban development across the world. These patterns reveal important relations between specific climate conditions, socio-economic framework and urban form, that have an important impact in the consumption of resources and ultimately on urban sustainability. To better understand these relations through a typological analysis, as it was shown, can constitute an interesting research perspective to address the problematic of resource consumption and urban sustainability.

- *Urban areas and energy consumption*

Urban areas are responsible for 60-80% of the world´s energy consumption (IEA,2008). The consumption of energy as well as the carbon emissions, are directly associated to the types of primary energy sources, but also to the energy technologies that are used to produce electricity and to the consumption of energy in buildings and transportation. According to OECD (2009:35) cities use over 2/3 of the world´s energy (estimated in 7900 Mtoe in 2006) even though they only account for around 50% of the world´s population. By 2030 cities will probably have 60% of the world's population and 73% of the world´s energy use (more than 12 400 Mtoe in energy according to IEA, 2008). The non-OECD countries (mostly in development or undeveloped countries) will account for 81% of the global energy use in 2030 (OECD, 2009:35).

OECD (2009:37) indicates that there are three types of final urban energy use in cities: electricity, thermal energy and transportation energy. Electricity is mainly used for lighting, and to a limited extent for water and space heating and even less for transportation; thermal energy is mainly used for space and water heating and cooking; and transportation energy is mainly used on vehicles and heavily dependent on oil (Table 16).

Table 16 Categories of urban energy use
Source: OECD (2009:37)

Type	Main energy sources (% total)	Main use
Electricity	Coal (41%), nuclear (27%), natural gas (17%), oil (5%) Percentages are for all OECD countries	Lights, appliances, electronics, industrial motors
Thermal energy	Natural gas, oil, electricity (n/a) Percentages are unclear[1]	Space heating, water heating, cooking, industrial process heat
Transportation energy	Oil (97%) Percentage is based on U.S. data[2]	Vehicles, transit systems (mobility)

Notes:
Thermal energy sources are difficult to isolate, but natural gas is typically the dominant source of space and water heating in OECD countries. In the U.S., for instance, natural gas accounted for 76% of residential and commercial primary energy consumption in 2008, most of which was for space and water heating.
There are no recent estimates for the composition of transportation energy use for OECD countries; we use the U.S. as a proxy here, and argue that this percentage is representative of typical OECD countries

Energy in urban areas is mainly consumed in buildings and transportation. According to Salat (2012:519) buildings are responsible for 40% of the final energy consumption in most cities in developed countries, being the rest of the final energy consumed by both transportation and industry. Energy associated with buildings can be divided into embodied energy (passive energy) and operating energy (active energy), being that according to Ramesh el al. (2010 in Salat, 2012:519) the later "*represents the dominant share of the global consumption in buildings*".

Therefore, urban form has a pivotal role in energy consumption and, consequently, in the GHG emissions of the urban areas. Ferrão and Fernandez (2013:139-140) indicate that "[...] urban form is a key element in the determination of prospects for urban sustainability" due to three main reasons:

1) "The nature and intensity of resource consumption along the gradient of urbanization is highly dependent on the coupling of population density and density of services and infrastructure, particularly transportation density" – a diverse mix of activities, with appropriate density levels of population and well served by public transport assures low levels of energy consumption in transport;

2) "[...] the placement, scale, and configuration of the urban built environment affect the manner and intensity with which households, commercial establishments, and industry consume energy and materials";

3) "[…] the dynamic interactions between buildings, open and green spaces, and urban infrastructure provide clues about the concentration of heat and urban pollutants that give rise to unhealthy and energy intensive "hot-spots" in the city".

Some of the first major studies on urban form and energy were based on the relation between density and energy consumption, more precisely on fuel consumption and density. The increasing use of car as the main transportation mode in urban areas and the consequences that reflected in urban daily life led to this research. One of the first studies with a major impact was the one of Newman and Kenworthy (1989) (Figure 30), in which a clear association appears between increasing density and lower fuel consumption and vice-versa. This research and other similar (e.g. Midali et. al, 2004) led to a public perception (even sometimes contrary to the intention of the authors) of an increasing association of urban form, and namely density, with more sustainable cities and lower density with unsustainability which, as it will be seen further ahead in this thesis, it is not so clear and straightforward as it might appear.

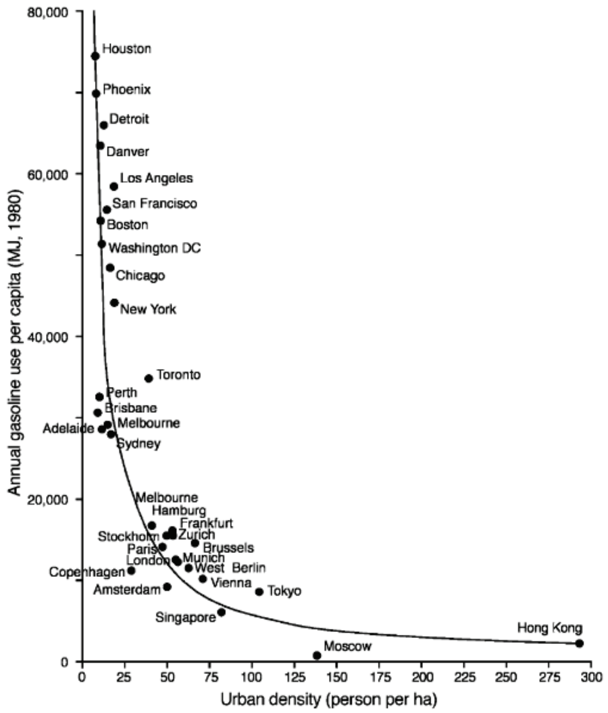


Figure 30: Annual gasoline use per capita vs. Urban density
Source: Newman and Kenworthy (1989)

It is also very interesting to note the relation between urban density and electricity consumption (per country), that presents a similar pattern when compared to the relation between fuel consumption and urban density, in which for lower urban densities correspond a higher electricity consumption (Figure 31). According to OECD (2009:43) "*Increasing density* *could significantly reduce consumption of electricity in urban areas. Where increased urbanization (estimated in terms of PU areas) has led not only to demographic and economic agglomeration, but also to higher levels of electricity demand, densification tends to decrease electricity demand".*

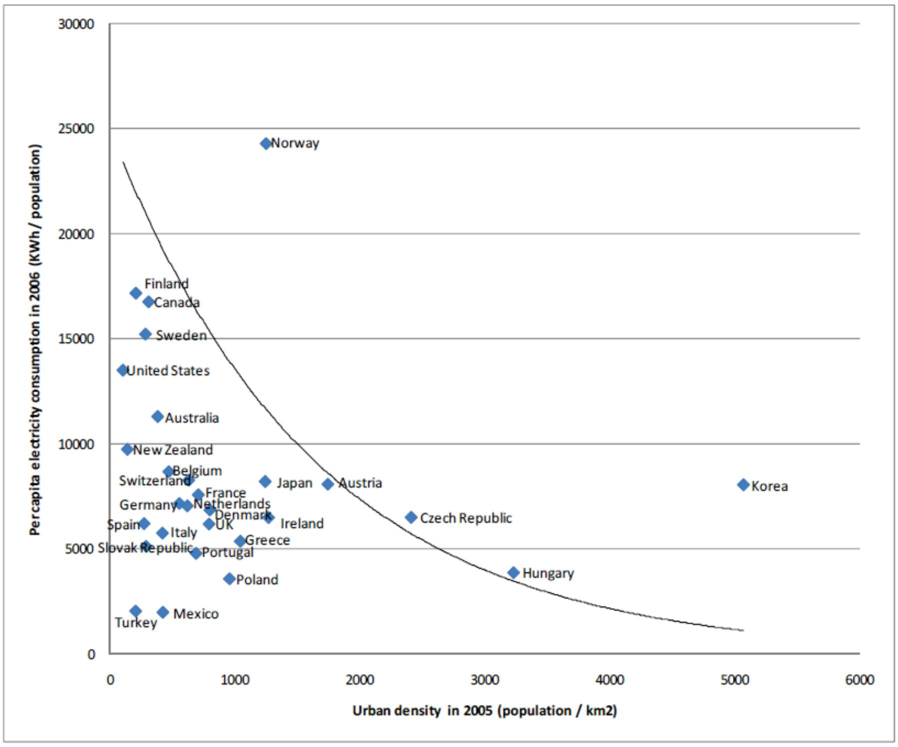


Figure 31: Urban density and electricity consumption
Source: OECD (2009:44)

If we look into the carbon emissions from the transportation sector there is a not so significant relation between carbon dioxide and density (Figure 32) when compared with Newman and Kenworthy (1989) data. This may be based on the cities that were chosen for the analysis that are not exactly the same; the calculation methods of CO_2 per capita; the fact the Newman and Kenworthy (1989) don´t use CO_2 per capita but annual gasoline use per capita (being diesel much more important now than it was at the time); and also different political, social, environmental and economic contexts since both analysis are separated by nearly 30 years. Despite these differences, there a is a negative tendency between density and CO_2 per capita, which reinforces the general idea of the importance of a higher density (up to some point) as a factor that contributes to a decrease in carbon dioxide.

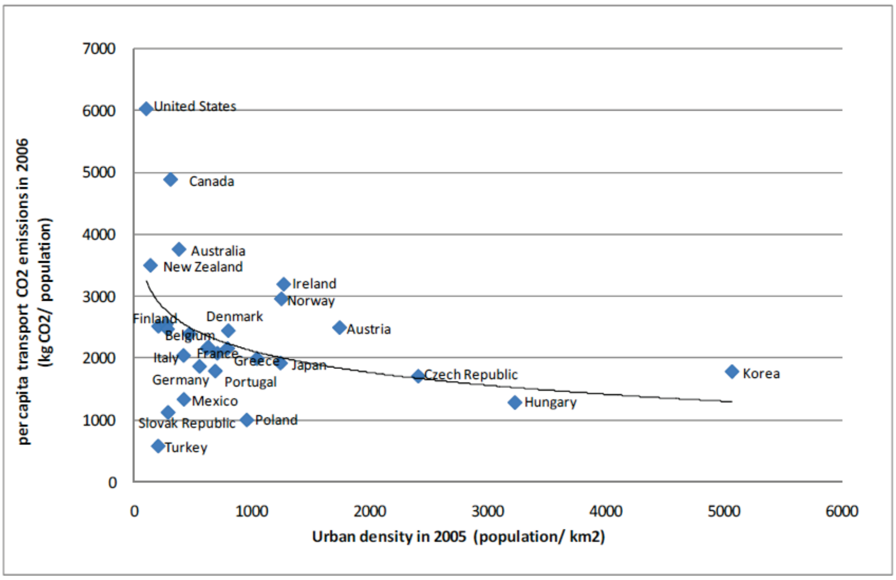


Figure 32: per capita transport CO_2 emissions and urban density
Source: OECD (2009:46)

Norman et al. (2006:19) compared high and low density residential urban areas, in the greater Toronto area, through life-cycle analysis of energy use and greenhouse gas emissions. They analyzed the material production, buildings operation and transportation. Transportation accounts for the largest share of GHG emissions in the low density areas (>50%), followed by building operations emissions (around 30%), and construction materials (around 5%). In the high density areas the transportation share decreases to around 40%, building operations account for 50% and the remaining 10% are construction materials. In what regards energy use for low density areas, the largest share goes to operational energy (> 50%) followed by transportation (around 25%) and construction with 10%. In the high density areas, the largest energy use share goes to operational energy (> 60%), transportation (20%) and materials (10%).

Norman et al. (2006:19) indicated that: a) Low density suburban development is 2.5x as energy and GHG emissions intensive as high-density urban core development per capita (Figure 33); b) Low density suburban development is 2.0x as energy and GHG emissions intensive as high-density urban core development per person (Figure 34); c) The choice of functional unit is highly relevant to understanding life-cycle density effects. It is however relevant to stress that switching the functional unit to square meters significantly lowers this difference.

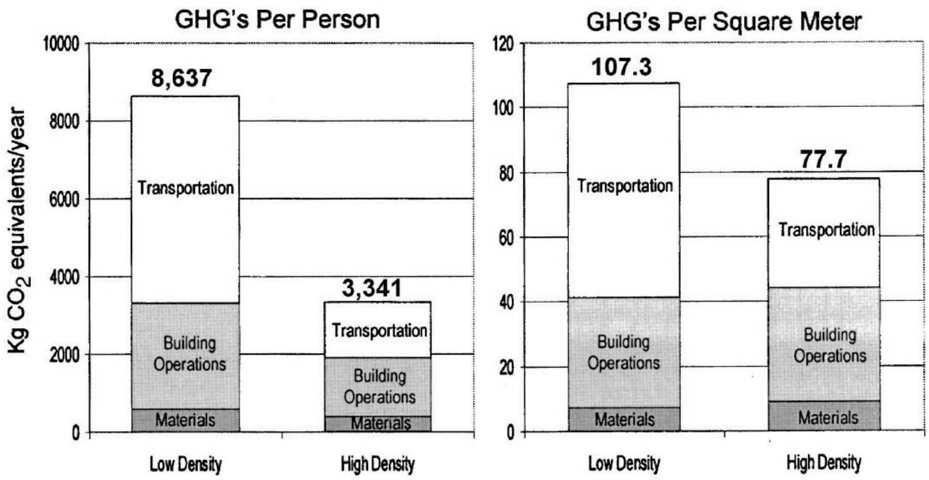


Figure 33: Annual greenhouse gas emissions associate with low and high density development
Source: Norman et al. (2006)

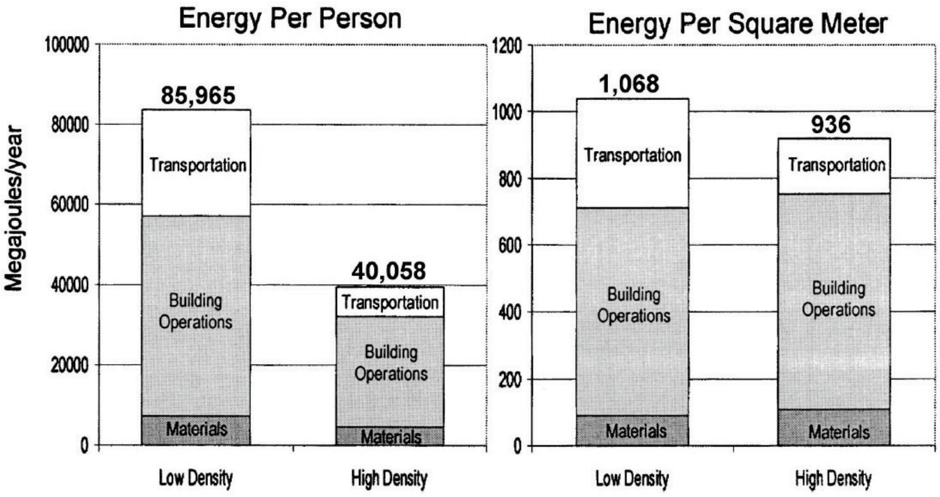


Figure 34: Annual energy use associated with low and high density development
Source: Norman et al. (2006)

Their results clearly show that urban planning oriented to the energy and climate issues should give top priority to policies that reduce the automobile dependency in the suburbs as are examples: mixed land use policies, urban integration that could reduce the travelling distances, implementation of district heating and cooling, increase in public transportation, and an increase in the density and growth around employment areas. The author also suggests that a change to alternative fuel sources and renewable energy could contribute to a less quantity on the GHG emissions that are associated to urban areas. The fact that energy per capita is more significant than the energy per square meter reinforces the idea that there is an effect of different buildings typologies, and consequently different capacities to accommodate people by building, in the resulting energy demand of a certain urban area. This way, buildings typologies which accommodate a larger share of people in less square meters (e.g. apartments), might be more sustainable than detached housing, that usually accommodates less people by square meter.

3.3 Modelling urban form and energy demand

To understand the relation between urban form and energy it is essential to understand how urban form affects and is affected by the specific urban micro-climate characteristics. Salat (2011:173) presented a simplified model to understand the relation between urban morphology and urban microclimate, and ultimately building energy consumption based on work done by Ratti, Raydan and Steemers (2003). Different archetypes were taken into account: 1- courtyard-type texture resembling the traditional Islamic courtyard houses of the Mediterranean with 3 levels high; 2- group of pavilions with three levels high; 3 – group of pavilions with 6 levels high, and with a two-way traffic street (Figure 35).

1

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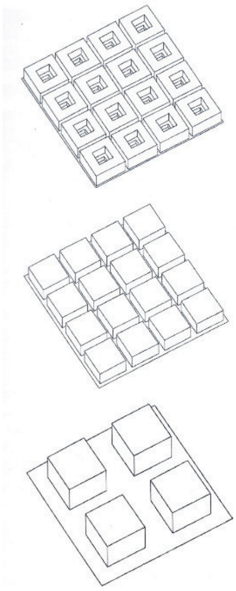


Figure 35: Axonometric representations of a site of 67.5 x 67.5 m with three urban forms of identical volume: courtyard-type structure and two pavilion type structures

Source: Ratti, Raydan and Steemers (2003, in Salat, 2011:174)

Three parameters were taken into account by Ratti, Raydan and Steemers (2003) (in Salat, 2011:174):

- The *surface-to-volume ratio* (S/V): describes the surface area of a building´s envelope in relation to its volume, and thus indicates the potential for interactions with the exterior environment through natural ventilation and sunlight. If the ratio is high, the heat losses in winter are high but so are the solar gains, in opposition if the ratio is low, there are very few heat losses in winter and also very few solar gains. Regarding the S/V ratio the first archetype had a ratio of 0.58, the second of 0.40 and the third of 0.27. Cold climates urban forms with small courtyards appear to be in disadvantage including in the increase in the heat gains in the summer; however taking into consideration an arid climate, with significant differences of day and night temperatures and the thermal inertia phenomenon, these textures seem to perform very well;

- *Shadow density*: courtyard urban forms tend to have a higher shadow density and less daylight availability, and thus are ideal for hot arid climates. Urban configurations with narrow streets tend to favor this aspect. To note that daylight availability is 2x higher in the courtyards than in the streets;
- *Sky view factor (SVF)*: according to Salat (2011:175) the SVF "[…] *measures the openness of an urban fabric to the sky*", and is often related with the phenomenon of the urban heat island. The pavilions archetypes usually maximize the SVF and hence minimize the effect of the urban heat island, however this is not true when taking into account hot arid climates, since its beneficial to the urban climate a higher night temperature (since in hot arid climates the night temperature is usually very low) and a not so high day temperature is possible due to the urban heat island, since it presents a lower peak of temperatures during the day. Above all the analysis on the impact of climate together with different shape factors, is very geographic sensitive, since the "best temperature" is not the same in different contexts.

Ratti, Raydan and Steemers (2003 in Salat, 2011) indicated that the Islamic courtyard houses structure were the most energy efficient (for hot arid climates) since they presented a greater envelope surface area and thermal mass; access to daylight through the courtyard and shallow plans; and narrow spaces providing shade and enhanced thermal comfort.

Expanding this analysis to six simplified generic forms – pavilions, slabs, terraces, terrace courts, pavilion courts and continuous fabrics of courts (Figure 36) – that are an extrapolation of both the courtyards and pavilions structures but now with the influence of streets, it can be understood in more detail the relation of urban micro-climate and urban form.

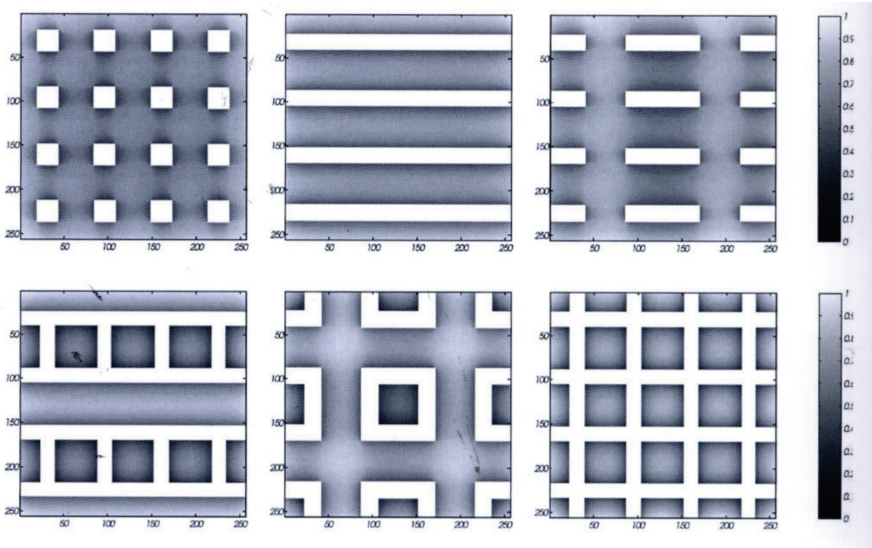


Figure 36: Graphic presentation of sky view factors for six generic urban forms: pavilions, slabs, terraces, terrace courts, pavilion courts and continuous fabrics of courts
Source: Ratti, Raydan and Steemers (2003)

In this analysis made on Project ZED[10] and research by Ratti, Raydan and Steemers (2003) by Salat (2011), only urban form was considered for the analysis, being that the height of the forms was adjusted to ensure the same built density and passive to volume ratio. Some results are presented (Salat, 2011:180):

- *Solar radiation analysis*: For the climate of London (with reflectance's of 40% for the walls and 20% for the ground) the pavilions is the urban form which received the highest amount of solar radiation in buildings and on the ground (however at a low density, if density would increase shading would have more importance and affect the radiation received); the continuous urban form is the one which receives the highest radiation on the roof which can be considered valuable for solar panels installation; the slab was the urban form that received the lower radiation values, due to its exposed area and also the strong effect that orientation has in this particular type of urban form; courtyards received the highest amount of radiation by m2 of open space, therefore being the most adapted to capture solar radiation, in particular if thermal or photovoltaic solar panels were to be introduced. Despite this result they receive very few radiation in the vertical facades which makes them particularly suited to hot climates;

[10] "Project ZED – towards Zero Emission urban Development, Koen Steemers

- *Wind analysis*: the porosity of urban form affects the dispersion by the wind of air pollutants, and depends on the direction of the wind in relation to the axes of the streets, open spaces and urban texture. Results indicate that open continuous streets aligned with the direction of the wind are more rapidly cleaned. Also the free standing pavilions create turbulence at a 45º angles that disperse more rapidly wind than other urban forms at 90º angles; and closed courtyards do not contribute positively for the wind dispersion, since they are more closed urban forms;
- *Reflectance analysis*: for all surface reflectance's urban fabrics absorb more solar energy than flat surfaces; complexity of urban form affects the amount of radiation absorbed; when the sun is low on the horizon more radiation energy is absorbed.

According to Salat (2011:183), the courtyard urban form was considered as the most energy efficient (even when considering different glazing ratios of 30% and 60%), while the most energy demanding urban form was the slab, because it presented the greatest obstructions to sunlight and limited useful solar gains. To note that these conclusions refer to the London climate.

In a review of building energy models and assessment systems at the district and city scales, Salat (2012) indicates that there are two ways of assessing energy consumption in cities: assessment systems and methods; and models and calculation tools. The former is mainly used to "[…] *assess the sustainability of projects that are larger than buildings* […] *which all aim at assessing urban sustainability in its wider context and are thus not limited to buildings energy consumption*"; while the later "[…] *have been developed to calculate, predict or anticipate buildings energy consumption and GHG emissions*" (Salat, 2012:519). The importance of understanding and modelling urban neighborhood energy profiles is that because this analysis cannot be simply an aggregation of buildings variables as it cannot be a raw disaggregation of city level variables. According to Salat (2012) "*When scaling up, complex interactions appear within urban fabric, which significantly alters the results that were valid on the building scale*", which is the reason why the neighborhood has been in the recent years a privileged framework of analysis for the urban energy studies, more in what regards the assessment systems and methods, due to the extreme complexity and level of information detail that is required. Salat (2012:520) building up on a typology of calculation tools of energy consumption and carbon emissions on the district and city scales by Nijkamp and Perrels (1994), frames four main types of calculation tools: agent based, economic, energy environment, and morphological (Table 17).

Table 17: Types of approaches to model urban energy demand
Source: Salat (2012:520)

Type	Description
Agent based	This type of model is based on individual behaviours. Energy consumptions are attributed to every activity within the city and refined according to the characteristics of buildings and residents. It relies on a global aggregation of individual consumptions
Economic	These models often based on econometric methods describe the relationships between economic variables: capital, work, energy, demand
Energy environment	These take into account the complexity of interactions between energy production, energy consumption and its impact on the environment (noise, air quality, climate change, etc.). These models are often based on large scales (city and region)
Morphological	The scale under consideration is typically the district and city scale. It stresses the impact of urban form on building energy efficiency, taking into account land-use, activities, localizations and intensities

Salat (2012:522) indicates that morphological models significantly differ from the three other approaches, however stressing also that "*morphological approaches to quantify energy consumptions and GHG emissions for the building sector remain rare*". The author gives as reference the works conducted by Yamaguchi (2003) and APUR (2007), however he indicates that neither the behavioral aspects nor energy systems efficiency is taken into account in the model proposed Yamaguchi (2003).

One very interesting approach is the one developed by Ratti et al. (2005) that lies on a factoring of four fundamental scales that contribute to the improvement of urban energy efficiency: urban context or morphology; buildings; systems; and occupants (Figure 37).

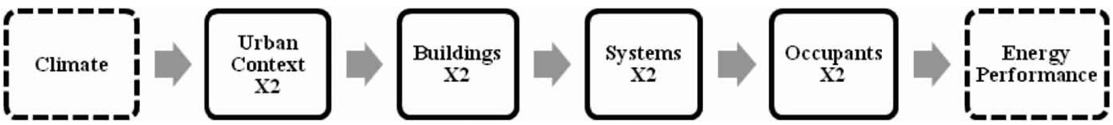


Figure 37: Factors that affect energy consumption in buildings
Source: Salat, (2012:522 adapted from Ratti et al., 2005 and Salat and Bourdic, 2011)

The approach followed by Ratti et al. (2005) in the paper "*Energy consumption and urban texture*" and the one by Salat (2009) on "*Energy loads, CO_2 emissions and building stocks: morphologies, typologies, energy systems and behavior*", will then be addressed since they share important methodological steps.

In what regards the contribution to the variation in energy consumption, Ratti et al. (2005:763) indicate that according to Baker and Steemers (2000) building design accounts for a 2.5x variation, systems efficiency for a 2x variation and occupant behavior for a 2x variation, which could lead, cumulatively, to a total variance of 10-fold (Figure 38). They also indicate that "*In practice, variance in energy consumption of buildings with similar functions can be as high as 20-fold*" (Ratti et al., 2005:763).

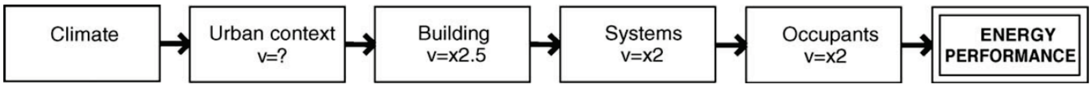


Figure 38: Factors that affect energy consumption in buildings; according to Baker and Steemers (2000) building design accounts for a 2.5x variation, system design and occupants for a 2x variation each; the contribution of the urban context is not quantified.
Source: Ratti (2005:763)

Ratti et al. (2005) focused only on the morphological aspects leaving the others to standard values. They first started to derive the built volume and built surface on a DEM, in order to calculate surface-to-volume ratios (or shape factor) for three different case studies: London, Berlin and Toulouse (Equation 2).

$$C = \sum_{\text{buildings}} \frac{A_{\text{ext}}}{V^{2/3}} \qquad [/]$$

Equation 1: Shape factor – where *C* is often called the compacity; A_{ext} is the external surface area; and *V* is the building volume. The author prefers the term 'shape factor' to 'compacity' because the higher the value of *C*, the less the building fabric is compact in the intuitive sense.
Source: Salat (2009:601, quoting Ratti et al. 2005)

The surface-to-volume ratio provides an important indicator of urban texture since it defines the amount of exposed building envelope per unit volume (Figure 39).

	London	Toulouse	Berlin
Ground floor area [m^2]	89,663	64,368	55,978
Un-built Area [m^2]	70,377	95,632	104,022
Built volume [m^3]	1,221,499	966,768	1,042,199
Vertical surface [m^3]	174,757	174,888	119,698
Surface to built volume ratio [m^{-1}]	0.216	0.248	0.169

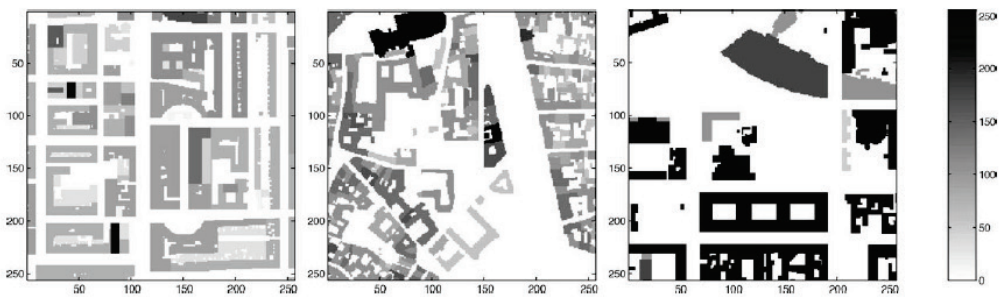


Figure 39: Data and DEM´s for London, Toulouse and Berlin. Height represented with a 256-level gray scale; maximum height in London h_{max}= 40 m, in Toulouse h_{max} = 32 max, in Berlin h_{max} = 21 m.
Source Ratti et al. (2005:766)

Also very important to take into consideration is the concept of passive and non-passive building zones, that "[…] *quantify the potential of each part of a building to use daylight, sunlight and natural ventilation*", being passive those that correspond to "[…] *all perimeter parts of buildings lying within 6 m of the façade, or twice the ceiling height* […]", and non-passive "[…] *all the other zones* […]" (Ratti et al. 2005:766) (Equation 2).

$$Ratio = \frac{\sum_{buildings} PassiveVolume}{\sum_{buildings} BuiltVolume}$$

Equation 2: Explanation of passive volume
Source: Salat, 2009:604 (quoting Ratti et al. 2005)

The analysis of the passive and non-passive volumes in each case study allowed the quantification of the total passive volume that was of 77% for London, 84% for Toulouse and 61% for Berlin ranked in a reverse fashion when compared to the surface-to-volume ratios. The authors then applied the LT (Lighting and Thermal) Model, an integrated energy model that generate the data for the LT method, which predicts the annual heating, lighting, ventilation and cooling energy use/m^2, based on the simulation of a 9m x 6m x 3m module with one exposed glazed wall. Default values where assigned to all variables of this model, with the exception of those related to urban geometry: 1) distance from the façade (passive/non-passive condition; 2) orientation of the façade; 3) urban horizon angle (UHA); 4) obstruction sky view (OSV).

The geometric parameters were passed from Matlab to the LT model on a per-pixel basis and then the LT model results were produced and overlaid onto de DEM (Figure 40). Results indicate that:

- Parts of the buildings that are within 6m of a façade present significant reductions in energy consumption (almost 50%) compared with non-passive ones;
- Energy consumption values summed over all heights are ranked in the order Toulouse, London and Berlin (0,0668, 0,0683 and 0,0731 respectively) which is a reverse order compared with the surface-to-volume ratio;
- The passive to non-passive area ratio seems a better indicator of energy consumption;
- Surface to volume ratio, while being an important urban form parameter, does not describe the total energy consumption in urban areas;
- Almost a 10% difference is shown between the annual per-meter energy consumption in Toulouse and Berlin only taking into account the effects of urban morphology.

	London	Toulouse	Berlin
Average energy consumption in passive & non-passive zones [$KWhm^{-2}year^{-1}$]	0.0683	0.0668	0.0731
Average energy consumption in passive zones zones [$KWhm^{-2}year^{-1}$]	0.0590	0.0599	0.0585
Average energy consumption in passive zones with the optimum glazing ratio [$KWhm^{-2}year^{-1}$]	0.0554	0.0568	0.0550

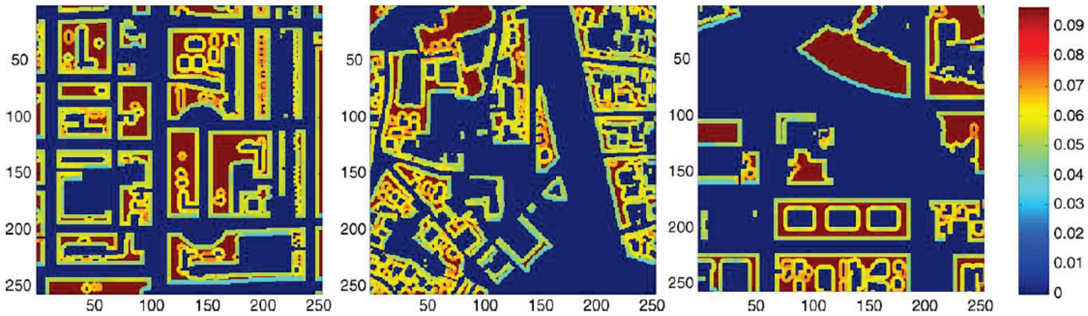


Figure 40: Data and DEM´s on energy consumption (kWh/m²/year) in London, Toulouse and Berlin. DEM´s indicate energy consumption on the second floor (height = 6 m); the glazing ratio is varied in an adaptive way and the value that minimizes energy consumption is attributed to each façade; energy consumption decreases, especially in small courtyards and obstructed areas.
Source: Ratti et al. (2005:773)

Salat (2009) analyzed the existing residential building stock of Paris, France, through the comparison of some environmental metrics of the city´s urban fabric with the thermal energy consumption of buildings. The objective was to reveal some impacts of urban morphology and building typology on the energy efficiency of different areas of Paris, and thus, their carbon dioxide intensity. He proposed the optimization of urban form in terms of density, building configuration, and morphology through a balanced view of the complex impacts of urban forms, typologies, energy systems and inhabitant behavior on energy loads and carbon dioxide emissions (Salat, 2009:598). Salat (2009:599) indicates that the existing building stock is a major energy consumer and consequently (directly or indirectly) a carbon dioxide emitter, depending on factors as the urban morphology, architectural typology, construction technology, energy systems and the behavior of their inhabitants. He built on the research developed by Ratti et al. (2005) to indicate that five factors impact the emissions of carbon dioxide in cities (2009:599) (Figure 41).

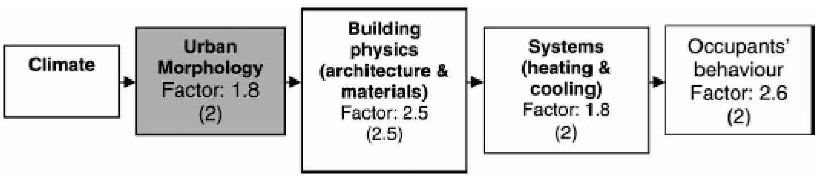


Figure 41 Individual factors affecting the energy usage of Paris as calculated by the Centre Scientifique et Technique du Batiment (CSTB). In parentheses those calculated by Ratti et al. (2005)
Source: Salat (2009:599)

The difference in the energy performance of various buildings blocks should be assessed through the multiplication of the factors presented, being the result of those multiplications the "product of factors", which provides an indication between the least and the most efficient statistical class of an existing building stock (Salat, 2009:600). The author points out the problem that in most cases the studies between density and energy are made at a very large scale, and thus "[…] *do not analyze the various morphological components of the cities, the impact of the grid, the fragmentation of the distribution of activities on the generation of mobility, or the impact of size, hierarchy, accessibility, and connectivity of movement networks*" (Salat, 2009:600). The impact of the urban fabric on energy consumption and carbon emissions is too important to be neglected, according to the author since it can reduce energy consumption by a factor of two. That can be accessed when comparing different urban fabrics (fig.X), where the modernist fabric consumes 1.8 times more energy for heating than contemporary or traditional urban blocks. Salat (2009:601) analyzed both the shape factor and the passive volume as Ratti (2005) in urban typologies of Shanghai and Paris and concluded that the "[…] *Paris´s historic urban fabric has an excellent shape factor compared with recent developments in Asia*" and that "*Traditional Paris courtyard buildings are more energy efficient due to their shape factor than modernist textures*".

Regarding the passive volume ratio Salat (2009:602) indicated that for Paris it represents around 82% of the total built volume, and specifically, that the Haussmannian texture and the old historic Paris (Marais) have a passive volume of around 90% when compared to the modernist texture that has 82%.

As Ratti (2005) Salat also calculated other urban form indicators as are the average height of the canopy, the floor area ratio, and occlusivity (openness to the sky). Floor area ratio is much higher in traditional courtyard blocks (around 4.5) than in modernist textures (1.0-2.0); the average height of the canopy of the modernist texture is relatively low (due to the importance of the empty areas that are taken into account); linear occlusivity (openness of the city to the sky) is greater in the modernist texture (composed mainly of tower-buildings), which allows a greater solar admittance (Salat, 2009:603).

For the estimation of the energy consumption it was used a model that assigned every building the same insulation and heating system (gas). The modernist texture consumes more energy per cubic meter for lighting than the other two, due to its lower passive volume ratio, and lower levels of common wall ownership and built area density that allow higher heat losses. When analyzing the impact of construction technology and architectural typology, Salat

(2009:604) focused on the thermal performance of buildings (*U-value*): the higher the *U-value* the lower the performance of the envelope. In what regards the specific case of Paris 3 different periods can be established, concerning the thermal performance of buildings: before 1945, where the thermal performance of buildings is relatively inefficient because the construction methods generate few thermal bridges and glazing surfaces are of little importance; 1945-1975 with low thermal performance due to width of the walls, use of concrete, high glazing ratio and no thermal bridges; after 1975, with high thermal performance where insulation is systematized, and thermal regulations take place. To compute the energy needs of a building Salat (2009) used the APUR (2007) study. According to this study the heating energy needed by a building is the one required to keep a building at 19º C all year; *GV* is defined as the heat loss coefficient in Watts per degree (W/^{o}C): *GV* = *DP* + *DR*. Where *DP* is the loss via the envelope of the building, and *DR* is the loss due to the exchange of air between the inside and outside of the building. *GV* needs also to be multiplied by a coefficient which depends on energy that comes into the building through the windows and quality of insulation of those windows, as well as the amount of heat that comes from internal production of energy (Salat, 2009:605). Salat also used real consumption data derived from the suppliers of energy, to separate the impact of the factors linked to urban morphology and building physics from those related to energy systems and behavior.

Results point out that "[…] *the 1960´s modernist high-rise blocks powered by district heating and collective gas use 11% more energy than expected for heating, while the electrical- and gas-powered urban blocks of the 1990´s use one-third less than anticipated. A similar effect on the resultant CO_2 emissions can be seen.*" (Salat, 2009:606) (Figure 42).

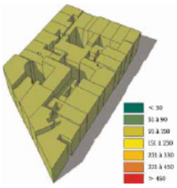
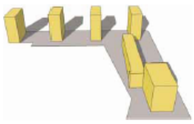
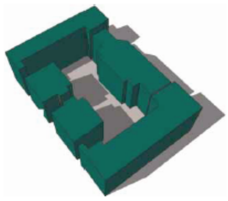
Urban typology	1851–1914	1945–1967	1990–1999
	Quai d' Orléans 	Porte de Vincennes 	Zac De Bercy 
Urban form	Traditional dense urban block 	Free-standing high rise blocks 	Large urban blocks, adjoining buildings of six to eight floors 
Construction technology	Stone walls, thickness 40–45 centimetres (base) to 30 centimetres (top); 1902 onwards brick and masonry	Modernist forms; increase of glazed surfaces; high thermal bridges; four free walls; no street alignment	Good-quality construction, increased insulation for improved acoustic and heating comfort, double glazing
Final heating energy theoretical needs (kWh/m^2/year)	133	176	39

Figure 42: Final energy use for heating due to building block form and construction technique
Source: Salat (2009:607)

The modernist parts of Paris are less energy-efficient compared with traditional urban fabric, while the carbon dioxide emissions depend not only on the quantity of energy consumption, but on the type of energy used. The modernist large-scale apartment blocks of the 1960´s use 6x more energy for heating and emit 9x more carbon dioxide (m^2/year) than the contemporary courtyards (Table 18).

Table 18: Theoretical / actual primary energy consumption of the 3 typologies (space heating/domestic hot water)
Source: Salat (2009:607)

Typology	1851–1914	1945–1967	1990–1999
Energy mix	30% individual gas 30% collective gas 30% electrical 10% urban heating	70% collective gas 30% district heating	75% electrical 25% city gas
Theoretical primary energy consumption (kWh/m^2/year)	306	340	155
Actual primary energy consumption (kWh/m^2/year)	241	377	103
Theoretical CO_2 emissions (kgCO_2e/m^2/year)	55	77	13
Actual CO_2 emissions (kgCO_2e/m^2/year)	46	82	9

In what regards the LSE (2014) study already referred before, where 25 urban typologies from 4 different cities were analyzed regarding urban morphology and heat energy consumption, some interesting results can be observed. The methodology used by LSE to calculate the heating energy needs followed the principles of and engineering based bottom up model (Swan and Ugursal, 2009 in LSE, 2014:54). It had two phase: in the first all parameters apart those related to form were fixed, including climate, then the simulation modelled solar heat gains and building surface heat losses from where average annual heat energy demand per m2 of indoor floor space was calculated; the second stage the effects of wall insulation, window U-value and glazing ratio and climate were analyzed (LSE, 2014:54). Urban morphological factors affecting heat energy demand (exposure do sun radiation, spatial and physical dimensions of buildings and their context) were incorporated in the analysis. Some results can be viewed in Figure 43.

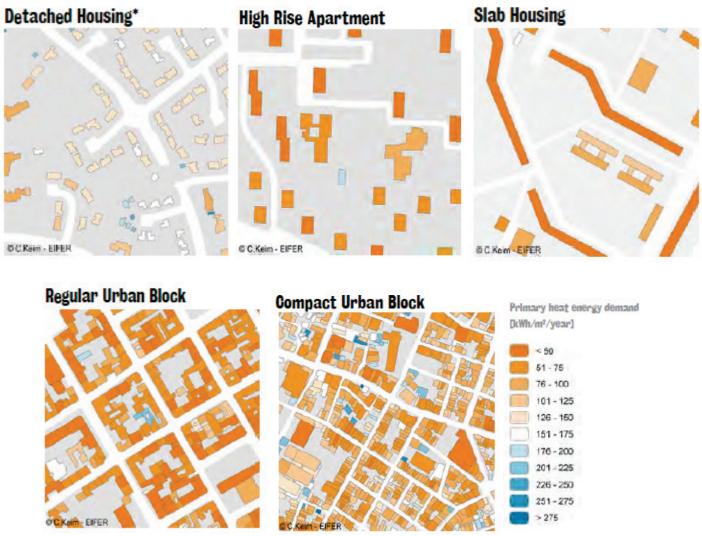


Figure 43: Different typologies and respective primary heat energy demand (kWh/m^2/year). Detached housing is from London, high rise apartments from Paris, slab housing from Berlin, regular urban block from Paris and compact urban block from Istanbul
Source: LSE (2014)

LSE (2014:70) points out that across all cities detached housing was the typology which performed worse with many values in the region of 150 kWh/m^2, and in the other end of the scale were the compact urban blocks which are around 75 kWh/m^2, and in the case of Paris going down to 50 kWh/m^2. This is clearly not the case with the compact urban blocks of Istanbul, clearly much more dense and complex, which present heating energy needs of more than 100 kWh/m^2. The performance of the other typologies is less consistent: high rise apartments of Paris and Istanbul perform around 75 kWh/m^2, while London and Berlin go from 100 kWh/m^2 to nearly 150 kWh/m^2; slab housing of London and Paris is very similar and in the range of 100 kWh/m^2 while Berlin and Istanbul have very different performances (nearly 60 kWh/m^2 and 150 kWh/m^2 respectively), and in what regards the regular urban block, both Paris, Berlin and Istanbul present similar values (ranging from 75 to 80 kWh/m^2), and London more than 100 kWh/m^2.

- Key findings of chapter 3

1) Climate change impacts:

- Worldwide, the main Climate Change impacts until 2100 are: in the temperature an increase of around 2ºC, with more frequent hot temperature extremes than cold (heat waves); oceans will continue to warm, with ocean acidification increasing; changes in precipitation will not be uniform, in mid to subtropical (dry regions) precipitation will likely decrease, and the inverse will occur in mid latitude and subtropical wet regions; extreme precipitation events over mid latitudes and wet tropical regions will very likely become more intense; ice sea reductions in the artic; permafrost area to decrease from 37% (RCP2.6) to 81% (RCP 8.5); globally, glaciers will decrease from 15%-55% (RCP 2.6) and 35%-85% (RCP 8.5), with exception of the Greenland and the Antarctic;

- In urban areas, the main climate change impacts until 2100 are: the largest urban areas, are situated in most of the urban areas which present the highest increase in temperature, both in registered temperature from 1901-2012, but also in projected temperature until 2100; by late-century, under the RCP 2.6 scenario, a number of the urban agglomerations that were among the largest in 2025 will be exposed to temperature rise of up to 2,5°C over pre-industrial levels (excluding urban heat island effects), especially in the high latitudes. This implies that mean temperature rise in some cities could be greater than 4°C; averages across all climate change scenarios, suggest a large increase in the already 150 million people which live in cities with perennial water shortage, possibly reaching up to 1 billion by 2050 (McDonald et al., 2011); the "top 20" cities identified for both population and asset exposure to coastal flooding in both the current and 2070 rankings are spread across low-, middle, and high-income nations, but are concentrated in Asian deltaic cities; estimates for global mean sea level rise are for between 26 and 98 cm by 2100, being that with a 0.5 m rise in sea level, the population at risk could more than triple while asset exposure is expected to increase more than 10-fold;

2) Urban areas and sustainability:

- According to Ferrão and Fernandez (2013), despite the uniqueness of each city, what recent research is demonstrating is that there are patterns, complex ones, in urban development across the world. These patterns reveal important relations between specific climate conditions, socio-economic framework and urban form, that have an important impact in the consumption of resources and ultimately on urban sustainability, being that the urban typologies analysis could constitute an important perspective on the problem;

- Energy in urban areas is mainly consumed in buildings and transportation. According to Salat (2012:519) buildings are responsible for 40% of the final energy consumption in most cities in developed countries, being the rest of the final energy consumed by both transportation and industry;

- Ferrão and Fernandez (2013:139-140) indicate that "[…] *urban form is a key element in the determination of prospects for urban sustainability*" due to three main reasons: 1) the nature and intensity of resource consumption which is highly dependent on the coupling of population density and density of services and infrastructure, 2) the placement, scale, and configuration of the urban built environment affect the manner and intensity with which households, commercial establishments, and industry consume energy and materials, 3) the dynamic interactions between buildings, open and green spaces, and urban infrastructure provide clues about the concentration of heat and urban pollutants that give rise to unhealthy and energy intensive "hot-spots" in the city;

3) Modelling energy demand on urban areas:

- According to Ratti (2005), the passive to non-passive area ratio seems a better indicator of energy consumption; surface to volume ratio, while being an important urban form parameter, does not describe the total energy consumption in urban areas;

- According to Salat (2012) "*When scaling up, complex interactions appear within urban fabric, which significantly alters the results that were valid on the building scale*", which is the reason why the neighborhood has been in the recent years a privileged framework of analysis for the urban energy studies; the author indicates that the modernist fabric consumes 1.8 times more energy for heating than contemporary or traditional urban blocks.

- LSE (2014:70) points out that across all cities detached housing was the typology which performed worse, and in the other end of the scale were the compact urban blocks. Traditional and complex typologies tend to perform worse than compact urban blocks.

SECTION C - Methodology

4. An integrated method to analyze the relation between urban form and energy

A new integrated method to analyze the relation between urban form and energy is proposed. This new integrated method builds up on the research gaps identified before, and has the objective of combining both the urban form and energy performance dimensions, in order to: 1) characterize in detail a pre-determined urban form (in this case Lisbon), in what regards the relations of the various elements that compose the urban form, and also define a set of urban typologies as critical units of analysis in the urban energy analysis step; and 2) understand the impact of urban form, through the urban typologies previously defined, on urban daylight and thermal energy needs. The scale of analysis, method and tools for each dimension are briefly summarized in Figure 44.

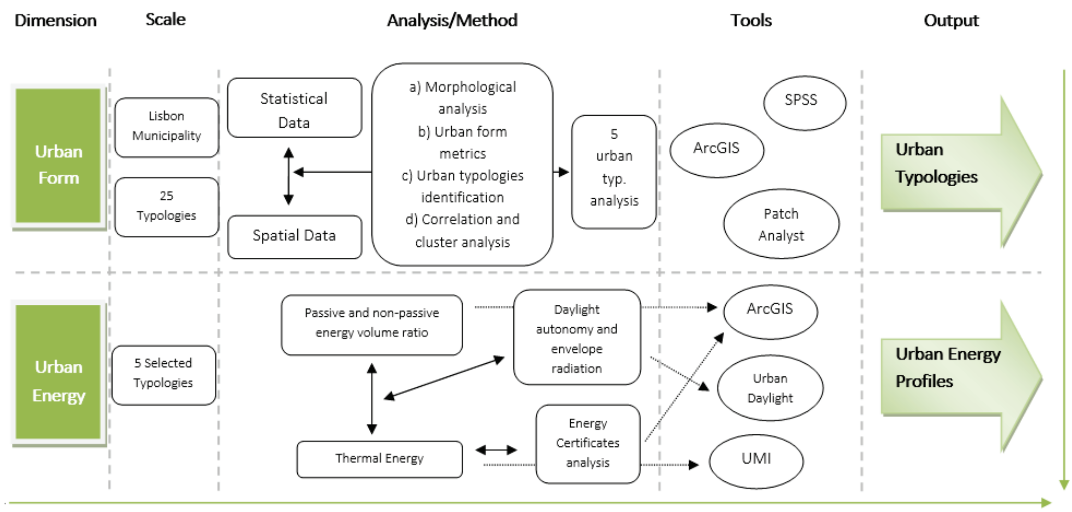


Figure 44: Methodology for the proposed urban form and urban energy analysis

This new integrated method has the objective of building on existing tools, integrating them in a new configuration model that could be extrapolated to different urban forms across the world (provided that the data is available), and that allows a comprehensive quantification of various urban form parameters, while at the same time creates a framework to relate these parameters with energy performance ones. Therefore the main contribution of the method proposed is precisely the integration of both the urban form and energy performance dimensions. Also urban form metrics were developed, expanded, grouped and related (with urban daylight and thermal energy) in new ways than previous research, thus allowing to better understand the potential of urban form for the World´s urban sustainability. To note also the scope of this analysis, that involved 5 urban typologies with hundreds of buildings simulated, which is significant given existing current research.

As indicated before, this integrated method is divided into 2 main dimensions: urban form and urban energy. In the first dimension both the city as whole, and 25 selected urban typologies will be analyzed. Methodological steps in this section are: a) morphological analysis of the city of Lisbon in which the urban form evolution of the city through time will be characterized (chapter 5.1. - Morphological evolution of the city); urban form metrics, namely the data that was used and calculation methods developed (chapter 6.1 - Data used for the metrics calculation and contextualization and chapter 6.2 - Metrics used and calculation methods); typology identification method, that will describe the method that was used to identify urban typologies (chapter 6.3 - Identification of urban typologies); and the correlation and cluster analysis that were used to understand the relation between metrics, and also how the urban typologies would group if the urban form metrics were taken into account in a cluster analysis (chapter 6.4 - Statistical analysis of metrics). In the urban energy dimension an analysis of Lisbon´s energy profile was made, in order to characterize the share of buildings in the total energy needs of the city, how energy needs are divided by type of use and also how Lisbon´s energy consumption has evolved in the last years (chapter 5.2 - Lisbon energy profile). The 5 urban typologies were analyzed in terms of passive and non-passive volume ratio (chapter 7.2 - Passive and non-passive volume ratio), daylight autonomy (chapter 7.3 - Urban daylight analysis) and thermal energy needs (chapter 7.4 - Modelling thermal energy needs). The objective was to access the impact of urban form on both the daylight availability, which influences directly the thermal energy needs, and also to estimate thermal energy needs based solely on urban form parameters, to understand how different typologies could perform. Lastly the thermal energy needs were also compared with Portuguese Energy Performance Certificates (EPC) for the typologies areas, and also relevant literature in order to access their accuracy. Results for the urban form analysis can be accessed on chapter 8 - Urban form analysis results, for the urban daylight and thermal energy needs results those are available in chapter 9 - Urban energy analysis results. The comparison of the Portuguese Energy Performance Certificates and relevant literature with the calculated thermal energy needs is available in chapter 10 - Main findings on the relation between urban form and energy.

5. Characterization of the city of Lisbon

5.1. Morphological evolution of the city

To understand Lisbon´s current urban form, it is fundamental to look into its history and also the specific geographical properties of the city, since urban form is a reflex of both the physical context of the city but also it socio-economic and cultural characteristics. Therefore it's a physical representation of the way people organize in a competitive space, being that Lisbon´s urban form will be addressed since the Roman occupation in order to illustrate how Lisbon's urban form evolved according to the city´s function and how nowadays Lisbon past is still important to understand how the city is organized and evolving. Lisbon is the capital city of Portugal, with a population of around half a million inhabitants and, with 84 sq. km, is the largest city in Portugal and the third largest city of the Iberian Peninsula after Madrid and Barcelona. It is situated near the Atlantic Ocean and in the mouth of the Tagus River. The Lisbon Metropolitan Area (LMA) (Figure 45) comprises a population of nearly 3 million inhabitants that correspond to more than 1/3 of the Portuguese population. The LMA comprises 25% of the total active population in Portugal, 30% of the national companies, 33% of the employment and contributes with more than 36% to the national GDP (AML, 2015).

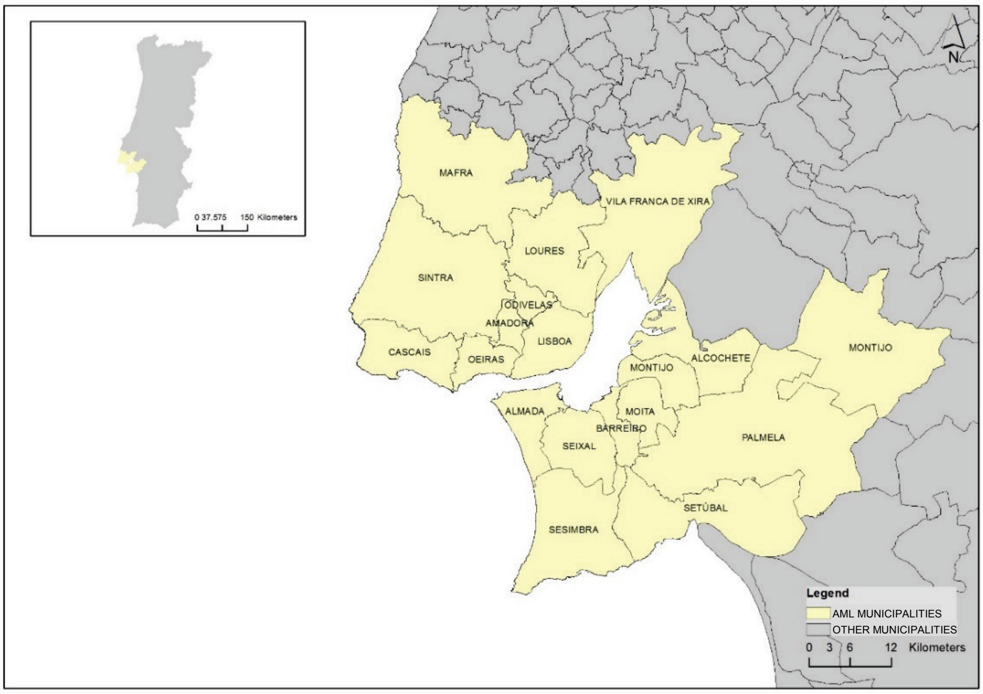


Figure 45: The municipalities of the LMA

According to Ribeiro (2013), very few cities take advantage of such key position as Lisbon. In a coast so regular, its harbor takes advantage of a high water depth and easy access to both the ocean and the inland. The city is composed of lines of hills which have in their intervals plain areas. The most primitive core of the city of Lisbon was situated precisely in one of those hills, with the highest slope and closer to the river. The author indicates that Lisbon is one of the last occidental examples of a Mediterranean city due to its location in a bay that is protected from the dominant wind, and important orography to defend the harbor. The oldest traces of civilization that were found in the place where today is the city of Lisbon, point out to a permanent human occupation by the Phoenicians already in 1200 B.C. The Romans created the first main settlement (Olisippo), building an Oppidum[11] in a plain area closer to the water. The city was then (according to traces of Roman structures) bigger than in the Arab period, which marks a regression in Lisbon´s urban life (Ribeiro, 2013:3). The city in the Arab period (Lichbouna) had then strong walls, a castle, and was located in a hill, more precisely in the slope that went down towards the river (in what is known today as Castelo and Alfama). With the Portuguese conquest of the city of Lisbon the city becomes the capital of Portugal (13th century) (Figure 46).

Figure 46: Lisbon in the 13th century
Source: Marques (2003)

[11] Main settlement in an administrative area in the time of the Romans

In the end of the Middle Age, the city was a great hub of commerce: his workers were associated through corporations, his harbor had hundreds of ships from many parts of the world, and also received a great flow of products from the south and center of Portugal that arrived through the Tagus river. Soon the population expanded behind the wall, establishing around convents or churches, and through the main axis of circulation. The strong connection to the rural zones and the agriculture (reminiscent of the Arabs), created a mix of rural elements in the city and vice-versa. In the middle of the two main hills on the west and east, right in front of the river and with easy access to the north and the rural fields, grown the most important commercial, political and leisure area that is nowadays Baixa and Terreiro do Paço (at that time also a square and the location of the King´s palace) (Figure 47).

Figure 47: Lisbon in 1650´s
Source: (Marques, 2003 according to J.N.Tinoco)

With the heartquake in 1755, which devastated almost all of the city centre, Lisbon known an important reconstruction plan that introduced a series of new constructions methods and urban design plans that "upgraded" the medieval city to a pre-industrial city (Figure 48). The beginning of the 19th century signaled an important growth era that corresponded to the growth of the city not only outwards but inwards filling the still rural landscape that existed in some areas. The neighborhoods grown towards north, where the orography is less evident, giving rise to planned urbanizations: streets became larger, the irregular network is replaced by a regular one, old buildings are demolished, empty spaces are converted into green areas. The growth and development of transportation modes and networks allowed a closer contact to areas that some years before were considered suburbs, converting the summer houses into permanent residences.

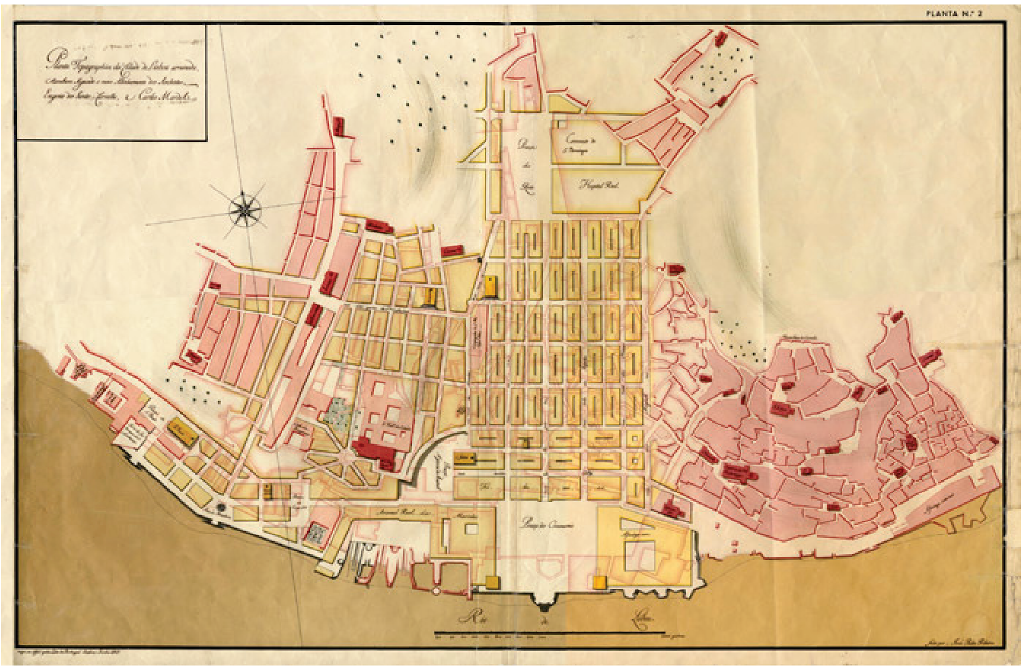


Figure 48: Downtown Lisbon after the heartquake of 1755
Source: Santos and Mardel (1756 in Wikipedia, 2012)

In the end of 19th century very important works were made in order to increase the harbor area, and in an extension of 12 km new shipyards, docks, and wharfs were made, but were not sufficient since it was necessary to build other infrastructures in the Tagus south margin, and along the north margin towards Vila Franca de Xira. This process of growth of the Lisbon harbor created a profound change that pushed away the nobility and royal houses and palaces that in the past were close to the river, and created an industrial zone, with workers, stevedores, sailors, fisherman's and others along the shore. On the river shores (both south and north), the predominant activity became the industry, and only on the Atlantic coast along Oeiras and Cascais, the land use was different, with sunny beaches, palaces and summer houses that belonged to the high class. The urbanization stretched along the shore, but remained along that line not growing to the north. That can be seen in Figure 49, which shows also the significant changes in the land use that occurred in the 20th century Lisbon, mainly outwards the center of Lisbon and towards the periphery.

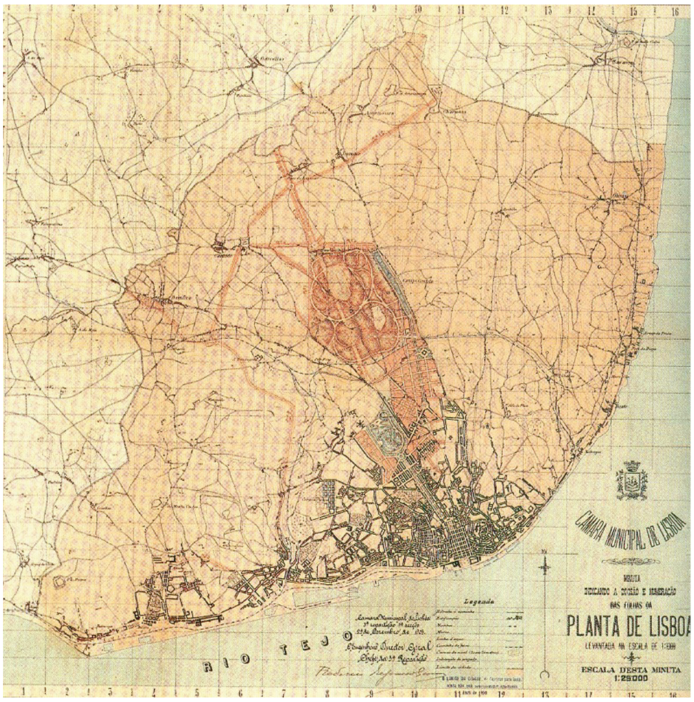


Figure 49: Lisbon in the beginning of the 20th century (1903). It is possible to observe the expansion of the city through the shore line, but also north through main communication axis of the city with the periphery. In the middle of the city and in orange it can be seen the Avenidas Novas (New Avenues) urbanization.
Source: CML (1903, in Cutcity2, 2016)

The beginning of the 20th century towards the 1950´s was marked by the construction of the Avenidas Novas (New Avenues) urbanization that allowed the creation of important and significant urban areas in the city of Lisbon, together with the development of public transport (trams, buses and the subway later in the 1960´s). Those urban areas are today the connection between the more historical center and the service and residential neighborhoods in the periphery of the city. The second part of the 20th century in Lisbon was characterized by the development of neighborhoods inspired by the Modernist movement as it were Olivais and Chelas (1960´s); mid-class residential neighborhoods Benfica (1960´s), Telheiras (1970´s), Lumiar (1980´s); and in the last decades mix-use neighborhoods like Alta de Lisboa and mainly Parque das Nações , that were planned according to some sustainability principles, with good access to public transportation, and modern housing.

To better understand the growth and evolution of the city of Lisbon that was described, it is important to look at the population evolution throughout the various periods of the city´s history. As it can be seen in Figure 50, the city of Lisbon as known an almost constant population growth since its origins until the 1960´s, where it stagnated and even had a decrease in its population, due to the war in the Portuguese former colonies and emigration flux. The city resumed its growth pattern in the 80´s with the independence of the former Portuguese colonies and the return of almost 1 million people to the country which settled in the major cities, and mainly in Lisbon, in precarious conditions. Then the city entered a phase of decline in terms of population that is felt until the present, due to the growth of the suburbs – on a first stage around the city of Lisbon in a 1st ring, and then even further in a 2nd and 3rd rings till the limits of what is nowadays the Lisbon Metropolitan Area.

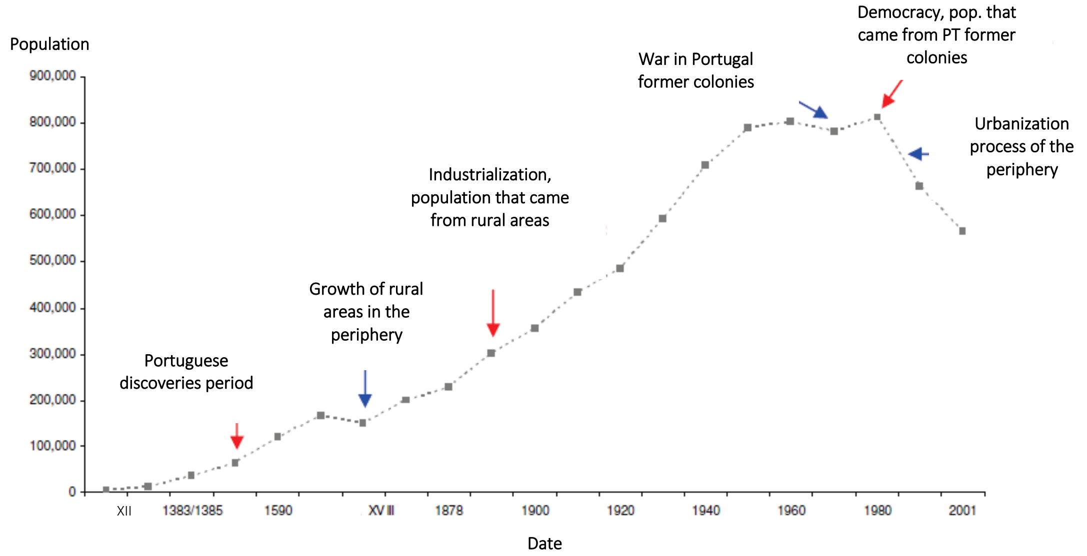


Figure 50: Demographic evolution of the city of Lisbon in the 20th century
Source: Adapted from Encarnação (2011:57)

The loss of population to the suburbs is evident if we look at the weight of the Lisbon city population in the LMA that went from 55% in 1960 to 18% in 2006 (Encarnação, 2011:58). This loss of population had, as main consequences, the aging of the existing population, the degradation and desertification of inner city areas (more than 50.000 abandoned households), and a large increase of daily commuting between the suburbs and central city areas (Climaco, 2012:55). Climaco (2012:55) also indicates other dynamics that were important to explain the current population displacement and that are: the excessive tertiary services in the center of Lisbon, the inadequacy of most living spaces to the current demand of comfort and space, the inadequacy of the supply/demand for both house purchase and renting, and the degradation of the quality of life in these areas. The fact that the Lisbon Metropolitan Area evolved from the center-outwards in terms of population location, together with a concentration of the economic activities in specific urban centers, contributed to a push and pull effect that is overloading the capacity of the LMA infrastructure in terms of the mobility network in order to respond to huge fluxes during the day, and in terms of infrastructure to accommodate the displacement of people, energy and materials (Figure 51).

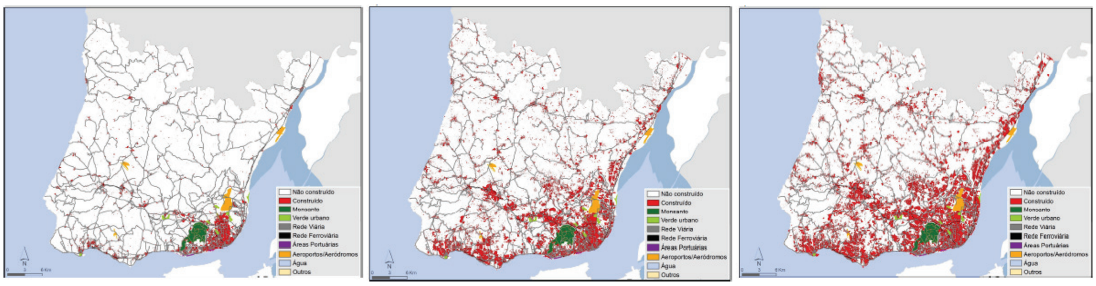


Figure 51: Evolution of the urban areas of the MAL (north margin) in 1960-1990-2004 (built up areas - red, green areas - green, roads - grey, railways - black, seaports - purple, airports - orange, water - blue, other - yellow)
Source: Encarnação (2011:90-91)

If we look closely at the evolution of both population and the number of buildings in the city of Lisbon in the last century (Figure 52), we can see that the evolution in the number of buildings is a response to the population evolution, but with some delay. A huge increase in the number of buildings has been registered from the 1950´s to the 1960´s in response to a constant increase in population in the last decades (1920-1950), but that already was stabilizing in the 1960´s. The 1970´s through the 1990´s was a period that generally constituted the inversion on the tendency of growth (with the exception of the 1980´s because of factors that were already addressed), but the number of buildings slightly grown mainly due to the immigration influx. It appears that the number of buildings and population growth both have aligned from 1990´s onward, since both population and number of buildings decreased. The decrease in the number of buildings mainly from the 1990´s onwards can be explained by the increase in the buildings size (buildings could accommodate higher quantities of people), but also the migration of population to the suburbs of the Metropolitan Area, which created vacant properties that were converted to infrastructure or bigger buildings. Other important factors were the programs for elimination of illegal or shanty housing that had a huge impact in the late 80´s but above all in the 90´s and 2000´s.

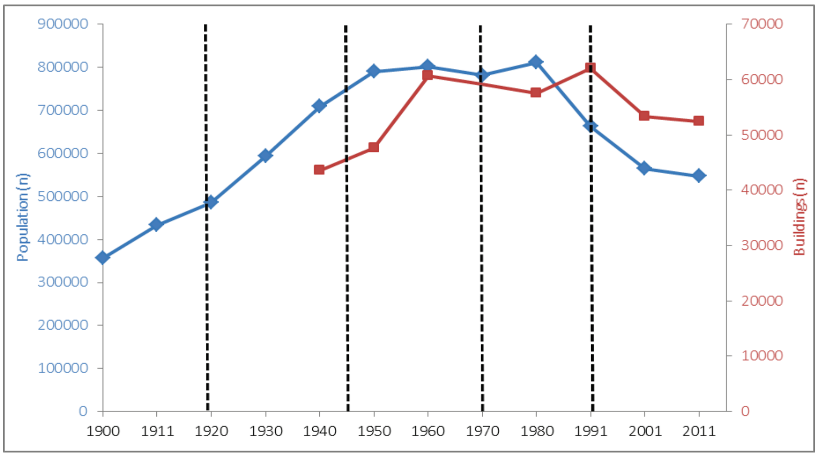


Figure 52 Population and buildings evolution through the 20th century in Lisbon, and divided by the 5 periods of construction used to define typologies
Source: Adapted from INE (1900-2011) PORDATA (2015), Marques (2003)

Looking at the household's evolution (Figure 53), it is possible to confirm the fact that through the 20th century (as it was also registered in other contemporary cities in developed countries), the buildings have increased in size, thus originating a higher number of dwellings per building. This way the number of households presented an increasing tendency throughout the century, which is a reverse tendency when compared with the population growth in the last 40 years. These different tendencies led to an increased number of vacant property in the city of Lisbon, a significant number of it in a poor state of condition.

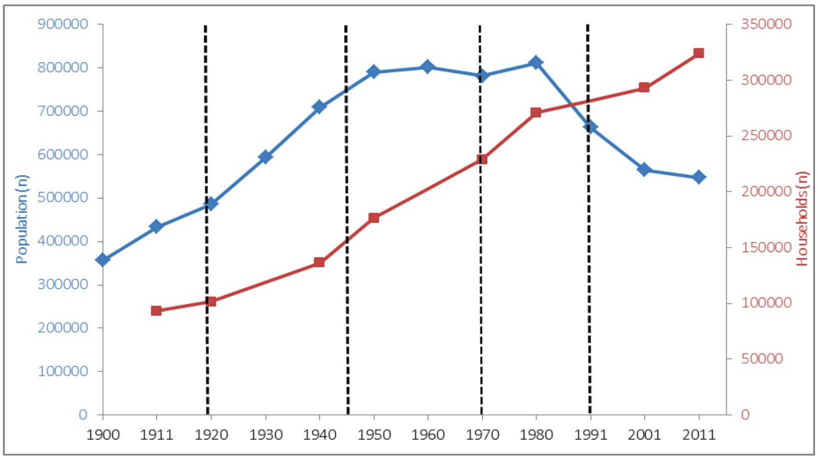


Figure 53 Population and households evolution through the 20th century in Lisbon, and divided by the 5 periods of construction used to define typologies
Source: Adapted from INE (1900-2011) PORDATA (2015), Marques (2003)

Spatially the population of the city is mainly concentrated in the north, in Benfica, Telheiras, and Lumiar neighborhoods that were built in the last 50 years and also in the CBD – central business district of the city that generally goes from Entrecampos towards Marquês de Pombal (Figure 54).

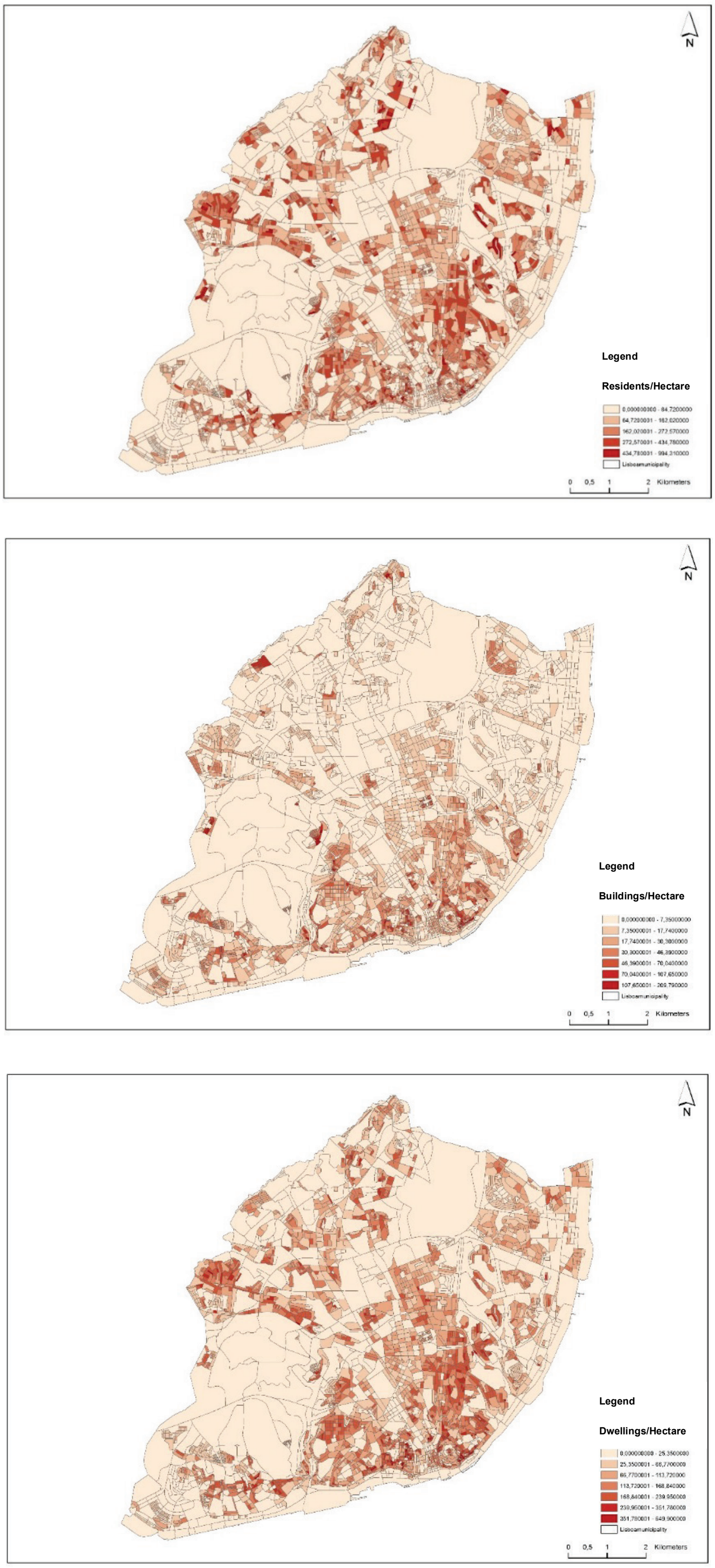


Figure 54: Population, buildings and dwellings per hectare in Lisbon
Source: Produced by the author (data from INE Census, 2011)

The traditional areas still aggregate an important share of population, also important are some areas of the oriental part of the city, such as Olivais, Chelas and Parque das Nações that aggregate a significant share of population. To note that the dwellings distribution is much more appropriate to understand population displacement since in the case of Lisbon, buildings have become larger accommodating a higher number of residents, this is particularly true in the North and Oriental parts of the city where the apartment towers have become the dominant typology.

According to Encarnação (2011:58) there were three main tendencies in the evolution of the urban form of the city of Lisbon:

1. Until 1750, the expansion of the new built areas occurred mainly in the neighboring of existent built areas, through a form of high compaction;
2. From 1750-1950, the spatial structure of the urban form reveals already a linear tendency of expansion through some axes of circulation;
3. From 1950 onwards it is evident the fulfilment of the interstitial spaces of the existing built areas which reveals a tendency for consolidation.

In the figures below, it is possible to observe the Lisbon´s urban form dynamics through time (Figure 55), the present building stock (Figure 56), and also how and where densification took place (Figure 57). In this regard, the importance of the axis of transportation (roads, trainlines and metroline) are fundamental for the urban form dynamics that were registered.

Figure 55: Urban structure in Lisbon from the 12th century until 1980
Source: Marques (2003:22)

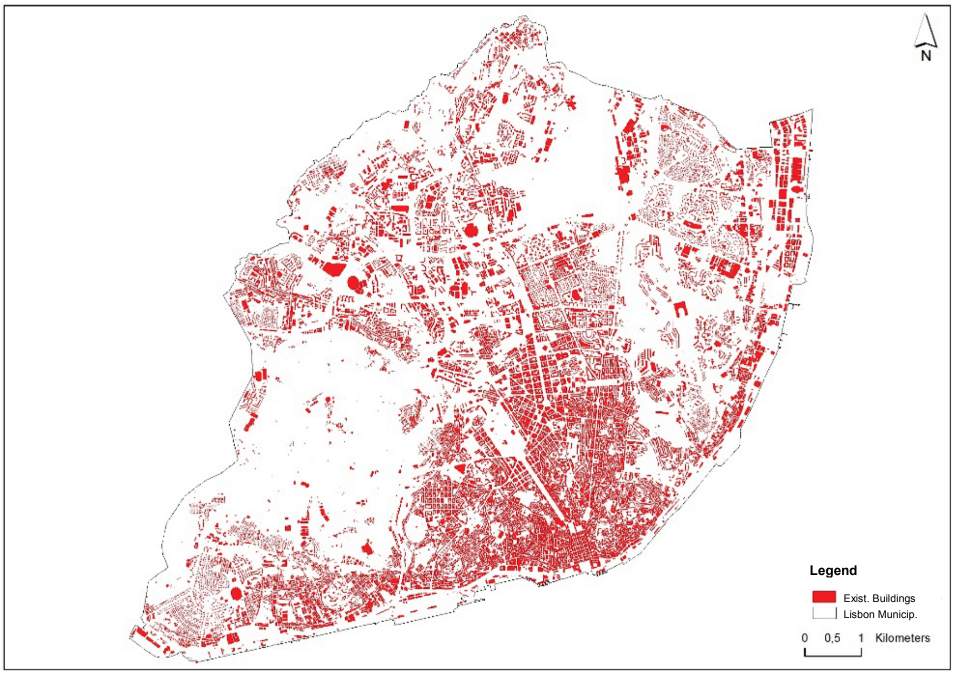


Figure 56: Lisbon present urban form

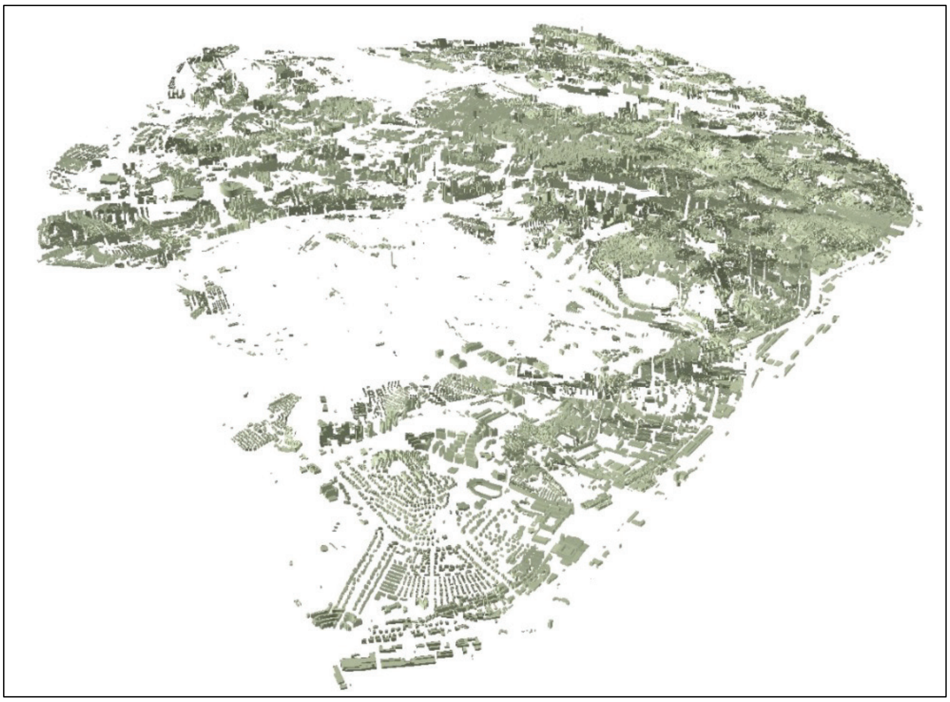


Figure 57: Lisbon present urban form (with buildings height)

Looking at the predominant period of construction by substatistical section, and merging the sections with the same period of construction in order to define larger areas with the same characteristics, we can confirm the pattern of location of predominance of older buildings in the center and more recent buildings in the periphery of the city, thus contributing to different urban forms (Figure 58).

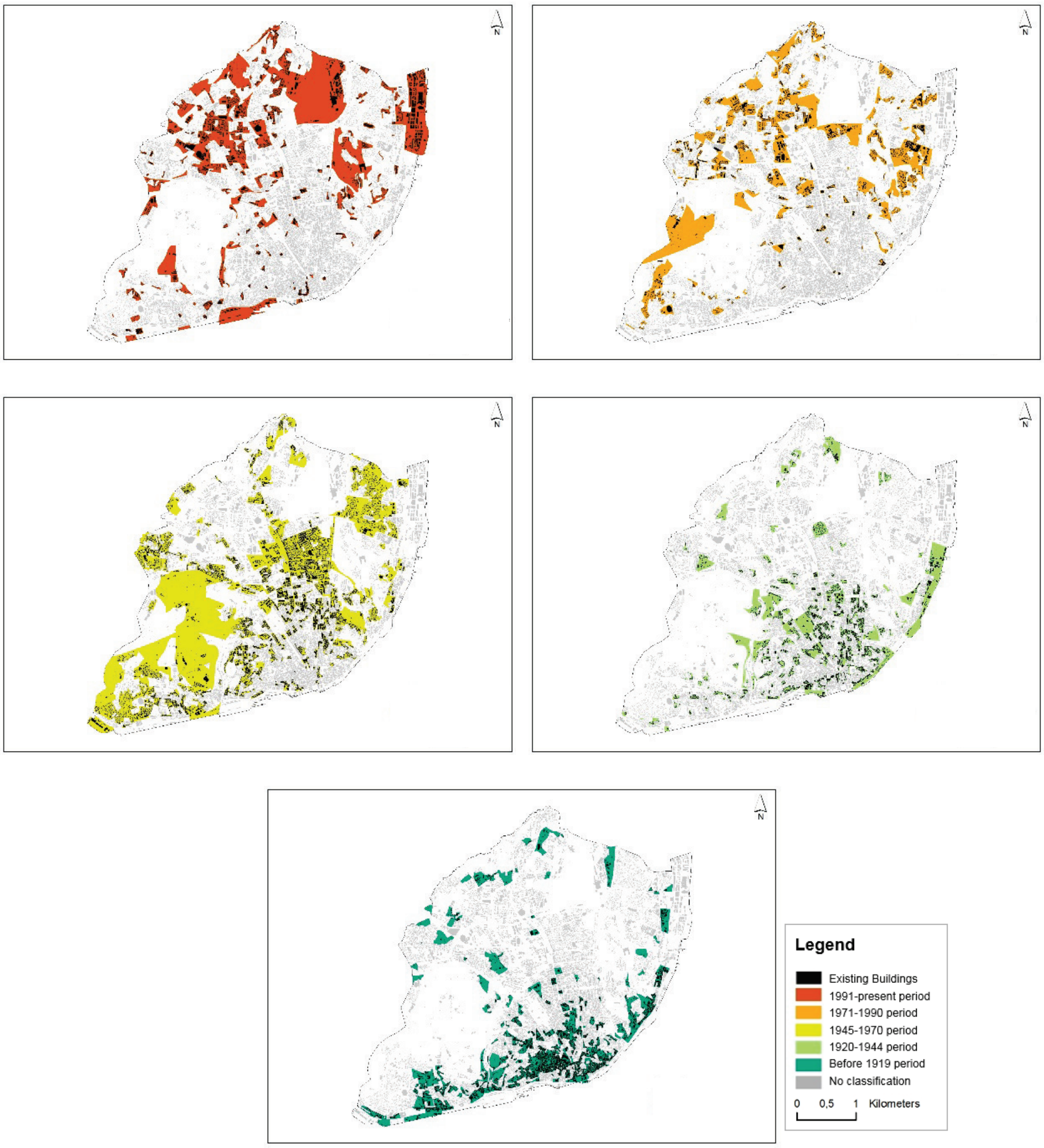


Figure 58: Distribution of buildings by the predominant period of construction classes in the city of Lisbon (with all classes and for each class): 1991-present, 1971-1990, 1946-1970, 1920-1945, before 1919, no buildings.
Source: Produced by the author (data from INE, 2011)

Also, it can be seen in the figure above that the period of construction with a greater number of buildings is the one of 1946-1970, a period of a great expansion of the city of Lisbon. Buildings before 1919 concentrate mainly around the first areas of development of the city –

along the river and main hills, especially near the castle and baixa. The buildings from 1920-1945 correspond to the urbanization phase of the Avenidas Novas plan, that had the objective of expanding the city outwards the centre. Buildings from 1971-1990 and 1991-present concentrate mainly in the periphery of the city, and corresponded to the last phase of Lisbon urbanization, as important planned areas, like Chelas (1970´s), Telheiras and Lumiar (1970´s-1990´s) and Parque das Nações (2000´s), but also as scattered small scale developments that emerged along main axis of circulation and filled important "vacant spaces" that were still peri-rural land.

In what regards its urban morphology, the city of Lisbon is very heterogeneous, with very different patterns of organization of the urban space that somehow reflect the historical context and the initial function in which they were built. According to Barata Salgueiro (2002:12) the urban typologies in the city of Lisbon can be divided into:

- *Old core*: that corresponds to the oldest neighborhoods in Lisbon – Alfama, Castelo, and partially the parishes of Graça and Santana, which have irregular urban patterns. This irregular pattern is due to its antiquity, Muslim influence, and the topography of the terrain;

- *Orthogonal patterns*: corresponds to planned urbanizations, with different variations depending the construction period where they were built. One of the firsts is the Bairro Alto neighborhood (16th century); Baixa (18th century) – due to the Lisbon heartquake a large urban area was built from the zero with a orthogonal pattern and with squares on both North and South to redistribute the network of streets and the fluxes; the "Avenidas Novas" (New Avenues) plan, that started in the late 19ths to the late 40´s of the 20th century and that consisted in an expansion of the urban area through main axes of circulation that arose from Avenida da Liberdade to the north, and that supported the growth of the bourgeoisie class and the housing business. Other example of an orthogonal pattern but drawing inspiration in the neighborhood unit (according to the Radburn[12] principles) was the Alvalade urbanization (1945).

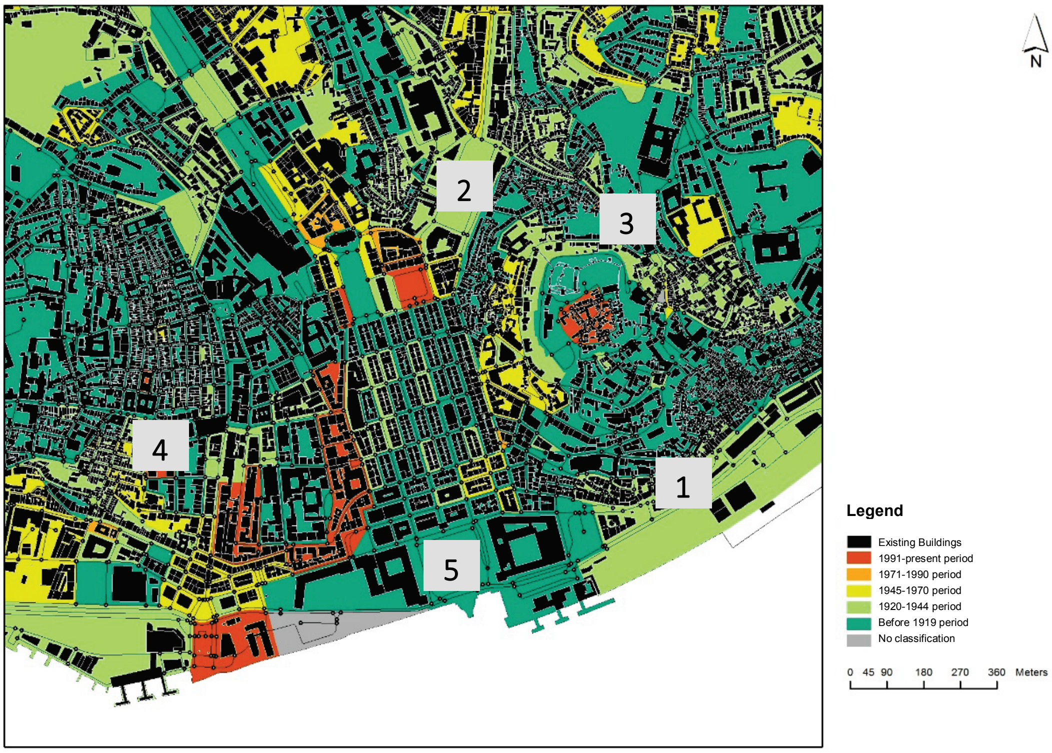
- *Modernist urban areas*: Strongly influenced by the Athens Charter, normally these are neighborhoods that were built many years after the publication of this important

[12] The Radburn principle acknowledges the separation of pedestrians and automobiles. The main streets are in the periphery of the residential units that are penetrated by a distribution network and culs de sac. It is normally composed of 5.000 inhabitants, a primary school and other equipment's in the center of the neighborhood.

document. Examples of these areas are the Estados Unidos Avenue (1953), Infanto Santo Avenue, and the Olivais plan (1958/1960) and Chelas (1962/1966), and the initial phase of Telheiras neighborhood (1973/1975).

The more recent urban areas, as are Parque das Nações and Alta de Lisboa, present a combination of both the organization of the orthogonal areas, and the relation with the road network that the Modernist areas have. Based on the identification of the predominant period of construction done before, and taking into consideration the historical and morfo-functional context, some of these patterns can be identified and better explained.

Figure 59 and Figure 60 illustrate (in dark green) all the areas whose predominant period of construction is before 1919. It corresponds to the historical centre of Lisbon. As indicated before, the historical typologies typically present an irregular pattern of both buildings and streets as is the case of Alfama (1), Mouraria (2) or Castelo (3). However, there are also urban patterns that were very innovative at that time and display a more orthogonal organization, with block configuration and wider streets. It is the case of Bairro Alto (4), but mainly Baixa (5), since Bairro Alto in what regards buildings and street network size resembles more the first three typologies.



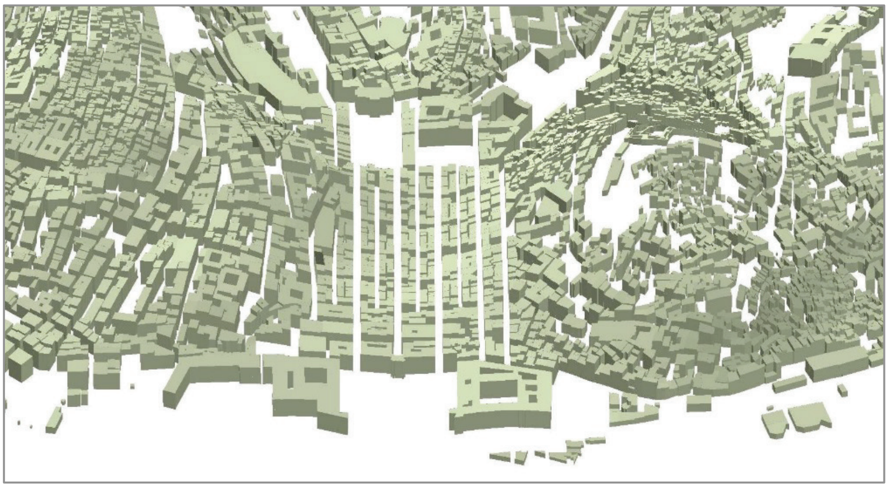
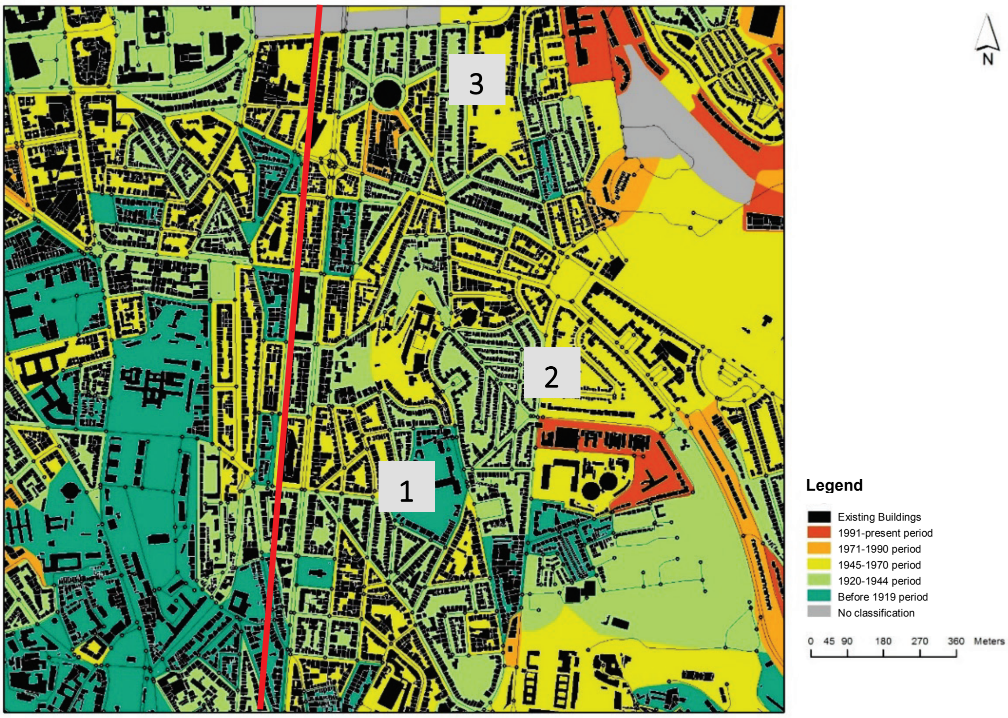


Figure 59: The historical or traditional city – predominant period of construction and building footprint
Figure 60 The historical or traditional city – buildings height

The 1920-1945 period of construction has more diverse patterns, as it was seen before, however some important predominant patterns can be framed. Figure 61 and Figure 62 illustrate the case of Av. Almirante Reis, and three important 1920-1945 typologies: Anjos (1), Penha de França (2) and Arroios (3). Buildings became larger (but small compared to nowadays), the block organization is predominant, as well as the organization around a center square (Anjos church and Arroios market) or small squares (Penha França).



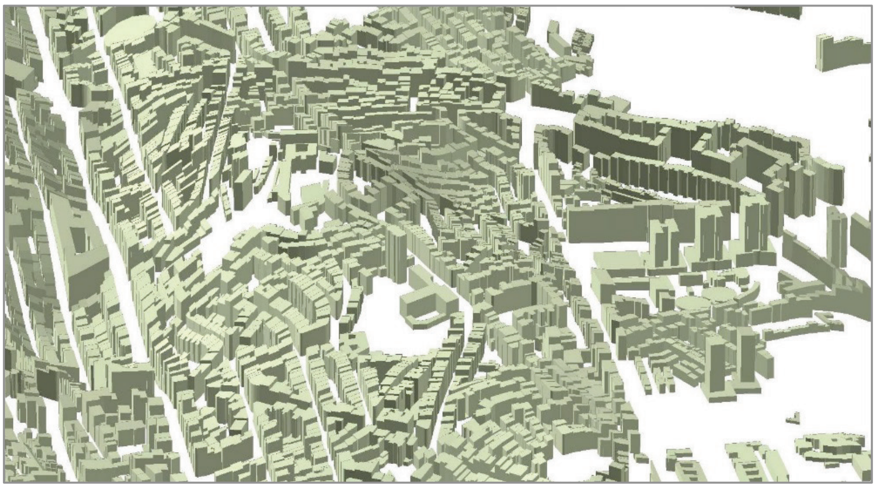


Figure 61: Anjos, Penha de França and Arroios - predominant period of construction and building footprint
Figure 62: Anjos, Penha de França and Arroios – building height

The 1946-1970´s period of construction is mainly characterized by great urbanization plans, namely Alvalade (Figure 63 and Figure 64) and Olivais (Figure 65 and Figure 66).

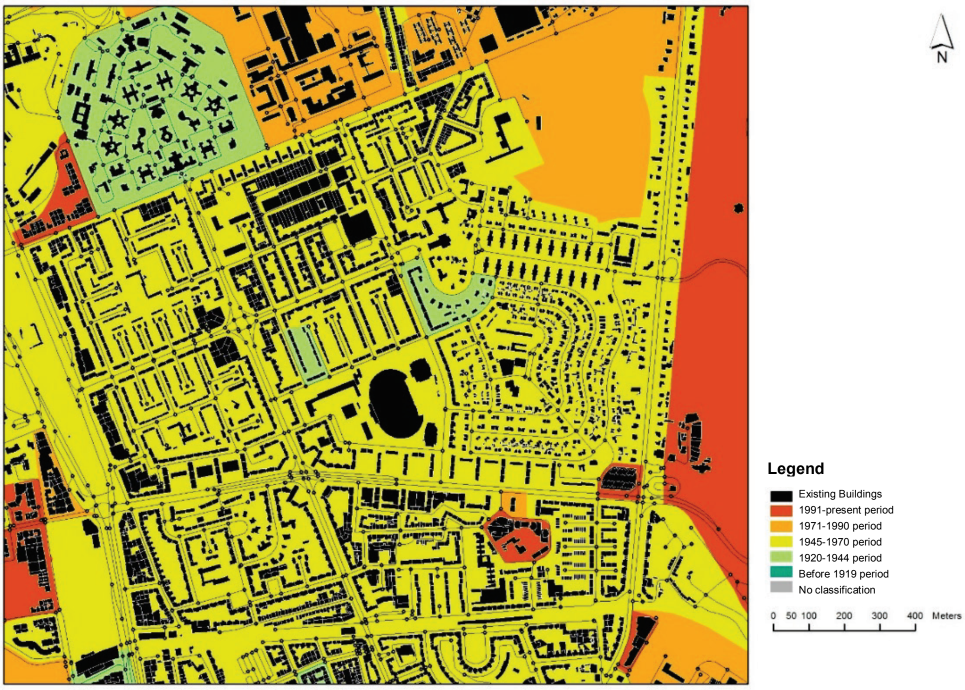


Figure 63: Alvalade (1945) urbanization - predominant period of construction and building footprint
Figure 64: Alvalade (1945) urbanization – buildings height

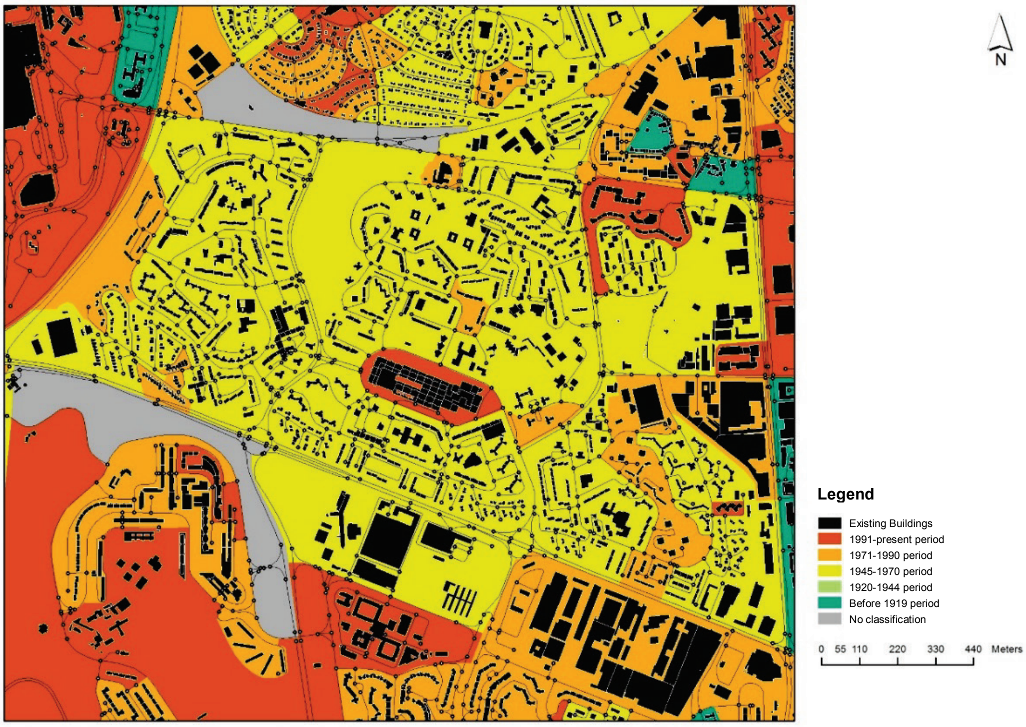


Figure 65: Olivais Sul (1960´s) urbanization - predominant period of construction and building footprint
Figure 66: Olivais Sul (1960´s) urbanization – buildings height

While Alvalade was designed around the 1940´s-1950´s, Olivais was designed in the 1960´s which resulted in very different urban forms. Alvalade, with an area of 230 ha. , for 45 000 inhabitants, was organized around 8 cells (housing units), structured around a central element that was the primary school (Figure 67). The majority of buildings would have in the inner parts of the cells 4 floors, with mixed development that had social housing, schools, market, civic centres, sports infrastructure, small industry, etc (Tostões, 2001: 67).

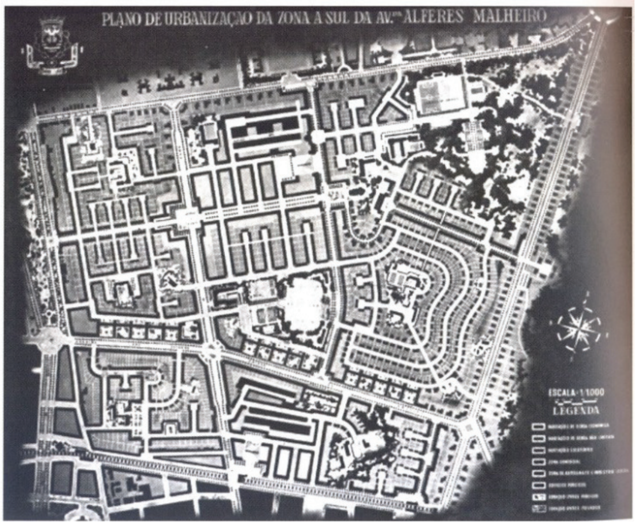


Figure 67: Alvalade urbanization plan
Source: Faria da Costa (1948 in Tostões, 2001:66)

The Olivais Norte and Sul urbanizations followed the necessity of building more housing units to accommodate a growing population in the 60´s[13]. The first urbanization to be developed was Olivais Norte, and according to Valssasina Heitor (2001:73) it was the result of a strong influence of the Athens Chart, while in Olivais Sul, there were already some derivations of this "doctrine" that derived from the debate around the modernist concepts and the way cities grow. However, both plans had some common elements, that were an influence of the new British cities introduced in the Cumbernauld Plan (Hugh Wilson, 1956) as it were the densification of the residential areas, the structuring of the buildings around a civic centre of great dimensions, and the abandon of the concept of neighbor unit (Valssasina Heitor, 2001:74) (Figure 68).

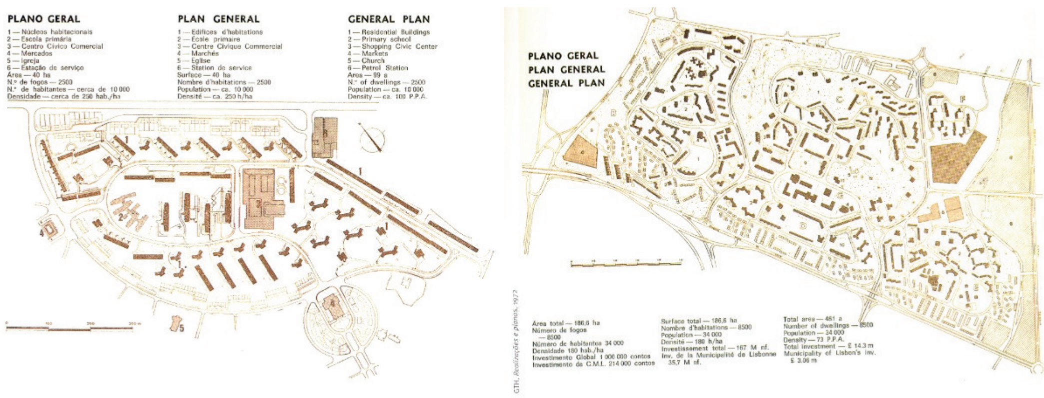


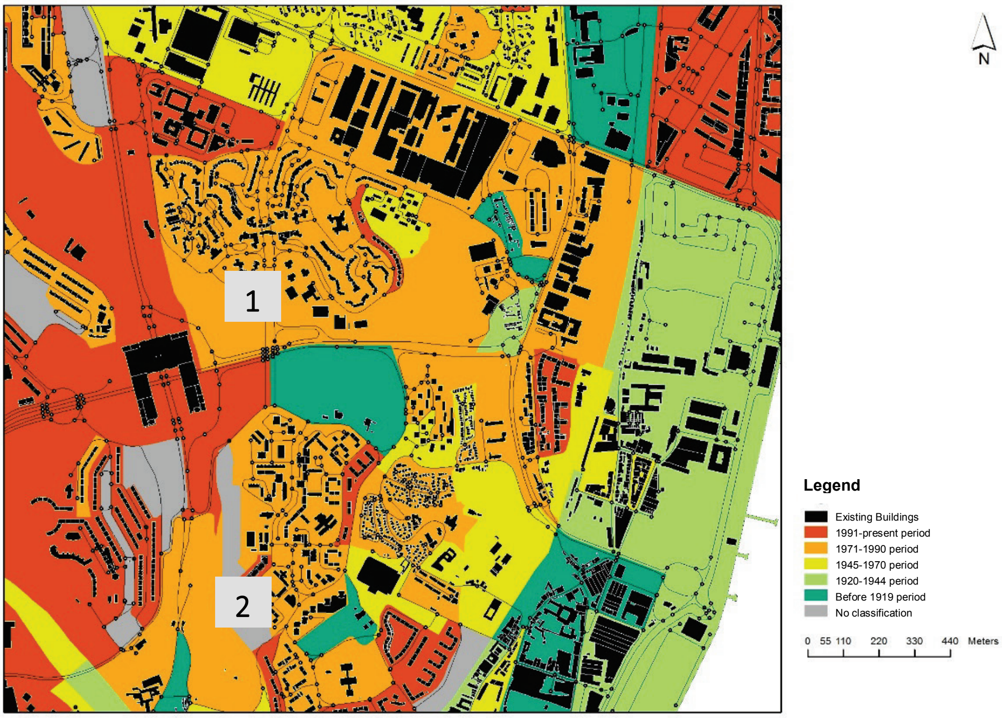
Figure 68: Olivais North (left) and Olivais Sul (right) urbanization plans
Source: GTH – Realizações e Planos (1972 in Valssasina Heitor, 2001:74-75)

[13] The law 42454, of 18 August 1959 established the bases for these types of urbanizations since it focused mainly in developing housing at affordable levels to families with less resources

A good example of 1970-1990 typologies is the one of the Chelas urbanization. Despite having been initiated in 1960, the first constructions of the Chelas plan are only from 1972. The initial plan contemplated a pluri-functional urban structure, socially diversified, integrated in the city and also focused on the river front towards the city of Vila Franca de Xira (Valssasina Heitor, 2001:77). Cores of high density housing units were built, together with a central core with equipment's and other activities (Figure 69).

Figure 69: Chelas initial plan with the 6 cores integrated in a pluri-functional structure of high density housing (cores N, M, I, J, L) and equipment's and other activities (O). In yellow the areas for housing, on purple industry, dark green parks, and on light green natural areas associated with road network.
Source: GTU, Plano de Urbanização de Chelas (1995 in Valssasina Heitor, 2001:78)

This layout was soon changed taking into account the results of the Olivais Norte urbanization, being that more traditional urbanization models solutions were used in particular cases to attenuate the initial intervention. The concept therefore went from a cellular structure to a more connected one, giving the street a more central role together with the articulation with the existing environment. However, in the present, Valsassina Heitor (2001:82) argues that the process of transformation of the urban space in Chelas has greatly deviated from the original proposal, due to the many changes in the political-constitutional framework and the non-adaptation of the plan to the new social-economic context. Today this is a highly fragmented and polarized space, with mono-functionality in terms of its activities and predominance of population with many social problems (Figure 70 and Figure 71).



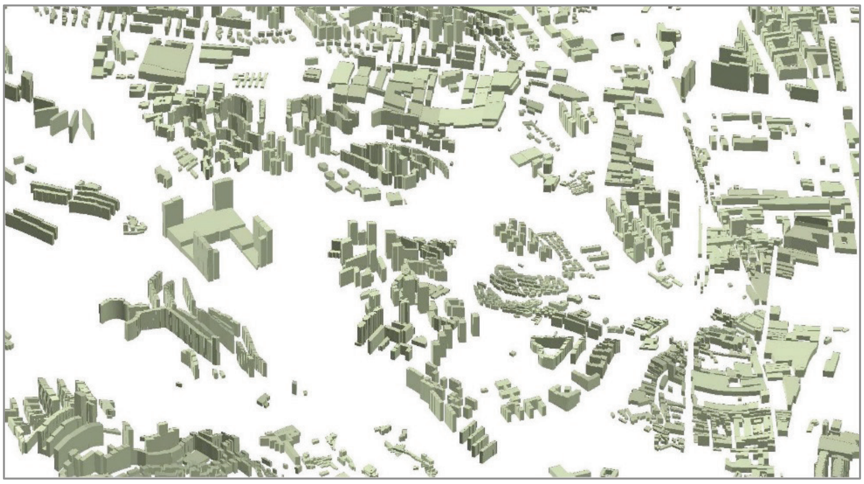
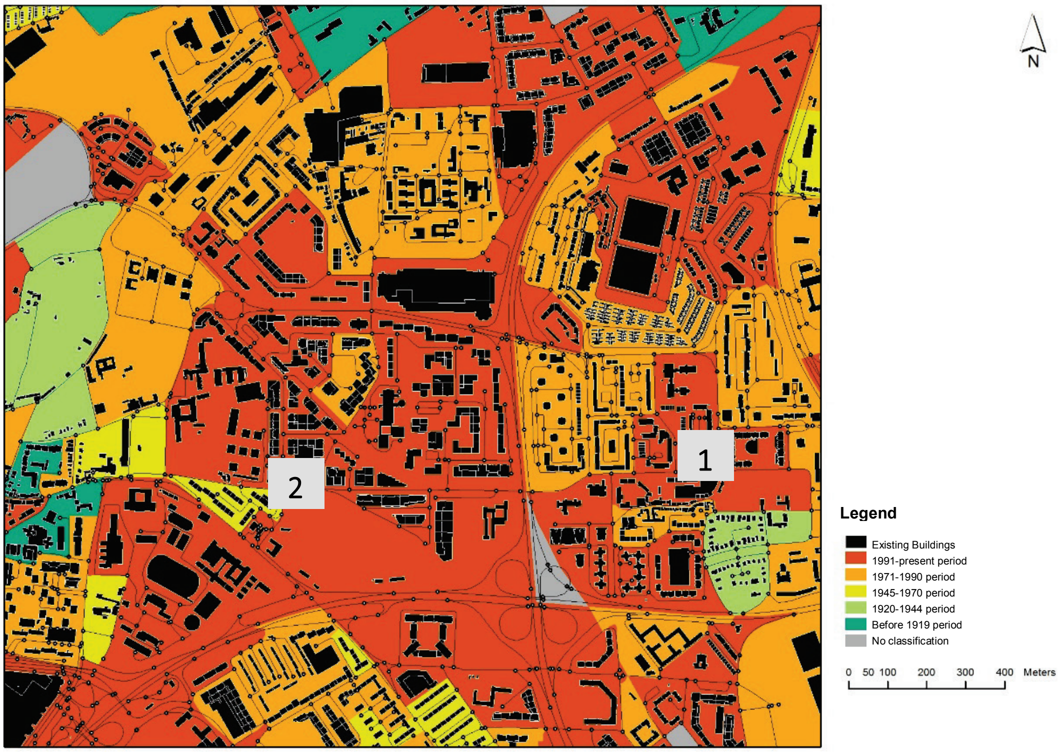


Figure 70 Chelas urbanization in the present (1 – 1960´s, 2- 1970´s) - predominant period of construction and building footprint
Figure 71 Chelas urbanization in the present (1 – 1960´s, 2- 1970´s) – buildings height

The Telheiras neighborhood (Figure 72 and Figure 73) in its modern configuration appeared in the 70´s in its first phase built by EPUL (Lisbon Urbanization Company). At the time it was one of the first examples of incorporation of modern architecture elements and concepts from the late 20th century in urban planning in Portugal. The first core (1 on the map) that is comprised by three main axes of transportation, as a hierarchical road network with main avenues, primary streets and secondary streets (varying from 18-25 m) that distribute traffic accordingly; green areas spread among cores of buildings; mixed uses; various types of transportation and housing. According to Andrade and Alcoforado (2008:226), the initial plan predicted that 37% of the area would be occupied by green spaces and equipped with recreational areas and 13.5% by housing and services. There is a predominance of apartment buildings (medium and high rise) that form blocks in lines along the side of streets; single family buildings, others taken up by social facilities (Andrade and Alcoforado, 2008:226). The second core (2 on the map), grew mainly in the 90´s and 2000´s, and is already a deviation from the initial development of the oldest core, since the street network is less hierarchical and more linear, there are less green spaces, the block configuration is not so common being the buildings displayed in a linear way along main avenues, buildings are higher and thus the contact with the street tend to become less relevant, as is the diversity of activities.



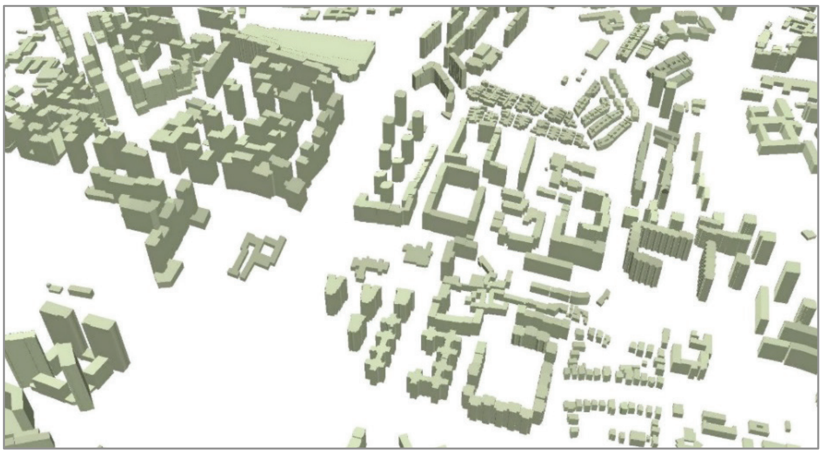
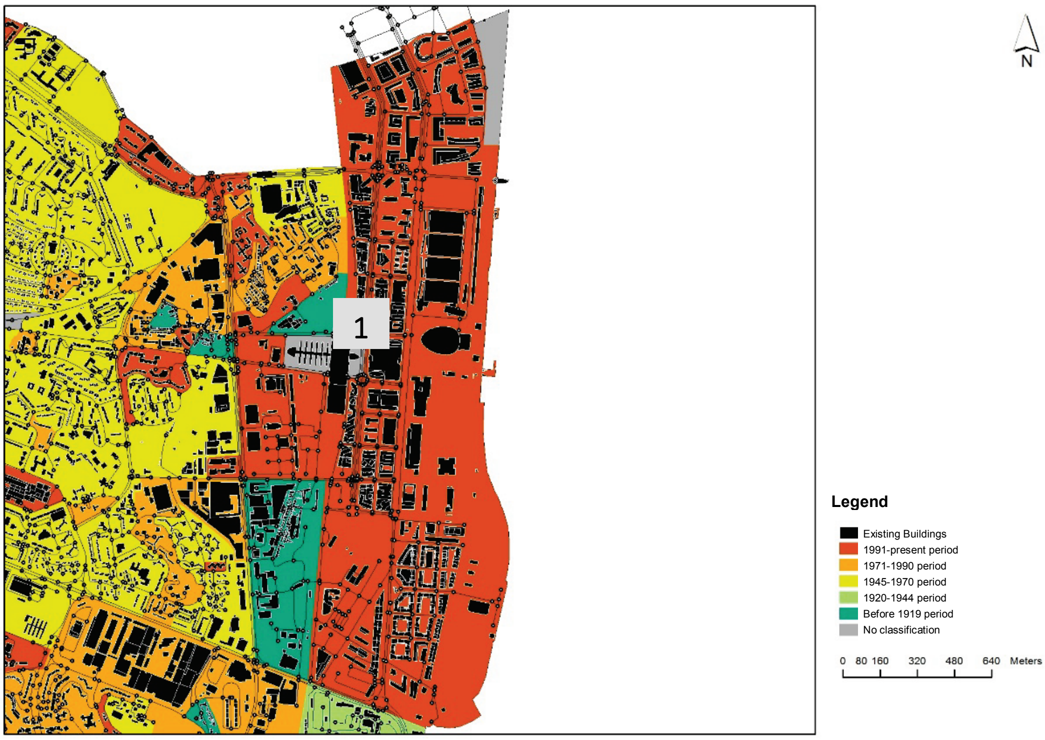


Figure 72: Telheiras Este [1] (built in the 1970´s) and Telheiras Oeste [2] (mainly built in the 90´s) - predominant period of construction and building footprint

Figure 73: Telheiras Este [1] (built in the 1970´s) and Telheiras Oeste [2] (mainly built in the 90´s) – buildings height

Parque das Nações (Figure 74 and Figure 75) is the newest urban area in the city of Lisbon, located in the Eastern part of the city, was the result of the World Expo 98. It was built from ground-up where before stood an industrial complex, and was the first neighborhood in Portugal to incorporate many principles and technologies associated with sustainable development, such are the Pneumatic Solid Waste Collection System and the District Heating and Cooling Network (Pedrosa, 2013:11). The design of Parque das Nações brought again the relevance of the building block organization, and the hierarchy in the street network, as well as public spaces with high quality standards, attributing a very important proportion of the construction area to green areas and relevant equipment's that are today landmarks in Lisbon as are the train station (Estação Oriente), concerts arena, theatre, oceanarium, among others. Transportation also received particular attention since the neighborhood is served by both train, metro and buses. Many high rise towers were built in the last years, which was not predicted in the initial plan, and are mainly for offices of both the state services and multinational companies, which contributed to the creation of one of the most important cores of employment, namely of the service sector in Lisbon. Population is mainly of high income, since the price of housing is very high (partially explained by all the amenities described before), even when compared with the city of Lisbon other high-income neighborhoods.



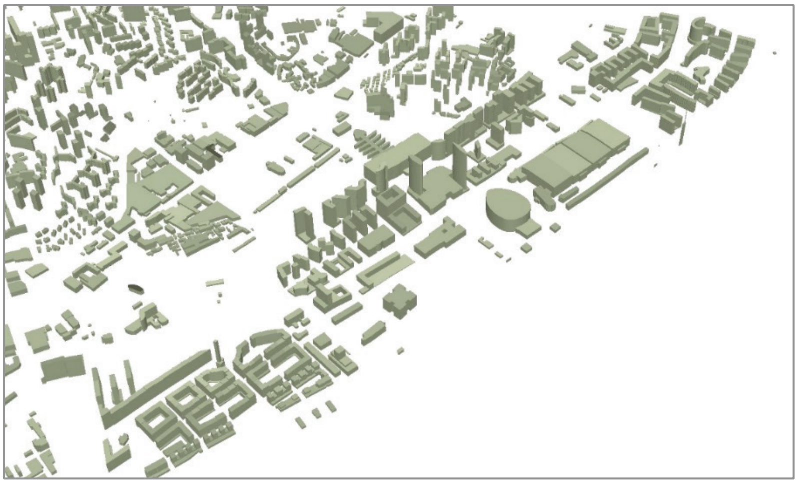


Figure 74: Parque das Nações (1998) - predominant period of construction and building footprint
Figure 75 Parque das Nações (1998) – buildings height

5.2 Lisbon energy profile

In Lisbon the majority of primary energy that was used was for the production of electricity (57%), followed by Diesel (21%), Natural Gas (14%), Gasoline (7%), GPL (1%), and others with less than 1% (Lisboa E-Nova, 2014:12). According to the Lisbon energy matrix (Lisboa E-NOVA, 2014:13), around 62% of the total primary energy that is consumed in the city is related to both the services and domestic sectors (43% in the services sector and 19% in the domestic sector). An important increase since the "Lisbon city Energy Matrix 2004" (E-Nova, 2009) where buildings had a total share of 50% of the city primary energy, with the services sector accounting for 34% and 16% in households (Figure 76).

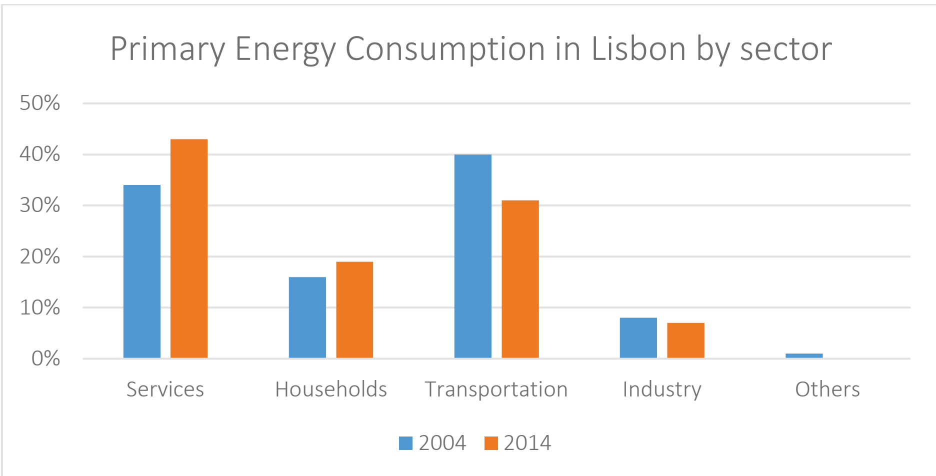


Figure 76: Primary energy consumption for the city of Lisbon according to the "Lisbon Energy Matrix"
Source: Lisboa E-Nova (2009) and Lisboa E-Nova (2014)

Carbon dioxide emissions from the building sector accounted for 58% of the total emissions in 2004 (40% in the services sector and 18% in households), and 54% of the total emissions in 2014. Despite the growth of the energy consumption in buildings registered from 2004 to 2014, the carbon dioxide emissions not only have not grown but they also decreased in what regards their share comparing with other sectors. This is explained by the integration of renewables or less intensive energy production energy sources for the production of electricity, and also to energy efficiency measures (Figure 77).

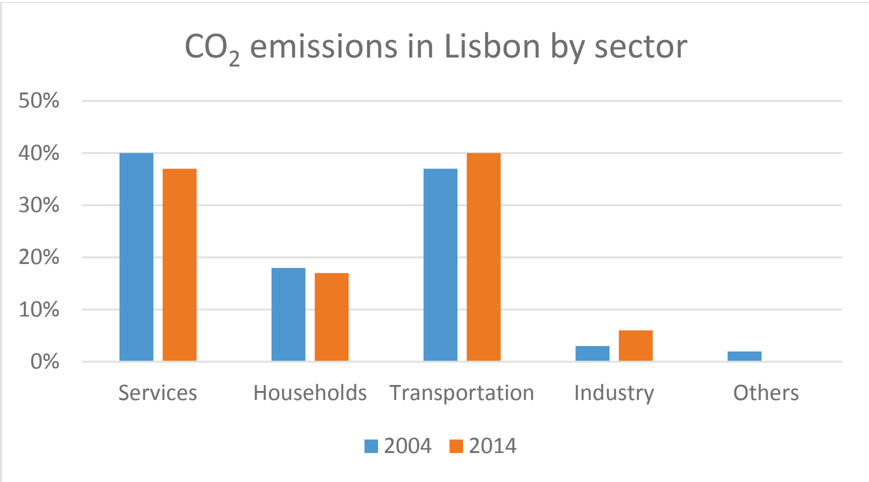


Figure 77: CO_2 emissions by sector for the city of Lisbon according to the "Lisbon Energy Matrix"
Source: Lisboa E-Nova (2009) and Lisboa E-Nova (2014)

In what regards the energy type used in buildings (services and households) the largest share is the electricity (82%), followed by natural gas (16%), being the other 2% divided by GPL, diesel and other. Looking specifically to the households, the share of energy type changes, since natural gas gains more importance (27% of the total energy consumption), and electricity represents 68%. Looking specifically into the share of primary energy in households by use (Figure 78), the main uses are for the kitchen and WC operations as are the water heating (20%), freezers and fridges (20%), meal preparation (14%) and washing (7%), that represent 61% of the total energy consumption; followed by space heating (18%), lighting (11%) and others (10%), which in the case of Lisbon according to Climaco (2015:15) are strongly influenced by the cooling energy needs.

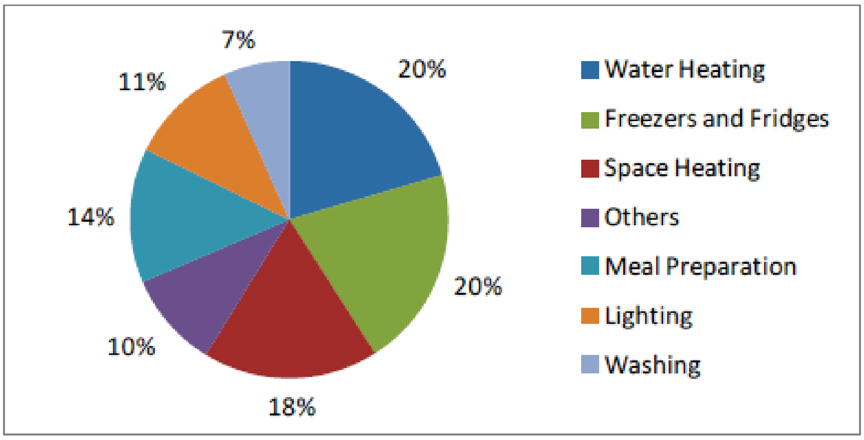


Figure 78: Lisbon - Primary energy consumption in households by end use
Source: E-Nova, 2009 (in Climaco:15)

According to DGEG and Pina (2016) Lisbon´s final energy consumption in the domestic sector in 2014 was 3930 kWh/m^2/year per household, if we consider 323.076 households in the city of Lisbon (INE, 2011). Taking into account this value, and considering an average size of the households in the Lisbon region is of 96 m^2 (INE, 2012), this results in 40,94 kWh/m^2/year of final energy consumption. If we look into the final energy consumption (by energy source) in the domestic sector since 2008, there is a general the tendency of decrease in the energy consumption until 2014 (Figure 79). The small increase from 2013 to 2014 might be related to the fact that data related to Butane, Propane and Diesel is not so robust therefore missing in some years.

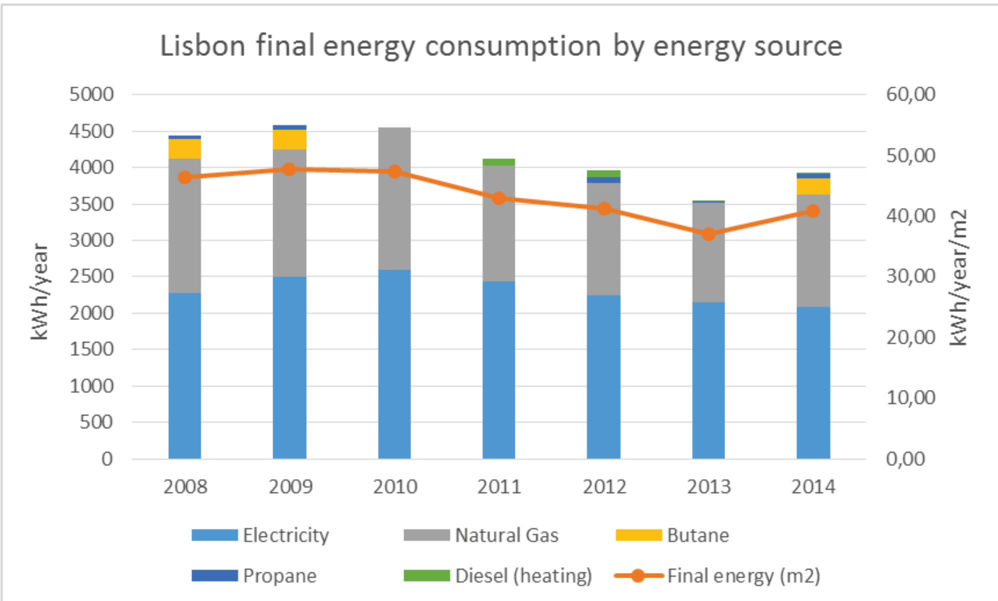


Figure 79: Lisbon final energy consumption by energy source
Source: DGEG and Pina (2016)

6. Urban Form analysis

6.1 Data used for the metrics calculation and contextualization

For the urban form analysis it was used a shapefile[14] with all the existing buildings in Lisbon from 2012 as the geographical base for the analysis. The existing buildings shapefile is composed of polygons that correspond to the buildings geometry in space, thus allowing a clear and detailed characterization of the urban form. Also very important for the urban form metrics calculation was the use of a shapefile with the existing buildings of Lisbon with detailed information regarding volume, height and number of floors from 2006. Other data that was used was the number of buildings by period of construction for each statistical sub-section of the city of Lisbon (obtained through the CENSOS 2011 database and merged with the ArcGIS shapefile of the statistical subsection division), in order to build and typify the various urban forms of the city of Lisbon. This data encompassed information from "before 1919" to 2011. In order to give more detail and clarification to the typologies and patterns identification, was used the urban atlas series for the city of Lisbon (EEA, 2010); the buildings typological classification; administrative limits (parishes both before 2011 and after 2011 with the new delimitation of the parishes boundaries); and road network (main avenues and streets often represent the limits from one neighborhood or parish to another). All the data that was used can be accessed in detail in the Appendix i.

6.2 Metrics used and calculation methods

Metrics were calculated in two groups. For the first urban form metrics were calculated using ArcGIS software and some layers of information: 2006 buildings shapefile (that contemplated information regarding the area of building, volume, height and number floors) and 2012 buildings shapefile (to cross check and consolidate with the second group of metrics); area of the typology layer (that comprehends a group of statistical subsections); and road network (with the streets length defined as attributes). Metrics were calculated both for the typologies and the city as a whole. For the second group of metrics, it was used an ArcGIS layer

[14] Shapefile: file type used in geographical information systems in a vector format used to represent spatial information

with Lisbon buildings information together with the Patch Analyst 5 software[15] (Rempel, Kaukinen, and Carr, 2012), an extension for ArcGIS that facilitates the spatial analysis of landscape patches, and modeling of attributes associated with patches. It is used for spatial pattern analysis, often in support of habitat modeling, biodiversity conservation and forest management. In this case it was applied to analyze urban patches, namely, buildings. The metrics that are used on the Patch Analyst 5 are based on the works of McGarigal and Marks (1994) and McGarigal and Marks (1995) and it was used the "spatial statistics" tool to calculate those metrics. The two groups of metrics can be viewed in full detail in Appendix ii. As it was made in the first group of metrics, two different calculations were made. One to access metrics at the level of the city, in which aggregate metrics were calculated for the city as a whole, and a second calculation was made for specific typologies of the city of Lisbon.

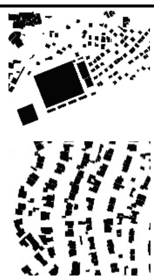
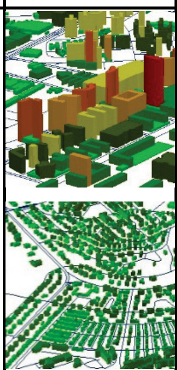
When performing the metrics calculation with the spatial statistics tool, 2 runs were made using 2 different attributes of the buildings 2012 layer (Shape Area and Shape Length), to understand if there were significant differences in the results. The tool was able to calculate metrics for the class (aggregate value for all polygons in a certain area) and also for each building polygon, presenting the same values both when using the area and the length of shapes. This was an expected result since most metrics take into account both perimeter and area of each shape. Two different sets of values are created with these calculations: one that corresponds to the metrics values that synthetize the information of the class (*aggregate metrics*), and other that has the metrics values for each building polygon (*building metrics*).

Apart from the metrics calculated with the Patch Analyst extension, two additional metrics were calculated to better explain the complexity of the urban form. That was the case with the Patch Density (PD) metric, to understand the dispersion of the urban form; and the Average Nearest Neighbor Distance (ANN) metric to understand the fragmentation of the urban form. The typologies total areas (that encompasses built and unbuilt areas) were derived from the ANN metric calculation. An urban typology usually doesn´t have an administrative limit that corresponds exactly to its borders, so the method that was used was to calculate the area of a box that would frame each typology urban form. That box was accessed through the ANN metric, namely the "Near Neighbor" tool, which in its method calculates the area of a box around polygons to understand their degree of fragmentation/compaction.

[15] http://cnfer.on.ca/SEP/patchanalyst/

Since a large number of metrics was calculated, and some of them only represent a statistical variation of the same meaning (e.g. mean patch size – median patch size), there was the necessity to synthetize the main metrics that could illustrate the fundamental dimensions of urban form. 10 metrics were selected and framed into four dimensions – Complexity, Heterogeneity, Compactness, and Density. This selection of both the 4 dimensions and the 10 metrics, was based on the literature review, namely on the most used metrics and dimensions by the majority of authors. The objective was to have a set of metrics that could characterize in full detail the complexity of the major dimensions of urban form – complexity, heterogeneity, compactness and density, and therefore contribute to current research on urban form with a new framework to quantify the material characteristics of urban form. (Table 19).

Table 19: The 4 dimensions and 10 metrics selected for the typological analysis
Source: Adapted from World Bank (2014), LSE (2014), Niza et al. (2013), McGarigal and Marks (1995)

Dimension	Spatial Representation	Description	Metrics	Units	Range
Complexity		Measures the building's design characteristics individually and as a whole at the neighborhood scale	- Mean Patch Fractal Dimension (MPFD)	-	1 ≤ MPFD ≤ 2
			- Edge Density (ED)	m./hect.	=/> 0
			- Surface-to-volume ratio (SVRatio)	-	=/> 0
Heterogeneity		Diversity of buildings sizes	- Patch Size Coefficient of Variation (PSCOV)	-	0-100
Compactness		Measures if the neighborhood is fragmented (clustered) with no or limited connection between its parts, or if there is a connection between buildings, therefore having a more compact design	- Patch Density (PD)	Build./Hect.	=/> 0
			- Average Near Neighbor (ANN)	-	ANN < 1 / ANN > 1
			- Coverage Ratio (CR)	-	0-1
Density		The vertical dimension of the neighborhood and the capacity to accommodate people, activities and transportation	- Floor Area Ratio (FAR)	-	=/> 0
			- Average height (AvHeight)	Meters	=/> 0
			- Road Density (RD)	m./sqm.	=/> 0

- Complexity

One of the most used metrics to explain complexity is the Fractal Dimension, both as Mean Patch Fractal Dimension (MPFD) (the average fractal dimension of a group – class – of patches) or the *Area Weighted Mean Path Fractal Dimension* (the average fractal dimension of the class of patches with individual patch area weighting applied to each patch) (Huang and Sellers, 2007:187; Herold et al, 2005:382). According to McGarigal et al (2012) "*the appeal of fractal analysis is that it can be applied to spatial features over a wide variety of scales*". Mandelbrot (1977, 1982) was responsible for the introduction of the concept of fractal – a geometric form that exhibits structure at all spatial scales – and proposed a perimeter-area method to calculate the fractal dimension of natural planar shapes. The perimeter-area method quantifies the degree of complexity of the planar shapes and the degree of complexity of a polygon is characterized by the fractal dimension (*D*), such that the perimeter (*P*) of a patch is related to the area (*A*) of the same patch by *P ≈ √AD* (i.e., log P ≈ ½D log A). For simple Euclidean shapes (e.g., circles and rectangles), *P ≈ √A* and *D = 1* (the dimension of a line), being that has for the polygons become more complex, the perimeter becomes increasingly plane-filling and *P ≈ A* with *D → 2* (McGarigal et al, 2012) (Equation 3).

$$MPFD = \frac{\sum_{Buildings} \frac{2 \ln p_{ij}}{\ln a_{ij}}}{nBuildings}$$

Equation 3: Mean Patch Fractal Dimension (MPFD)

According to Thomas et al. (2008:100) fractal behavior is associated with a scaling principle that governs how the constituent elements of a structure are distributed in space. The best way to illustrate this property is to look at how a theoretical fractal is constructed by iteration – the Fournier Dust (Figure 80). The initiator is the square a) that has a length of *l0* that is reduced by a factor *r*= ¼ into *N*=8 elements. The square b) is called a generator that has smaller replicates of the initiator with base length *l1 = rl0*. The square c) is the first iteration and is obtained after repeating the process. According to Thomas et al. (2008:100) "*The hierarchical aspect becomes obvious as smaller and smaller elements lying closer and closer together are generated in further steps*" which shows that the "[…] *clusters* […] *are distributed in a non-uniform way since the spaces separating the clusters are different*". This means that as the distribution in space becomes more heterogeneous so the fractal dimension decreases (in this case the less similar the width of the lanes) and vice-versa.

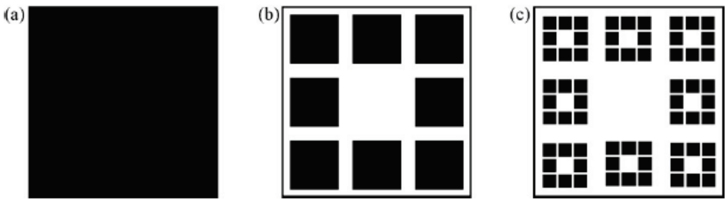


Figure 80: First steps in generating a Fournier dust: initiator (a), generator (b) and first iteration (c)
Source: Thomas et al (2008:100)

The Fractal Dimension (*D*) does not depend on the shape of the initial figure, or on the position of the elements in the generator, but on *N* (number of elements) and *r* (reduction factor) and the spatial hierarchy that is linked to the number of clusters. Comparing fractals that consist of one cluster, the Sierpinsky carpets as they are called (Thomas et al. 2008:101), with the Fourier dust, it is possible to see that in fig. a) all the lanes separating the black squares have the same width, which is not the case with fig. b) where the lanes follow a well-defined hierarchy, and more than one cluster. The stronger the spatial hierarchy the lower the fractal dimension. This can be seen looking at both generators on a) and b) which applying different reduction factors façade tend to produce different *D* values (*D*=1.89 for Sierpinski carpet and *D*=1.50 for the Fourier dust) (Figure 81).

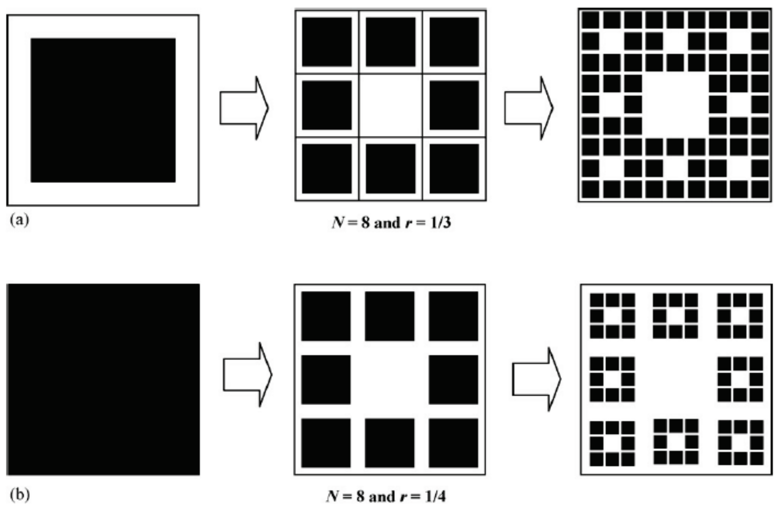


Figure 81: Two generators with identical Ns, but different reduction factors, r, forming a Sierpinski carpet (a) or a Fournier dust (b), depending on the initiator.
Source: Thomas et al (2008:101)

The Edge Density (ED) is the amount of edge regarding the area of each typology. It is calculated according to:

$$ED = \frac{\sum_{Buildings} TE}{TLA}$$

Where:

TE = the Total Edge (sum of all edges of a building)

TLA = the Total Landscape Area (equal to the area of the typology)

Equation 4: Edge Density (ED) calculations

It is a complementary metric to the MPFD, since it also indicates a degree of complexity of the urban form. Typologies with a high ED have a more complex urban form, since their buildings have many edges and thus more irregular forms, whereas a low ED means a less complex and more linear urban form, in which buildings have a low amount of edges, being more regular.

The Surface-to-Volume ratio (SVRatio) is the ratio of the surface of a building (external facades and roof), *S* (m2), to the entire volume of that building, *V* (m^3):

$$SVRatio = \sum_{Buildings} \frac{S}{V}$$

Where:

S = Surface Area

V = Volume

Equation 5: Surface-to-volume ratio (SVRatio)

Source: (adapted from LSE, 2011:2-1)

The SVRatio is often called Shape Factor, and is associated with the Volumetric Compactness concept, that is one of the form factors that is more useful in a thermal analysis of buildings since it has a direct impact in their theoretical heating needs. According to Salat (2011:489) the Volumetric Compactness is the product of two factors: the *size factor*, corresponding to the edge length of the equivalent cube ($V^{1/3}$) and the *form factor*, which is adimensional and from which the bias introduced by the size of the analyzed objects has been removed ($C= S/V^{2/3}$). According to LSE (2011: 4) in the 4 cities that this study analyzed – London, Berlin, Paris, Istanbul – the "*Surface-to-volume ratios of compact urban blocks are relatively low and typically in the region of 0.25*" (Figure 82).

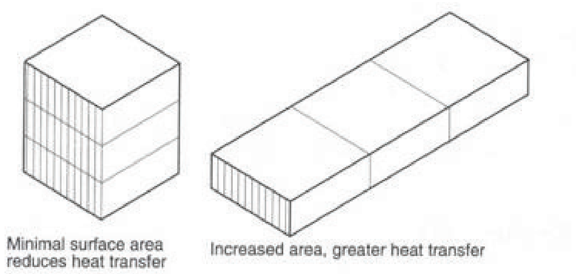


Figure 82: Example of different SVRatios
Source: CLEAR (2013)

It is a very important metric on urban energy analysis since "*The ratio indicates the potential for interactions with the exterior environment through natural ventilation and sunlight* [being that] *when this ratio is high, the heat losses in winter are high but the solar gains are high too*" (Salat, 2011:174). The metric needs always to be analyzed together with the local climate specific characteristics, since a low or high SVRatio can contribute positively or negatively to energy consumption depending on the climate variables. For the SVRatio calculation, four important variables that were available for each building were used: building area, building perimeter, building height and building volume. The building volume was already available in the ArcGIS layer attributes table and corresponded to the building area (m^2) x height (m). The Surface Area (m^2) value was not available and was calculated. Since for the calculation of the surface area only the exterior walls are taken into account (not the ones that are shared between buildings) the "Polygon Neighbor" tool for ArcGIS 10.1 was then used to calculate the length of the shared walls only. The value of the shared walls was subtracted to the building total perimeter value, resulting in the formula (Equation 6).

$$Surface\ Area = \sum_{Buildings} \big((EWP\ x\ BH) + BA\big) - SW$$

Where:

EWP = Building External Walls Perimeter (m)

BH = Building Height (m)

BA = Building Area (m^2)

SW = Shared Walls (m^2)

Equation 6: Surface area calculations

- Heterogeneity

The Patch Size Coefficient of Variance (PSCoV) is the coefficient of variation of patches. It is calculated according to:

$$PSCoV = \sum_{Buildings} \frac{PSSD}{MPS} \times 100$$

Where:

PSSD = the Patch Size Standard Deviation

MPS = the Median Patch Size

Equation 7: Patch Size Coefficient of Variance (PSCoV) calculations

It corresponds to the variance in each typology area of the sizes of the buildings, and is a good indicator of the heterogeneity of buildings sizes across a certain typology. Typologies with a high PSCoV typically have very large buildings (Universities, Hospitals, Shopping Centres, etc) together with detached housing or small to medium size apartment buildings. On the contrary a low PSCoV indicates that the majority of buildings are of the same size.

- Compactness

Coverage ratio is defined as "[…] *the ratio of the sum of the building footprint areas to that of the sample area*" (LSE, 2014:4). It was calculated through:

$$CR = \frac{\sum_{Buildings} BftA}{TA}$$

Where:

BftA = Building Footprint Area (m^2)
TA = Typology Area (m^2).

Equation 8: Coverage ratio (CR) calculations

Source: LSE (2014)

The building footprint area value was obtained through the Class Area metric that calculated for each typology the area of each patch (building). Generally it indicates if the urban form is more space filling, thus occupying the typology area, or on the contrary if it corresponds to a fraction of the typology area, and thus it is not so important. Compact urban blocks generally occupy the same coverage ratio band of between 50% and 75%.

Patch Density has been used in other works to explain the urban compactness/dispersion (Herold et al, 2003; Herold et al, 2005; Niza et al, 2013). A low patch density corresponds to highly dispersed areas, as there are a low number of patches per area, and a high patch density corresponds to more concentrated areas, as there are a high number of patches per area.

$$PD = \frac{NumP}{TA}$$

Where:

NumP= Number of buildings of the urban typologies
TA = Total Land Area of the typology (hectares)

Equation 9: Patch density (PD) calculations

Fragmentation is explained by the Average Nearest Neighbor Distance (ANN). This metric and similar have been used in other works to explain this dimension (Herold et al, 2005; Niza et al, 2013). The Nearest Neighbor Index is expressed as the ratio of the observed mean distance to the expected mean distance. The expected distance is the average distance between neighbors in a hypothetical random distribution. If the index is less than 1, the pattern exhibits clustering; if the index is greater than 1, the trend is towards dispersion or competition.

The Average Nearest Neighbor ratio is given as:

$$ANN = \frac{\bar{D}_O}{\bar{D}_E} \quad (1)$$

where $\bar{D}_O$ is the observed mean distance between each feature and its nearest neighbor:

$$\bar{D}_O = \frac{\sum_{i=1}^{n} d_i}{n} \quad (2)$$

and $\bar{D}_E$ is the expected mean distance for the features given in a random pattern:

$$\bar{D}_E = \frac{0.5}{\sqrt{n/A}} \quad (3)$$

In the above equations, d_i equals the distance between feature i and it's nearest neighboring feature, n corresponds to the total number of features, and A is the area of a minimum enclosing rectangle around all features, or it's a user-specified Area value.

The average nearest neighbor z-score for the statistic is calculated as:

$$z = \frac{\bar{D}_O - \bar{D}_E}{SE} \quad (4)$$

where:

$$SE = \frac{0.26136}{\sqrt{n^2/A}} \quad (5)$$

Equation 10: Average Nearest Neighbor (ANN) calculations
Source: ArcGIS (2016)

A low ANN ratio corresponds to areas which are highly fragmented, and thus clustered, since most patches are located far away from each other but tend to group into clusters, and a high ANN ratio correspond to more homogeneous areas where patches present a more space filling pattern. The ANN metric was calculated with the Arcgis 10.1 software, namely through the following method: *1) Average Nearest Neighbor Tool; 2) Feature to Point Tool; 3) Point Density Tool*. The *1) Average Nearest Neighbor tool* calculates a nearest neighbor index based on the average distance from each feature to its nearest neighboring feature (ArcGIS, 2010). The tool indicates if the points (buildings) are more clustered (fragmented), randomly distributed, or dispersed (space filling). Since the scale that is being used in this analysis is very small (high resolution), caution should be made in analyzing the results in order for them to illustrate correctly the reality. If in an abstract way the clustering/dispersion patterns that the tool indicates are correct, when they are used to understand local urban dynamics, as it is this case, a proper context-specific analysis shall be made: e.g. in what regards the clustered pattern, if we are analyzing a group of cities (each one corresponding to one point) it indicates that at the metropolitan scale, there is little fragmentation of the urban form, but if we look into a neighborhood (where each point is a building) the result is the inverse; the same with the dispersion pattern, when looking into a metropolitan area it corresponds to a dispersed urban form, but when looking into a neighborhood we are looking to an homogeneous and space filling distribution. Other important factor to the ANN result is the overall urban form of each typology – more elongated urban forms tend to have lower ANN results (more clustered), and more circular urban forms tend to have higher ANN results (more dispersed) because a greater distance is registered in the first since the edges of the urban form are farther from each other (Figure 83).

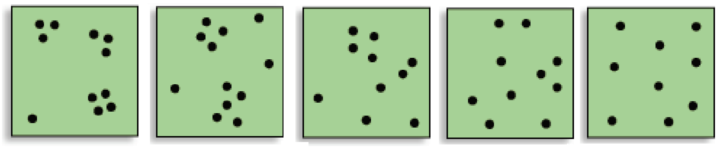


Figure 83: Examples of patterns that are analyzed by the Average Nearest Neighbor tool – from clustered (left) to dispersed (right)
Source: ArcGIS (2010)

The ANN tool calculates, given a certain study area (that in this case was established in an automatic way for all areas, and that corresponded to the area of the minimum enclosing rectangle that would encompass all buildings of each typology (Figure 84), the observed mean distance, the expected mean distance and the nearest neighbor ratio. It also calculates the significance level (p-value) and the critical value (z-score), in order to give the significance value of the result (Figure 85).

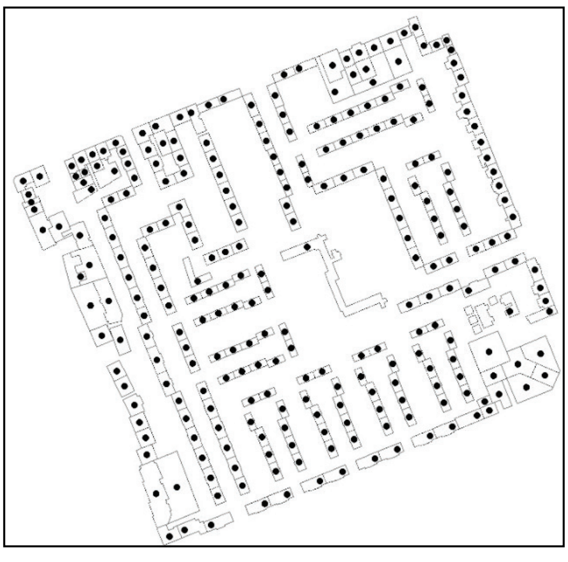
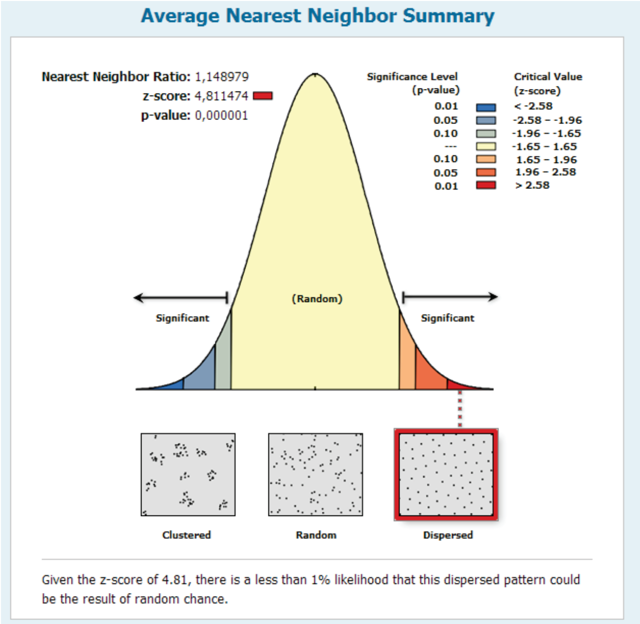


Figure 84: Example of the area window that the tool uses to compute the study area that is used to calculate the observed mean distance, the expected mean distance and the nearest neighbor ratio.



Average Nearest Neighbor Summary

Observed Mean Distance:	6,820945
Expected Mean Distance:	5,936528
Nearest Neighbor Ratio:	1,148979
z-score:	4,811474
p-value:	0,000001

Dataset Information

Input Feature Class:	TIPOLOGIAS_EXEMPLO1\edificios_antes1919_sample
Distance Method:	EUCLIDEAN
Study Area:	40176,292286

Figure 85 Sample results window of the Average Nearest Neighbor Tool.
Source: Produced by the author/ ArcMap 10.1

To better explain spatially the clustering/dispersion tendencies that were observed the buildings centroids were converted to points with the (*2) Feature to Point Tool* and then the *3) Point Density Tool*, was used to illustrate spatially the clustered zones and the dispersed ones.

- Density

Road density is a country´s total road length dividing by total land area expressed in km/100 km^2. In this case, since the area that is being analyzed is very small compared to a country area, the unit that was used was the meter (*m*):

$$RD = \frac{\sum_{Roads} TRL}{TLA}$$

Where:

TRL = Total Road Length

TLA = Total Land Area

Equation 11: Road Density (RD) calculations
Source: World Bank (2014)

The total road length (*TRL*) was calculated through the calculate geometry function of ArcGIS, that calculated for each typology road shapefile the length of each line, and then summed them all.

Floor area ratio (FAR) is defined as the "[…] *total number of m^2* […] *of floors divided by the area of the plot*" (Salat, 2011:490):

$$FAR = \sum_{Buildings} \frac{BFA}{BftA}$$

Where:

BFA = is the building floor area (m^2)

BftA = is the building footprint area (m^2)

Equation 12: Floor Area Ratio (FAR) calculations
Source: Salat (2011)

This metric is often used to explain density. In the case of the LSE study (2014), the building densities of compact urban blocks ranged between FAR 1.5 and 2.5, with the significant exception of Paris (FAR 4.5 – 5.2). The lower density levels of compact urban blocks were observed in Istanbul and London, with FARs between 1 and 1.3.

Finally, Average height (AVHeight) is, as the name suggests, the average of the heights of all buildings in the typology area:

$$AVHeight = \frac{\sum_{Buildings} TBH}{TNB}$$

Where:

TBH = the total building height

TNB = the total number of buildings

Equation 13: Average Height (AVHeight) calculations

According to LSE (2014:8) this indicator is very useful in an urban energy analysis particularly "*Average building height was found to be the best indicator of heat energy demand. This variable was found to best fit a logarithmic relationship, with heat energy demand decreasing with increasing height*".

6.3 Identification of urban typologies

To identify the main typologies of the city of Lisbon, it was used the Census 2011 information regarding number of buildings by period of construction, an information that was available at the statistical sub-section scale (normally comprises an area similar to the block). Also, it was used geographical information from the Lisbon Municipality regarding the existing buildings stock (buildings 2006 and 2012 layers), and that was transformed in a way that irrelevant information for the characterization of the urban form was made inactive (metro stations and underground parking for instance). A statistical analysis was made, which selected for each statistical subsection the period of construction which had the highest number of buildings associated, in order to identify the most common period in each statistical sub-section. Statistical sub-sections which had a null value, were classified regarding the period of construction by analyzing the neighboring polygons urban characteristics and historical data. The same statistical analysis was made now taking into account the five periods of construction that were identified has being representative of the main built form dynamics of the city of Lisbon: <1919, 1919-1945, 1946-1970, 1971-1990 and 1991-present. The repetition of this analysis for the aggregation of periods of construction into classes was important, since the grouping of those periods lead, in certain cases, to different predominance's (Table 20).

Table 20: Example of predominance analysis for one statistical subsection, taking into account all INE classes regarding period of construction, or taking into account the selected groupings of classes

All classes	Before -1919	1920-1945	1946-1960	1961-1970	1971-1980	1981-1990	1991-1995	1996-2000	2001-2005	2006-2011
N Builds.	6	2	0	0	0	1	1	3	0	4
5 Classes	Before -1919	1920-1945	1946-1970		1971-1990		1991-2011			
N Builds.	6	2	0		1		8			

Then the *select attribute* option in the attributes table of ArcGIS was used to create 5 layers each one comprising one of the periods of construction identified. An additional layer was created for the statistical subsections which didn´t had any building. These periods of construction that were chosen to define the urban typologies were selected based on the following criteria:

- Analysis of the main socio-economic and morphologic dynamics of the city of Lisbon during the 20th century;
- Lisbon building stock evolution through its typological classification;
- Available data: statistical information about the number of buildings by period of construction at the sub statistical level was only available in the following data series: before 1919, 1919-1945, 1945-1960, 1960-1970, 1970-1980, 1980-1990, 1991-1995, 1996-2000, 2001-2005, 2006-2011.

With the 5 shapefiles created, the *Dissolve* tool was used to merge all polygons of the same period, and then the *clip* tool was used to clip all the existing buildings into the areas that comprised each period (Figure 86):

1) Data: Shapefile period of construction and Shapefile number of buildings by period of construction and statistical subsection;
2) Normalize all the 0´s values through neighborhood analysis;
3) Statistical analysis to define predominant period of construction for all periods and for defined classes
3) Select by attributes to create a shapefile for each “aggregate” period of construction (no buildings, before 1919, 1920-1945, 1946-1970, 1971-1990, 1991-present);
4) Dissolve polygons to create an homogenous area for each class;
5) Clip the existing buildings layer into that area in order to have the respective buildings/period construction.

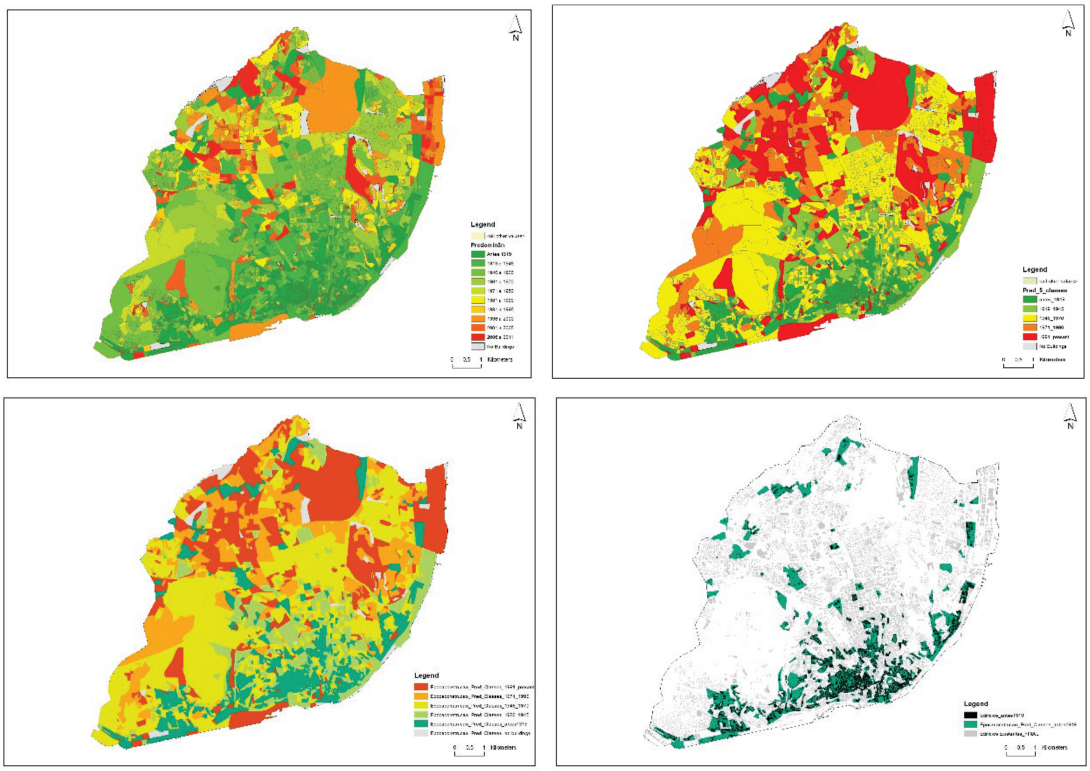


Figure 86: Method used to spatially define predominant periods of construction (colours indicate different periods of construction) - 1) Predominant period of construction by substatistical section according to INE classes; 2) Predominant period of construction by substatistical section according to the defined periods of construction; 3) Merged areas with the same period of construction; 4) Example of the buildings that correspond to the "before 1919" period of construction class

Source: Produced by the author (data is from INE, 2011)

The selection of the sample areas for each typology (that aggregate many statistical subsections) was based on similar analysis made by Thomas et al. (2012) that took into consideration their morphology, predominant function (activities or residential), road network (identification of main roads that divide different typologies) and historical information. Quantitatively the selection was based on a predominance analysis regarding the period of construction by sample area. Only areas that had a predominance of 50% or higher of the period of construction that was being analyzed were selected, to ensure that there was a strong representativeness of the buildings that characterize that period (Figure 87). To ensure this result a statistical analysis was made that took into consideration the proportion of all the buildings that were being analyzed in that area regarding the buildings of the specific period of construction that was being analyzed (Appendix iii). Other important aspect is that of the difference in size between the typological examples. Normally, the size of the sample areas is smaller in more traditional typologies than in more modern typologies, and this is strongly related with the buildings characteristics but also the road network: historical dense urban contexts tend to have smaller buildings, with smaller living areas and number of divisions, and a road network comprised of streets with only one circulation lane for each side or even only for pedestrians, when in more recent typologies it is more common large avenues and larger buildings.

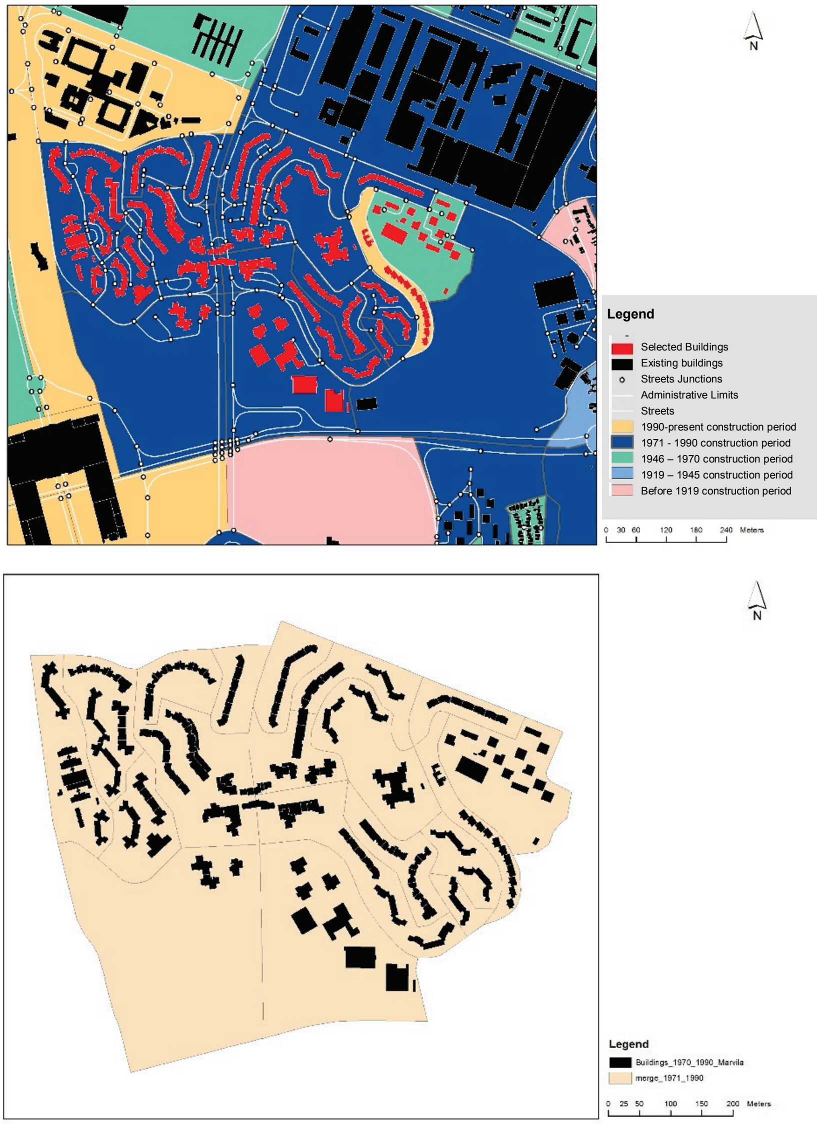


Figure 87: Method used to define urban typologies - 1) Identification of typology based on urban form design, road network and predominant period of construction; 2) Resulting case study
Source: Produced by the author (data from INE, 2011)

6.4 Statistical analysis of metrics

Metrics were analyzed both at the intra-typology scale, regarding the proportion of each typological sample value regarding the typology average to understand how urban forms of the same period performed between them; and was also made an inter-typologies analysis comparing their averages and also comparing with the results for the city of Lisbon as a whole (chapters 8.1.1 and 8.1.2). A Pearson correlation analysis was made (two tiers) to access the level of correlation between metrics (chapter 8.1.3). Finally a Hierarchical cluster analysis was made to the 10 metrics across the 25 typologies (chapter 8.1.4). All values were normalized before both the correlation and cluster analysis, due to the huge discrepancy in the values magnitude: e.g. fractal dimension values normally range in a scale of 0-2, while edge density values don´t have a limit and normally are from 1000´s up. Values where normalized with IBM SPSS Statistics, through the "*Descriptives*" tool that converted the values into Z-scores.

The hierarchical cluster method was the chosen method since it allows understanding how and when each typological sample grouped with one another, but also how typological samples grouped when defined a set of clusters. This was important since the objective was to assess if maintaining 5 groups – as was the case in the period of construction – the metrics would group the same way (according to period of construction) or not, thus allowing to understand if there were common design characteristics of a certain period, or if design varies even in urban areas of the same construction period, and also allowing to understand what are the key design variables that contribute to the results. The hierarchical cluster method is used typically in situations where there isn´t a large amount of data, as this is the case. This method has already been used to identify urban typologies at the municipality scale (Marques da Costa, 2009), city scale (Huang and Sellers, 2007; Schwarz, 2010), and neighborhood scale (Song et al., 2013). The Ward´s method was chosen, with the interval through the squared Euclidean distance. This method was also used by Schwarz (2010) and Song et al. (2013) and is very precise and efficient, since cluster membership is assessed by calculating the total sum of squared deviations from the mean of a cluster (Burns and Burns 2009:557). A cluster membership table was produced in a solution with 5 clusters, also an agglomeration schedule and proximity matrix tables were created. The 5 resulting typologies are characterized in chapter 8.2 Analysis of the selected case studies.

7. Urban Energy Analysis

7.1 Data and software used in the urban energy analysis

The urban energy analysis seeks to develop and expand the methodological approach of Ratti et al. (2004), Salat (2009), Salat (2011) and LSE (2014). It analyzes the impact of urban form on the heating and cooling energy needs of selected typologies, while maintaining the other variables that contribute to energy needs constant. It will use the previous calculated urban form metrics as context variables, and will expand the urban-energy analysis with the passive volume ratio, envelope radiation, continuous daylight analysis and operational energy metrics. The objective is to assess, while analyzing solely the urban form, if there are differences in the energy related variables of selected urban typologies. The ArcGIS shapefile that was used to access the urban form metrics of chapter 6. Urban Form analysis, was imported to Rhino 5, using a grasshopper component created by Cerezo and Irani of MIT. The ArcGIS shapefile represents the buildings of each one of the 5 typologies in 3 dimensions, as well as the buildings that constitute the context of the typologies. It was important to incorporate the context of each typology since it influences by shading effect the radiation that the typologies buildings receive during the year, and consequently their energy consumption. Passive volume ratio was calculated with ArcGIS 10.2, envelope radiation and continuous daylight analysis were calculated with the Urban Daylight plugin of Rhino 5.

In what regards the heating and cooling energy needs, it was used the UMI plugin for Rhino 5, where the following variables were defined: climate (local climate conditions throughout the year); urban form (buildings geometric properties); buildings structure and systems (constructions materials, equipment's); and behavior (building schedule of occupation and type of occupation).

7.2 Passive and non-passive volume ratio

It was calculated through ArcGIS 10.1, and according to Equation 2 (Explanation of passive volume ratio calculations) namely through the *buffer analysis tool*, and the *clip tool*. The passive volume is very important in an urban-energy analysis since it allows to understand what is the ratio of the area of a certain building (and when extrapolated a typological sample) that corresponds to the passive energy area definition, that is, an area that is situated up till 6 m from the window, and thus that has natural ventilation and solar radiation. According to Ratti et al. (2005:772) "*Parts of buildings within 6 m of a façade present a significant reduction in energy consumption (almost 50%) compared with non-passive ones*". It continues saying that the order on the energy consumption values that they obtained had a reverse order compared with the surface-to-volume ratio, meaning that "[…] *heat losses through the building envelope are not the most prominent component of the total energy budget in buildings. On the contrary, the passive to non-passive area ratio seems a better indicator of energy consumption*" (Ratti et al. 2005: 773). Passive volume ratio results are available in chapter 9.1 Passive and non-passive volume ratio.

7.3 Urban daylight analysis

The exposure to sun radiation is of critical importance in assessing the impact of the urban form on energy performance since "*Heating and cooling loads are obviously* […] *greatly influenced by solar radiation*" (Franzetti et al. 2004 in Dogan et al. 2012). Ratti etl al (2005) used the Lighting and Thermal Model (LT Model) to estimate energy consumption in urban typologies through 4 variables. Apart from the passive/non passive zones concept, three urban geometry variables that greatly influence the energy performance were used: orientation of the façade, urban horizon angle and the obstruction sky view. The Urban Daylight plugin incorporates these three variables for the calculations of the daylight availability and envelope radiation since it takes into account the local climatic conditions (and thus the buildings relation to sun), but also the spatial relation of the buildings between themselves and that proportionate areas with a higher or lower shadow density due to proximity effect. According to LSE (2014:1-8) "[…] *research has produced evidence that increased solar gain is associated with reduced built densities, while at the same time leading to greater heat losses*", quoting also Steemers (2003) that highlighted a 22% increase in heating energy for 30º obstruction of a south-facing façade compared with an unobstructed façade and Yannas (1994) that found 40% higher heating savings when comparing apartments with detached housing, and concludes that building densities with a theoretical FAR of 2.5 might represent the optimum density for reducing heat energy demand.

For the daylight availability calculation it was used the UrbanDaylight plugin for Rhino5 and Grasshopper plugin. The Urban Daylight plugin for Rhino 5 was a plugin created by Dogan, Reinhart and Michalatos (2012), with the objective of allowing "[…] *designers to simulate and evaluate the daylight potential of urban master plan proposals*". The plugin simulates hourly solar radiation levels on all facades of an urban scene based on the Radiance/Daysim software; then exterior radiation levels are converted into hourly interior illuminance distributions using a generalized impulse response; climate based daylighting metrics are computed also as it is the daylight autonomy metric. Three types of geometric elements can be computed into the simulation: buildings, blockage and shading. The builder menu creates horizontal sections to represent floor plates and mesh the floors and inputs Breps [16] to create sensor points for the simulation. Several inputs are needed to complement the geometrical information of buildings:

- Building information: Floor subdivision (stipulate floor height); Façade Opening Ratios;
- Daylight: Target Illuminance, namely Perimeter [lux] and Core [lux] (usually are between 300-500 (ArchSim, 2016)) and tolerable maximum [lux]; Blind Systems, namely what is the limit above which the blinds are pulled to reduce illuminance (default set to 10000 lux) and the fraction of light that passes the blind system (default set to 0.5%);
- Meshing parameters: Envelope Resolution, the average sensor point distance on the façade (set to 2); Rad File Resolution, that sets the meshing resolution of the simulation scene geometry (set to 0); Floor Resolution, that controls the interior sampling rate (Set to 2).

Blockage geometry can be used to model contextual buildings that directly touch the analysis building units, and shading geometry is used to model arbitrary contextual geometry (e.g. trees). The settings menu allows for other contextual information on the simulation such as the climate data file (set to Lisbon epw. file), the number of hours that are taken into account in the simulation (set to a complete year = 8760 hours), the radiance parameters (set to default) and the simulation steps (*Files* writes out additional sensor point data and hour illuminance profiles for the interior; *Rtrace* controls the DAYSIM simulation; *Impulse* controls the light-solver). Regarding the radiance parameters: AB = set the number of ambient bounces (set to 3); AD = Set the number of ambient divisions (set to 1024); AS = Set the number of ambient super-samples (set to 512); AR = Set the ambient resolution (set to 256); AA = Set the ambient accuracy (set to 0.1). Three metrics are calculated: Continuous Daylight Autonomy (CDA); Spatial Daylight Autonomy (DA), and Envelope Radiation (ER).

The Spatial Daylight Autonomy (DA) metrics is based on the IES Daylight Metrics Committee that has the objective of assessing "how much "of a certain" space or building is adequately illuminated. It is therefore a metric that evaluates the daylight sufficiency with a threshold of

[16] Brep: Boundary Representation, a computer design method used to represent shapes using their limits.

50%, that means that a certain illuminance threshold has to be achieved at least 50% of the occupied hours to consider a space adequately daylit (Reinhart et al., 2006) (Figure 88).

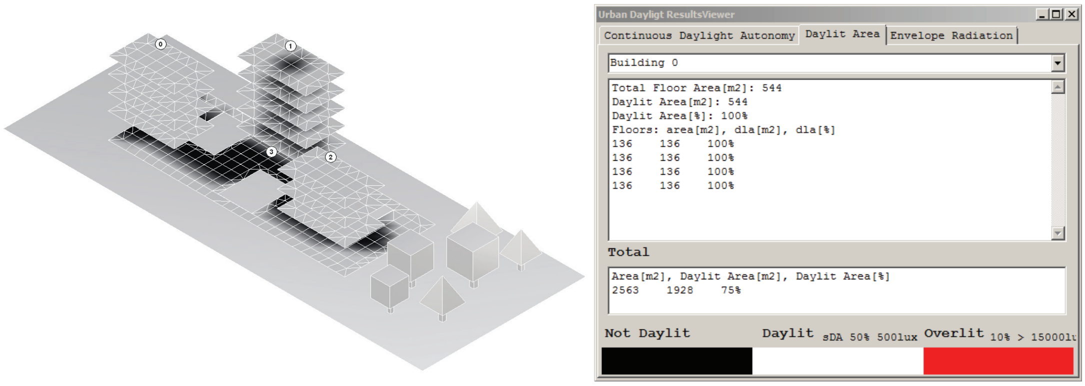


Figure 88: Spatial daylight autonomy metric
Source: Reinhart et al. (2006)/UMI (2016)

The CDA metric was based on the Reinhart et al. work (2006). The CDA value corresponds to the percentage of the floor area that exceeds 500 lux (value defined) for at least 50% of the time giving a partial credit for time steps below 500 lux (Figure 89). Contrary to the Spatial Daylight Autonomy (DA) the CDA takes into account the underperforming areas of buildings. For example, say a certain interior grid point has 150 lux due to daylight at a given time step, DA with 300 lux would give it 0 credit for that time step whereas CDA with 300 lux would give it 150/300=0.5 credit for that time step (Figure 90).

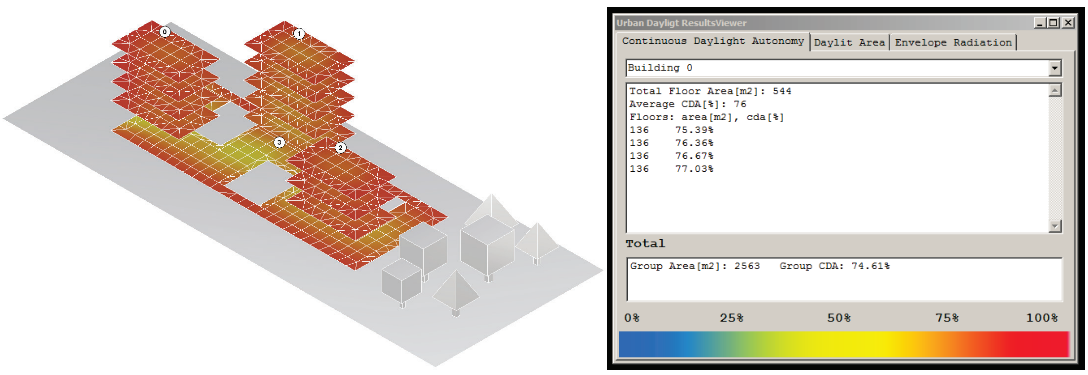


Figure 89: Continuous daylight autonomy metric
Source: Reinhart et al. (2006)/UMI (2016)

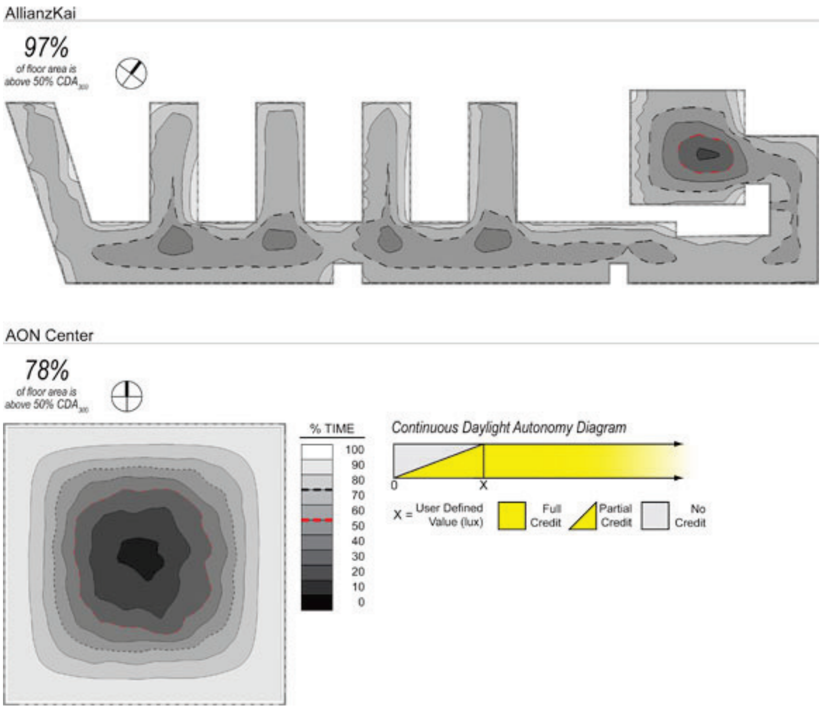


Figure 90: Continuous daylight autonomy metric example
Source: Advanced Buildings (2016)

The Envelope Radiation (ER) metrics assesses the accumulated solar radiation (Mlux) for a given time frame, in this case for 1 year. Apart from the total values, the ER metric was also calculated proportionally to the area of the façade of the selected typologies buildings (Figure 91).

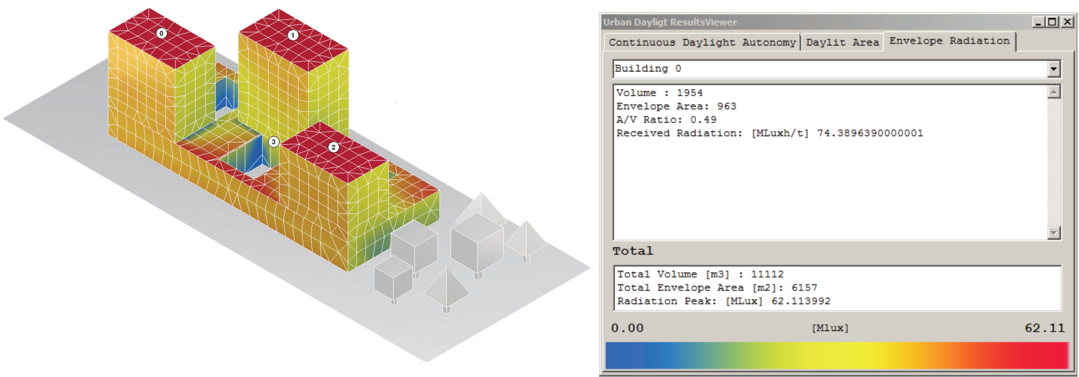


Figure 91: Envelope Radiation metric
Source: UMI (2016)

Urban daylight results are available in chapter 9.2 - Urban daylight analysis.

7.4 Modelling thermal energy needs

Urban form (namely, the buildings shapes factors and their spatial relation with one another) and its relation with the heating and cooling energy needs will be accessed through the Urban Modelling Interface (UMI) plugin for Rhino5. It is a Rhino tool developed at MIT in the Sustainable Design Lab[17], with the objective of analyzing the energy consumption (operational and embodied), walkability and daylight potential of neighborhoods and cities. For this thesis only the operational energy module was used. The urban typologies that were analyzed in UMI were imported to Rhino through a model designed in Grasshopper by Carlos Cerezo and Ali Irani (MIT) that converted the ArcGIS shapefiles into a Rhino-based format, including the import of 4 attributes from the shapefiles attributes tables to Rhino format. UMI requires the specification of a *local climate file* and a *building template file* in order to characterize in detail the specific urban typology that is being analyzed.

7.4.1 The UMI climate file

The climate file (.epw[18]) that was used was the one for Lisbon (Lisboa LNEG-DGEG) for the reference year of 2011. The data series indicated an average temperature of 16,9 ºC, a maximum average temperature of 25,3 ºC and minimum average temperature of 8,5 ºC (Figure 92).

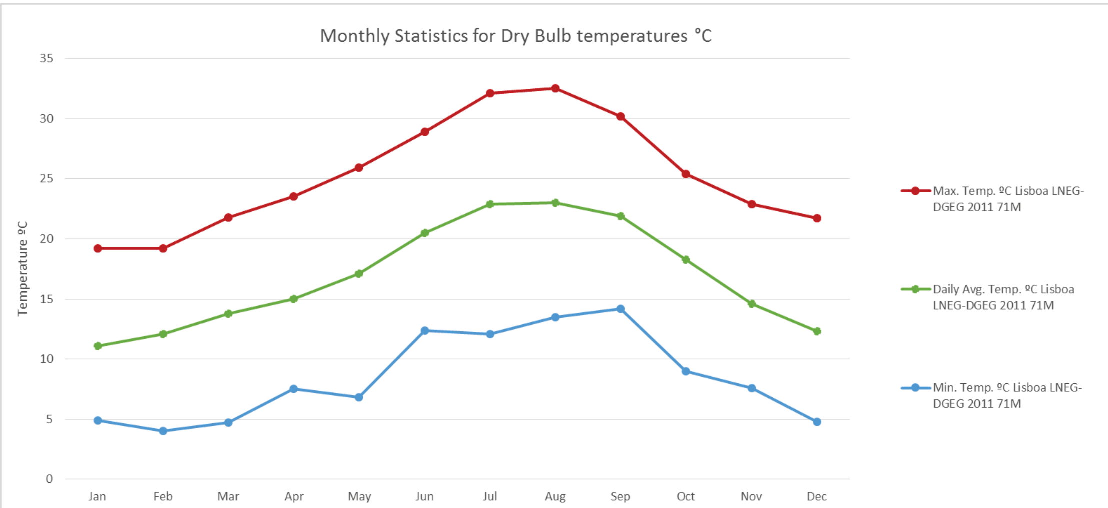


Figure 92: Monthly statistics for Dry Bulb temperatures for Lisbon (ºC)

[17] http://urbanmodellinginterface.ning.com/

[18] Epw. format : EnergyPlus software weather file format

The average of relative humidity was 78,5%, the maximum relative humidity average was of 98% and the minimum relative humidity average was of 44% (Figure 93).

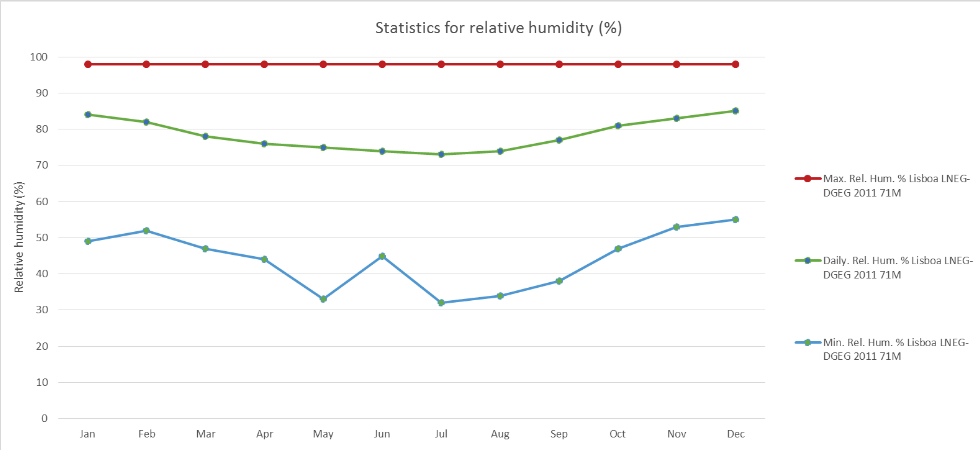


Figure 93: Monthly statistics for relative humidity for Lisbon (%)

In what regards solar radiation, direct maximum solar radiation average was of 9475,5 Wh/m^2, direct average solar radiation was of 5627,7 Wh/m^2, diffuse average solar radiation was of 1615,8 Wh/m^2 and the global average solar radiation was of 4833,3 Wh/m^2 (Figure 94).

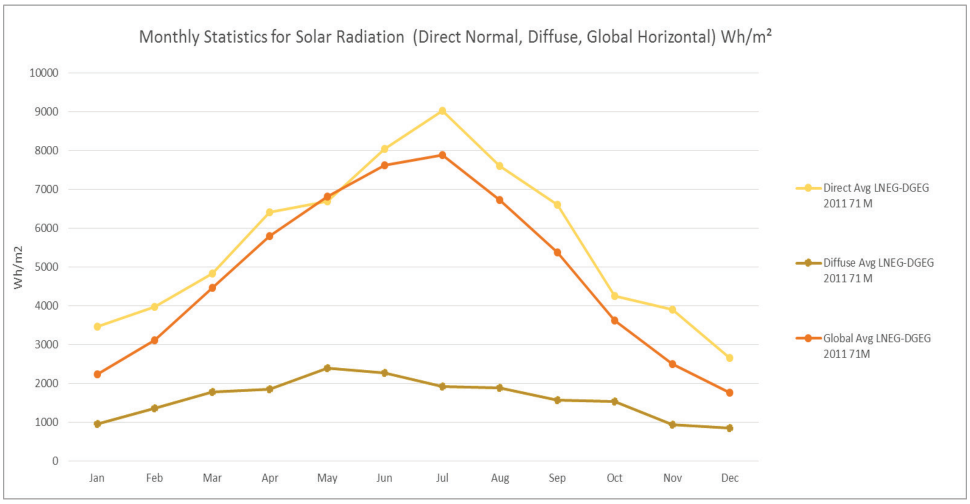


Figure 94: Monthly statistics for Solar Radiation (Direct Normal, Diffuse, Global Horizontal) Wh/m^2 for Lisbon

Finally, regarding total sky cover, an average of 52,80% of total sky cover was registered (Figure 95). To better understand the effect of different local climate on the buildings energy needs, an analysis was made on chapter 9.3 - Heating and cooling energy results, in which climate data series from 2005 were used and compared with the used 2011 data series, and also data series for 2100 were projected in order to access future climate changes impact on thermal energy needs. More information on the 2011 data series can be found in the Appendix iv, Appendix v and Appendix vi.

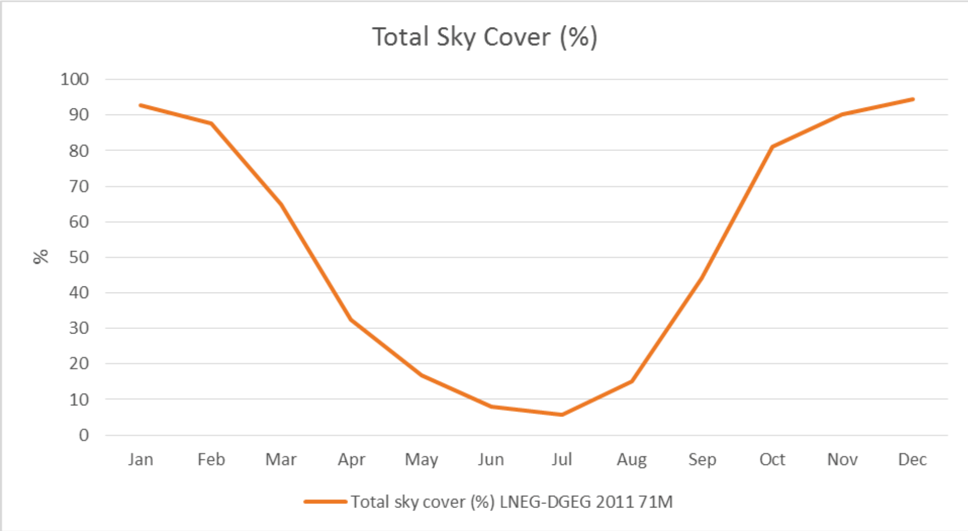


Figure 95: Total Sky Cover for Lisbon (%)

7.4.2 The UMI template file

The building template file represents the buildings characteristics, in terms of materials, schedule of occupation and equipment's type and configuration. A unique building template was used for all typologies. This option allowed to understand the specific effects of urban form on energy demand putting aside context specificities that may exist. It is recognized that some detail is sacrificed, and that the energy analysis results will not represent with great detail the concrete realities that are being analyzed, but for the purpose of understanding the specific impact of urban geometry on energy demand this is the most appropriate analysis, as Ratti et al. (2005), Salat (2009) and LSE (2014) indicate. Particularly the LSE study (2014:3-1) indicates that "*If we assume that variables such as insulation, climatic conditions and social preferences are constant and ignore other technical differences, the physical dimensions of the buildings and the syntax of the urban fabric come to the fore, with their effects isolated and quantifiable at the scale of the urban block. Using this approach it has been possible to understand the energy performance of an urban type solely in relation to its spatial (volumetric and relational) configuration. Due to the constant reference scenario, this performance data can be comparatively analysed*".

The UMI plugin calculates the lighting, equipment (appliances and meal preparation), heating, cooling and domestic hot water energy required by a building. In the case of this thesis the objective was to access the heating and cooling energy needs. Domestic hot water was not considered in the calculations, since it does not have a direct effect on the thermal energy needs.

The UMI template file (Figure 96) aggregates various types of building information such as:

- 1) Building templates: name of template, type of building, lifespan;
- 2) Materials information: types of materials (opaque and glazing), also the specific gas used in windows;
- 3) Construction information: façade wall type; roof, ground, interior, exterior floor type; basement wall type; glazing type; structure type; partition type and ratio (m part/m2); thermal mass type and ratio (m^2/m^2);
- 4) Schedules: schedules of operation for different building systems divided by day, week, year
- 5) Zone information:
    - o Construction: materials specified in 2)
    - o Thermal loads: occupation density (pp/m^2), equipment and lighting density (W/m^2), and respective schedules; also light dimming type and illuminance target
    - o Conditioning: heating and cooling set point, schedule, limit type, capacity, flow and CoP; mechanical ventilation availability, schedule and distribution (m^3), economizer type and heat recovery availability;
    - o Natural ventilation: infiltration rate; natural ventilation min. and max. outdoor air temperature, rel. humidity, schedule and zone temperature set point; schedule ventilation availability, ACH schedule and set point; buoyancy, wind and Afn.
    - o Domestic Hot water availability, schedule, supply temperature, Inlet temperature and flow rate;
    - o Windows: Windows type, construction and operable area; shading availability, schedule, set point, transmittance and type; zone mixing; virtual partition; airflow network discharge coefficient, temperature set point and window availability.

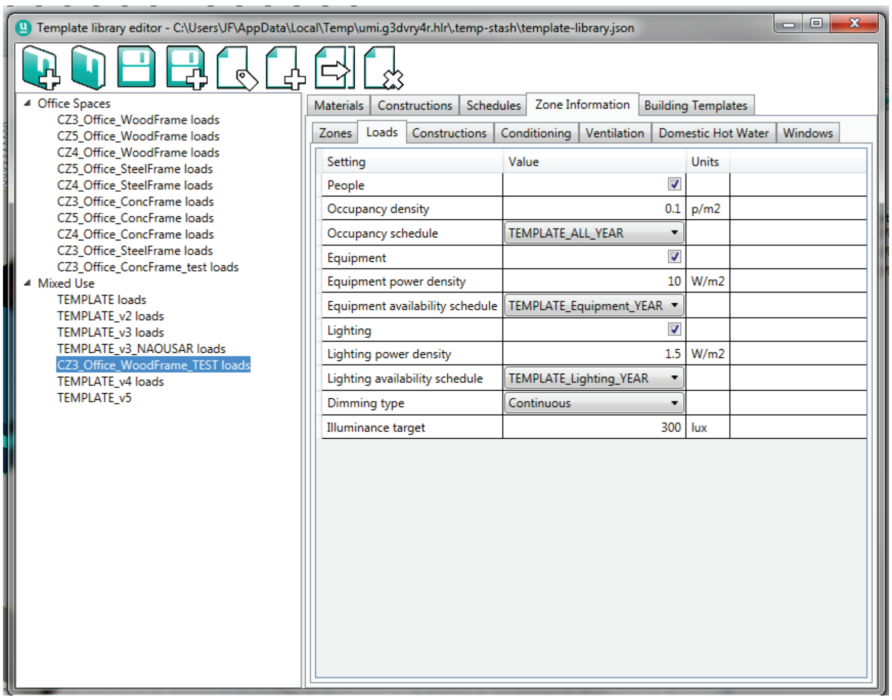


Figure 96: UMI template file example

- *Building template, materials and construction information*

In what regards the "Building template", the specified lifespan of the buildings was the default (60 years). Partition ratio was 0,25. The window-to-wall ratio used for all facades (North, West, South and East) was of 30%. For the building construction information it was necessary to identify both the types of materials and the respective U values that better characterize the Lisbon building stock. In what regards the materials, and to create a building construction properties profile that could summarize the predominant materials properties of the Lisbon building stock, it is important to define what are the main buildings typologies (regarding their materials) and what is their proportion in the total building stock of the city of Lisbon. In what regards Lisbon´s building types of construction Cóias (2005, also adapted from Climaco, 2012) indicated the following main groups (Figure 97):

- <1755 (Pré-pombalinos): Buildings prior to the earthquake of 1755 [Masonry structure];
- 1755 – 1880 (Pombalinos): Buildings related to the phase of post-earthquake reconstruction – [Masonry structure reinforced with wood, from Pombalino period and similar];
- 1880 – 1930 (Gaioleiros): Buildings related to the urban expansion of the town in the last third of the XIXth century [gaioleiro type masonry structure];
- 1930 – 1940: Buildings of the transition from masonry/wood to concrete [mixed structure of masonry and concrete];
- 1940 – 1960: Buildings from the first phase of concrete, prior to more antique earthquake engineering [mixed structure of concrete and masonry];
- 1960 – 1985: Buildings from the second phase of concrete, prior to modern earthquake engineering regulation [concrete];
- >1985: Contemporary buildings of reinforced or pre-stressed concrete. The division provided for buildings with concrete structure is not usually considered, but just justified by the large difference in structural composition and levels of performance of concrete material, along with the deep changes induced in two stages over the course of earthquake engineering.

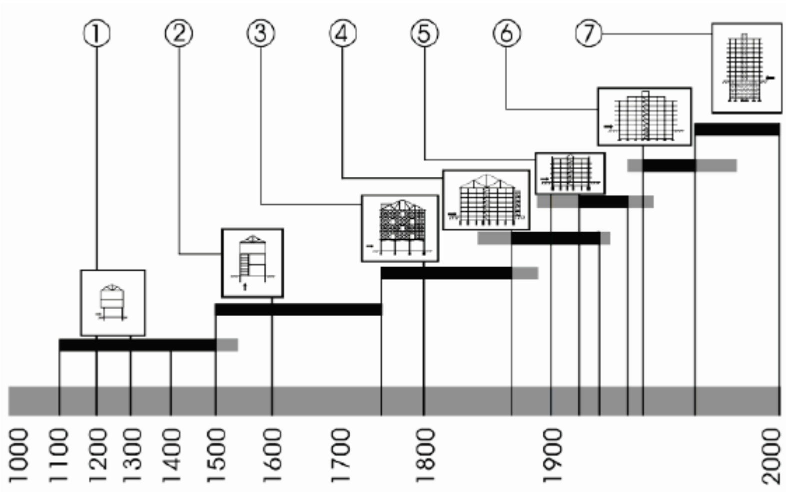


Figure 97: Evolution of the building typologies in Portugal: 1,2 – before 1755; 3 – Pombalino; 4 – "Gaioleiro"; 5 – Mixed mansonry and concrete; 6,7 – reinforced concrete
Source: Cóias (2005) and Climaco (2012)

In what regards the distribution of material types in the city of Lisbon, as it can be seen in Figure 98, the main type of building structure in Lisbon is the reinforced concrete. Buildings with concrete in their structure (both normal and reinforced concrete) represent nearly 63% of the total building stock in Lisbon. Buildings without concrete and constituted mainly by masonry tend to be significant until 1960´s, and then progressively became less significant. Buildings with a structure mainly from reinforced concrete are predominant since precisely 1960´s onwards. Masonry is one of the most common materials used in Lisbon buildings, above all in bricks that are used in both the exterior and interior surfaces of buildings. The most commonly used coating is the traditional plaster or marmorite (Figure 99). The majority of buildings roofs are pitched and are made of ceramic roof tiles (Figure 100).

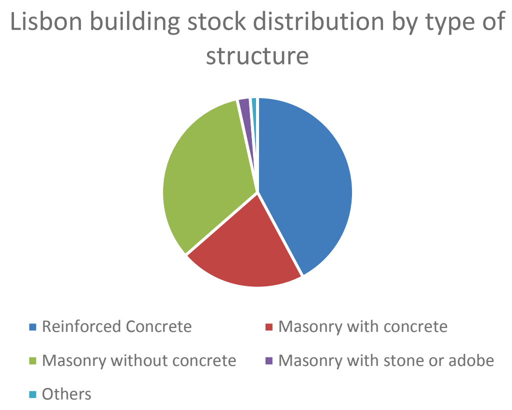


Figure 98: Lisbon building stock distribution by type of structure
Source: INE Census (2011)

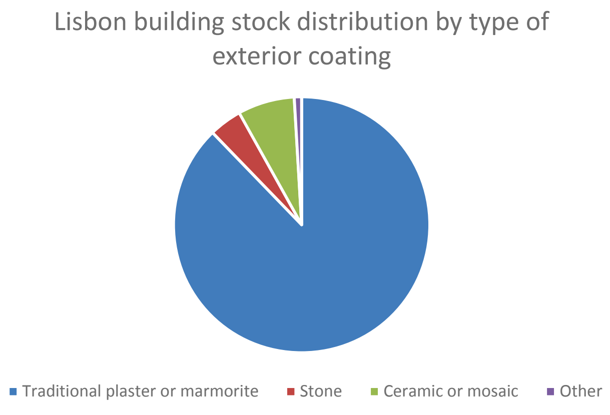


Figure 99: Lisbon building stock distribution by type of exterior coating
Source: INE Census (2011)

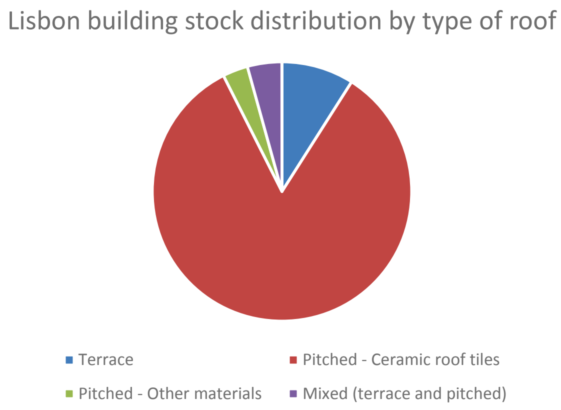


Figure 100: Lisbon building stock distribution by type of roof
Source: INE Census (2011)

In what regards the construction properties U-Values, the template that was created was based on reference U-Values U_{ref} [W/(m^2.°C)] that meet the minimum requirements for buildings components for a standard building in Portugal, climatic zone of Lisbon (I1), for the 2012-2016 period, and also based on the most common buildings properties in Lisbon defined through the analysis presented before. In what regards the reference U-Values (Table 21), those were established through the Portaria nº 349-B/2013 de 29 de Novembro, that was a result of the Decreto-Lei nº 118/2013 de 20 de Agosto that approved the Energy Certification System for Portugal, the regulations for the Energy Performance of Residential Buildings and the regulations for the Energy Performance of the Commercial and Services Buildings. The U value is important since it is a measure of the thermal conductivity (or loss) that each material has. It is the inverse of the total thermal resistance of a building facade. The lower the U value the lower the heat loss and vice-versa. In the figure below it is summarized the evolution of minimum requirements in Portugal for building components and final energy needs from 1990 to 2021, where is present the 2012-2016 reference period that was used.

Table 21: Evolution of minimum requirements in Portugal for building components and final energy needs from 1990 to 2021 (expected)
Source: Santos, P., Mateus, P., Fragoso, R. (2013:299)

Time interval		Before 1990	1990-2006		2006-2012		2012-2016		2016-2021		After 2021	
			Lisbon	Bragança	Lisbon	Bragança	Lisbon	Bragança	Lisbon	Bragança	Lisbon	Bragança
U-value [W/(m2.K]	External **walls**	None	1.4	0.95	0.7	0.5	0.5	0.35	0.4	0.3	0.35	0.25
	External **roof/floor**		1.1	0.75	0.5	0.4	0.4	0.3	0.35	0.25	0.3	0.2
	External **window**		4.2	4.2	4.2	3.3	2.9	2.4	2.8	2.2	2.4	1.8
	Flat thermal		None		2xU-value (closest element)							
Maximum energy needs kWh/(m2.year)	**heating**[1]		64	135	52	117	Currently not available					
	cooling[1]		18				18	15	18	15	18	15
	DHW[1]		None		38.9		Requirements on equipments efficiency					
Maximum window solar gain factor **g-value**			0.15 (light inertia) 0.56 (medium/heavy inertia)									
Ventilation (ACH)			None		≥ 0.6		≥ 0.4					
Renewable energy systems			None		RES mandatory							
Minimum **air conditioning** eficiency			None				Label C[2]		Label B[2]		Label A[2]	
Minimum **boiler** efficiency			None				86%		89%		92%	

1- Values for an average size (120 m^2) building
2- Eurovent label

Table 22 summarizes the materials and respective U-Values used in the definition of the construction materials of the UMI template. Both the materials and values were defined using the reference u-values in the Portuguese legislation and also the most common building material for each of Lisbon buildings constituent parts. The objective was to use the most common materials used in Lisbon buildings, but as if they were already intervened towards a compliance with the necessary energy efficiency requirements. UMI already had available pre-defined material types according to EnergyPlus, when these types matched the material type and the U value specific of Lisbon those were used, when not, new materials were created to match the specific requirements of Lisbon.

Table 22: UMI template construction type elements
Source: a) Censos 2011 (INE, 2011) and Coias (2006), b) Portaria nº 349-B/2013

Type	Sub-Type	Lisbon Predominant Construction Type (a)	Reference U-Value (W/m2.k) (b)	UMI Material Name	U-Value (W/m2.k) used
Walls	Façade Wall Type	Reinforced Concrete, brick and traditional plaster or marmorite**	0.5	MYMassWALL Brick Polystyrene Reinforced Concrete Cement plaster	0.5
	Basement Wall Type	Reinforced Concrete*	0.5	CZ5_BelowGradewall_cementplaster Reinforced Concrete Polystyrene Plaster	0.5
Floor	Roof Floor Type	Ceramic tiles or/and concrete*	0.4	MYROOF Roof tiles Polystyrene Concret	0.4
	Ground Floor Type	Reinforced Concrete*	0.5	CZ5_BelowGradewall_ Ground Reinforced Concrete Polystyrene Plaster Terrazo	0.5
	Interior Floor Type	Reinforced Concrete*, isolation and wood or ceramic floorings	-	BASE_Concrete_1Wslab Carpet urethane Plywood wood panels Reinforced Concrete Polystyrene	0.73
	Exterior Floor Type	-	0.4	MYEXTERIORFLOOR Terrazo Reinforced concrete Polystyrene	0.4
	Glazing Type (v2)	-	2.9	Dbl_Clr_6_6_Air Double window 6mm with air filling	3.058***
Structure	Structure Type	Reinforced Concrete*	-	RC_Frame_6FL	-
	Partition Type	-	-	MYMassWall_interior Brick Polystyrene Gypsum Plaster	0.57

*Censos 2011 – Buildings by construction period and main materials used in construction
** Adapted from buildings by construction period and main materials used in construction
*** According to EnergyPlus v 8.4.0

- *Building zone information – thermal loads*

In what regards the buildings Thermal Loads, occupation density (pp/m2) was established as 0.02 (an average of 2 persons per 100m^2, taking into account the average of 1,69 persons per household according to 2011 Census (INE, 2011)). Regarding equipment density it was considered a value of 3.5 W/m^2 (above the average of the occupancy non-sleeping and sleeping periods and unoccupied hours according to Climaco, 2011:222). In what regards the lighting density a value of 1,5W/m^2 was defined according to Climaco (2012:222).

The occupation and lighting schedules (Figure 101) were defined using ASHRAE 90.1 User’s Manual (Table B-6 for a Midrise Apartment Hourly Operation Schedule for all days) and generally based on the work of Climaco (2012:218).

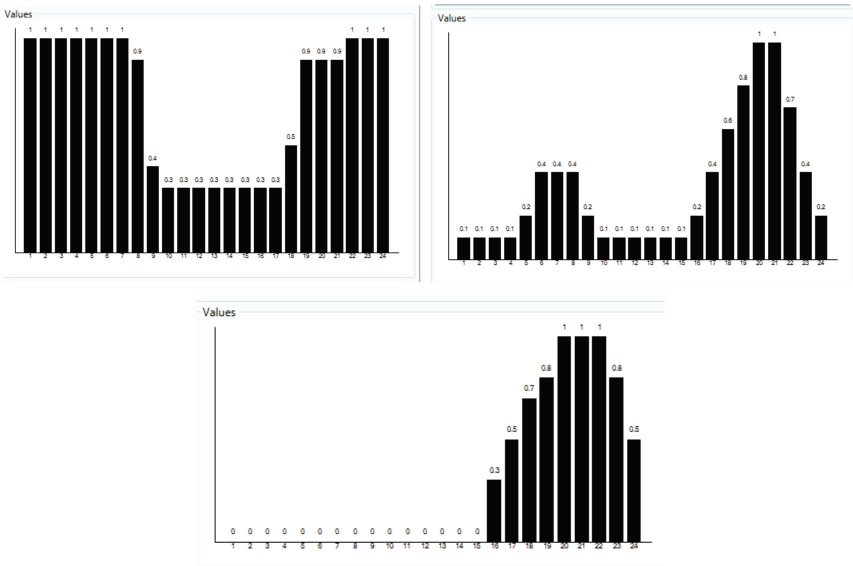


Figure 101: Occupation schedules defined: a) general, b) lighting and c) HVAC
Source: UMI (2015) and ASHRAE 90.1

- *Building zone information – conditioning and ventilation*

The heating and cooling schedule (Figure 101) was defined according to the occupation schedule and generally based on the work of Climaco (2012:232) which indicated a general use from 18h00-24h00 and an usage factor of 0.25. Since the occupation and lighting schedules were defined for a general occupation (with no distinction between weekdays and weekends) the same approach was used on the heating and cooling schedule. In what regards the heating and cooling setting, heating and cooling options were considered, being the heating set point (Cº) set to 19ºC, and the cooling set point to 26 ºC, as it was also defined by Climaco for Portugal, Lisbon (Climaco, 2012:230).

Mechanical ventilation was considered as non-existent and maintained as 0 (default values). In what regards the natural ventilation, it was considered when the outside temperature was below the indoor temperature and above 20ºC, and when indoor temperatures were above 24ºC. An infiltration rate of 0.6 ach was defined (according to RCCTE, 2006) and the air renovation rate was specified as 4 ach (the rate from which the impact of air ventilation in the households cooling is not so significant), according to Climaco (2012:316).

- *Building zone information – windows*

Regarding lighting/shading, a value of 500 lux was defined as Lux Target, and of 10000 as lux maximum (the same value than the one used in the urban daylight analysis). Window shadings were included, with a shading transmittance value of 0 for a PVC Rolling Shutter window (Climaco, 2012:216) and a shading setpoint of 8000 lux, which indicates that when the radiation peaks this value windows shutters take place. Shading schedule defined was similarly to the occupation schedule which indicates that shutters completely close from 10 p.m. onwards until 8 p.m. and will open (and close) progressively from 20h00-22h00, approximately what was defined by Climaco (2012:219).

Once the template file for the buildings typologies is defined, a simulation was made for the selected cases, to calculate the operational energy. The period that the simulation took into account was of 1 year. The specific effects of buildings geometry and context, as well as the effect of local climate are addressed in chapter 9.3 - Heating and cooling energy results.

7.4.3 UMI Operational Energy Simulations

The operational energy model simulation uses the buildings settings both from the ArcGIS shapefile (the typology buildings, the contextual buildings and shading objects) and the template file with the buildings specific information. The method to calculate the operational energy of a set of buildings was created by Dogan, T. and Reinhart, C. (2013) and involves an insolation analysis, a thermal ´shoebox´ model operation to cluster the insolation analysis values and assign them an area weight, and EnergyPlus software to calculate the energy demand of the specific building. The simplicity of the method (that requires a minimal model setup), its fastness in the energy demand calculations, and the fact that it can be applied to large groups of buildings while taking into account their contextual impact and also the shading properties, were the reasons why this was the chosen method. Dogan, T. and Reinhart, C. (2013:3751) indicate that the biggest potential of their new method lies in informing master plan designs since it "*allows extremely large parametric search spaces at the urban scale. [...] The gained findings could then be used to give simulation based recommendations for the optimal grid spacing, allocation of residential and commercial usages based on their different microclimatic needs, optimal opening ratios and more*". A description of the method step by step can be seen in Figure 102.

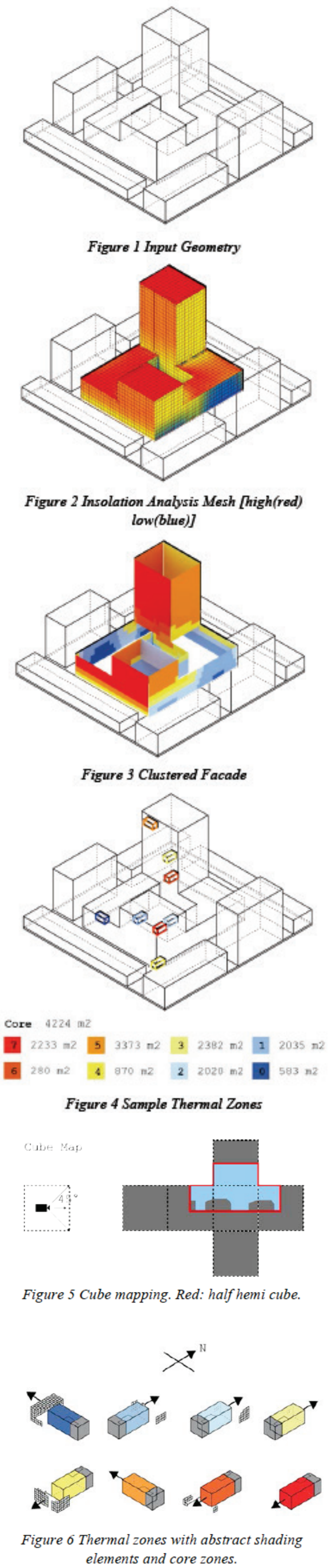


Figure 102: Method for operational energy calculations

Source: Dogan, T. and Reinhart, C. (2013)

Input Geometry: Various information layers are created and separated into two groups: buildings – that represent the buildings to be analyzed; and context – which represents all the contextual information such as shading, boundary objects (that are the objects that limit the area of analysis) among others.

Insolation Analysis: For the insolation analysis a floor-to-ceiling height is defined (in this case 3 m, the default value) which cuts the polygons into slices of 3m of height. Along the polygon outlines a series of virtual sensors are placed at which incident solar radiation levels are calculated. The calculation method takes into account local weather data as well as the effect of neighboring buildings.

Clustering: Sensors are divided into similarity clusters. As it can be seen (fig 3) buildings were divided in a core region plus 8 façade-clusters. For the representation in the shoebox thermal model it is made an identification of the sensor point closest to the mean incident solar radiation of a group and captured its shading information.

Shading: A "cube-mapping" technique (Greene, 1986 in Dogan, T. and Reinhart, C., 2013) is applied which allows the detection of sky view obstructions at the above sensor point similar to a shading mask (Marsh, 2005 in Dogan, T. and Reinhart, C., 2013). Each of the facades of the cube are just but a small resolution renderings with a 90 degree viewing angle looking in all cardinal directions (also up and down). Only the sky view obstructers for vertical walls are taken into account so the lower half of the cube is discarded, resulting in a half semi cube marked in red (fig. 5).

Shoebox thermal model (fig.4): With the information obtained it is possible to build the geometry of a "shoebox" thermal model with the orientation of the point and the correct shading situation which takes into account the pixel data of the cube map texture for shading effect (fig.6). Once buildings templates are read, the reference shoebox models are generated and thermal simulations are made through EnergyPlus.

When the authors compared the shoebox model approach with the “whole building” one (takes into consideration the building as a whole and not the sum of its parts), the shoebox approach required much less time (1 min. vs. 28 min.). Three simples shapes (plate, bar and box), as well as the example shape (fig.1 in Figure 102) were compared to the example shape but in EnergyPlus format, being the first three shapes simulated with 4 samples and without context and the example shape with both 4 and 8 samples and with and without context. In total the mean percentage error for the different shapes ranged from -3.3% (example shape without context and 4 samples) to 5.5 % (example shape with 8 samples without context). It was in the lighting calculation where the error was more significant (18% - 24%), in particular in the example shape both in the 4-8 samples and with and without context. Dogan, T. and Reinhart, s C. (2013:3750), attribute this result as an influence of the fact that different room sizes/widths are compared since “*The “whole building” energy model behaves more like an open plan office type whereas the shoebox represents an individual office space with a smaller window area per floor area.*”. Limitations of the model focus in the fact that for each floor it is not possible yet to take into account the interior design and divisions of each building, which makes it not possible to model the heat exchange between adjacent zones. Results on the heating and cooling energy needs can be accessed in chapter 9.3 - Heating and cooling energy results.

SECTION D - Results

8. Urban form analysis results

8.1 Characterization and analysis of the urban typological samples

For the intra-urban analysis 25 typological samples were defined which corresponded to 5 runs through the 5 urban typologies identified in the methodology section (Figure 104). The location of each typology can be seen in Figure 103. The typologies that will be analyzed will be the following:

1) "before 1919": Alfama, Mouraria, Bairro Alto, Lapa and Baixa;

2) "1920-1945": Penha de França, Arroios, Avenidas Novas, Arco do Cego, Anjos;

3) "1946-1970": Campo Grande/Alvalade, Alvalade, Olivais, Benfica, Estrada de Benfica;

4) "1971-1990": Marvila, Av. Brasil, Chelas, Carnide, S. Domingos de Benfica 1;

5) "1991-present": Parque das Nações, Telheiras, Lumiar 1, S. Domingos de Benfica 2; and Lumiar 2.

A comprehensive display of all metrics that were calculated is available in the Appendix vii , Appendix viii and Appendix ix (in this case the values were standardized in order to correlate them and apply the cluster analysis, as it was described in the methodology). Next, the 10 metrics that were taken into account in the typologies analysis will be presented.

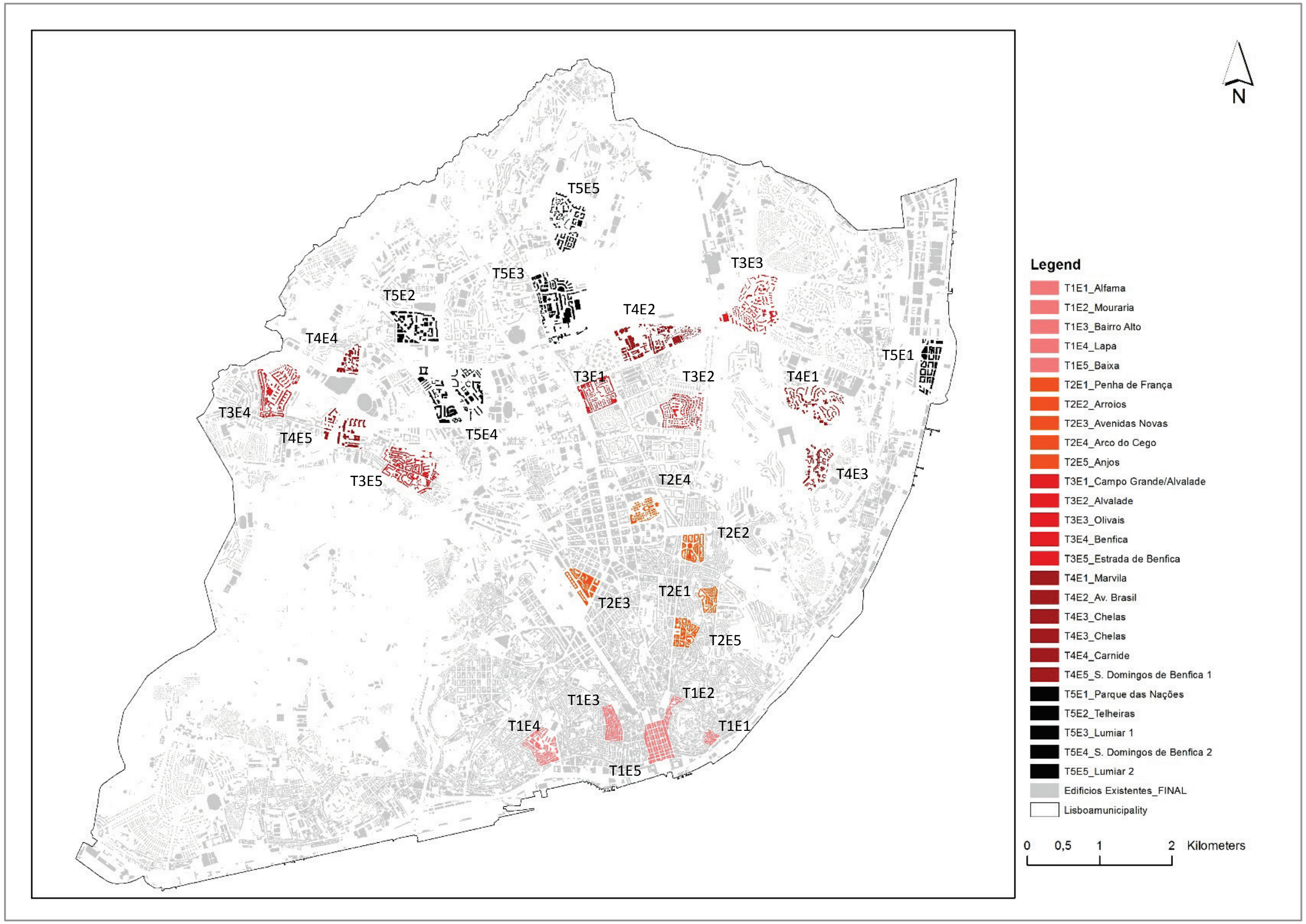


Figure 103: Location of the 25 typologies

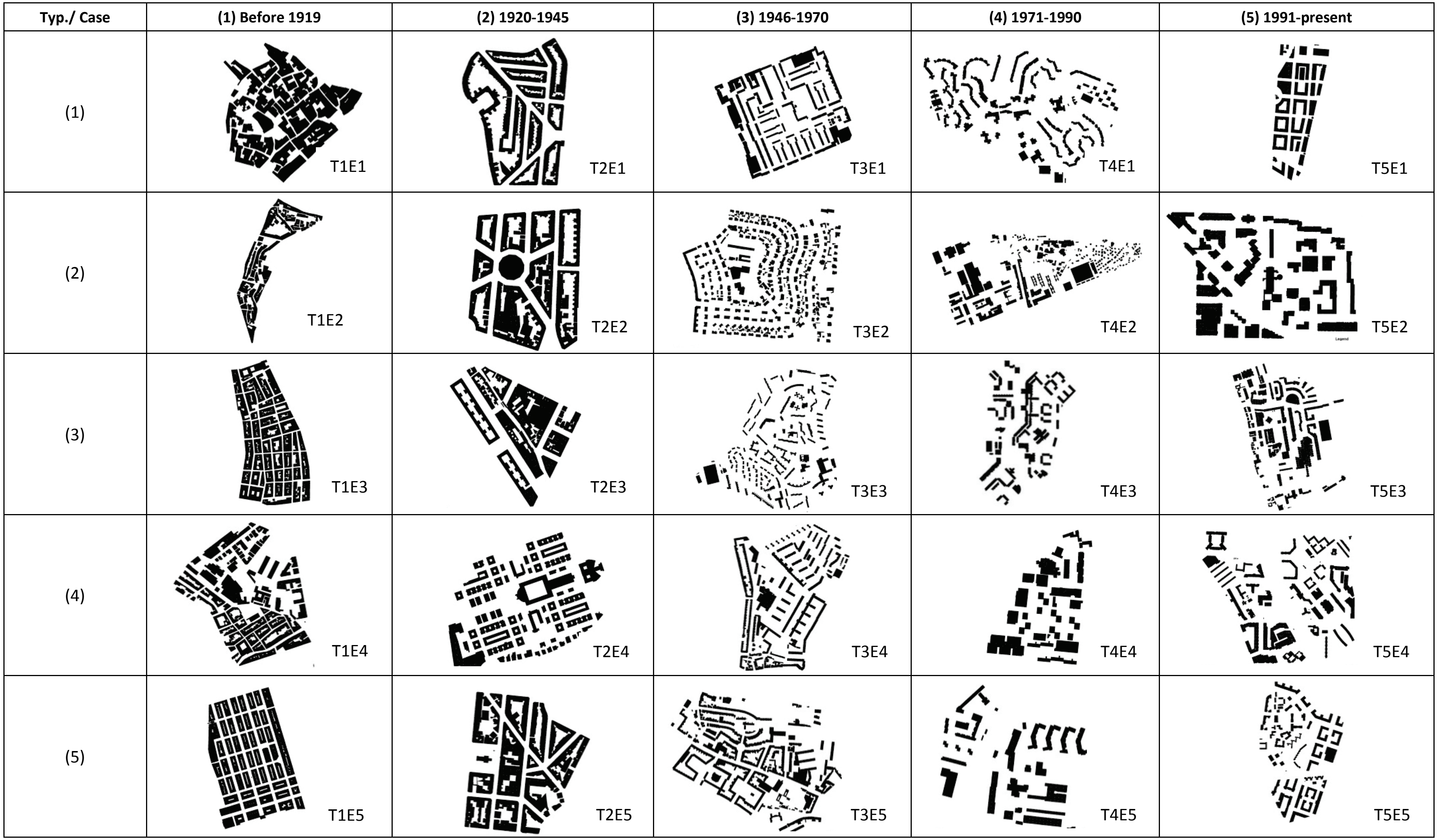


Figure 104: The 25 urban typologies that were studied and that correspond to 5 runs and 5 periods of construction

8.1.1 Inter-typologies analysis

- *Complexity*

The Fractal Dimension (MPFD) metric was calculated in what regards the Mean Patch Fractal Dimension (MPFD), which corresponds to the mean of the individual FD values calculated for each building. Comparing the average values for the city of Lisbon and for each typology (Figure 105), it can be observed that according to the MPFD metric there is a high fractality of the urban form in more traditional typologies than in contemporary ones. The MPFD and ED metrics also present a similar behaviour, being possible to identify (due to their similar values) three main groups of typologies – one that encompasses buildings that were built before 1919, other of buildings that go from 1920-1970 and the other of buildings that are from the 1970´s onwards.

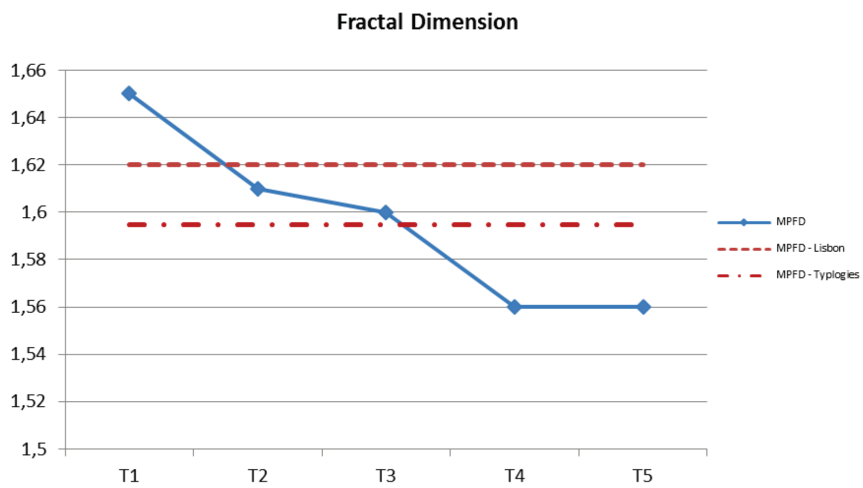


Figure 105: Fractal Dimension results for the selected typologies and Lisbon

The highest FD value (1,72) was obtained in the typology T1E1 (Alfama), one of the oldest neighborhoods in Lisbon, with a traditional, compact, and complex urban form that is composed of small and irregular buildings and narrow streets. The lowest FD value was obtained for the typology T4E4 (Carnide), in an area that is mainly composed by apartment towers that correspond to large and more regular buildings, and also large avenues (Figure 106).

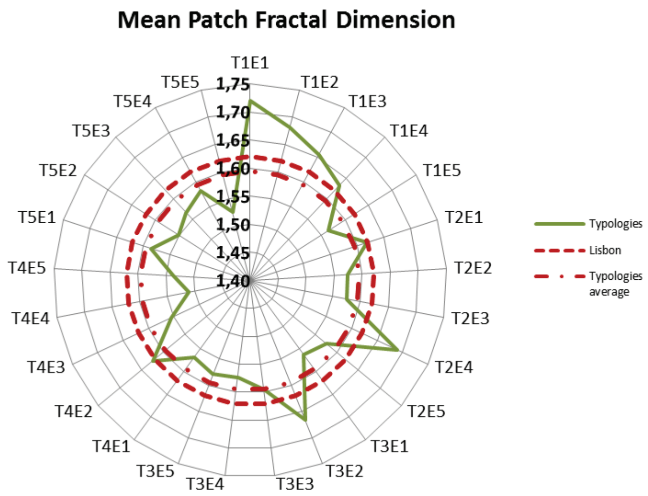


Figure 106: Mean Patch Fractal Dimension results for each case

In what regards the Fractal Dimension calculated for the city of Lisbon, the resulting value was of 1,62. Higher FD values were registered for urban areas which had more space filling and smaller and irregular buildings, while in the case of low values, those corresponded to more regular – squared or rectangular – and bigger buildings, which often result in a more dispersed and fragmented urban form (Figure 107 and Figure 108). According to the values that were presented, Lisbon is situated in the range of values that correspond to the majority of the other cities that were studied (chapter 2.3.2 Measuring urban form: contributes from the complexity science and examples of urban form metrics, fractal analysis), which indicates that the value that was obtained has some validity.

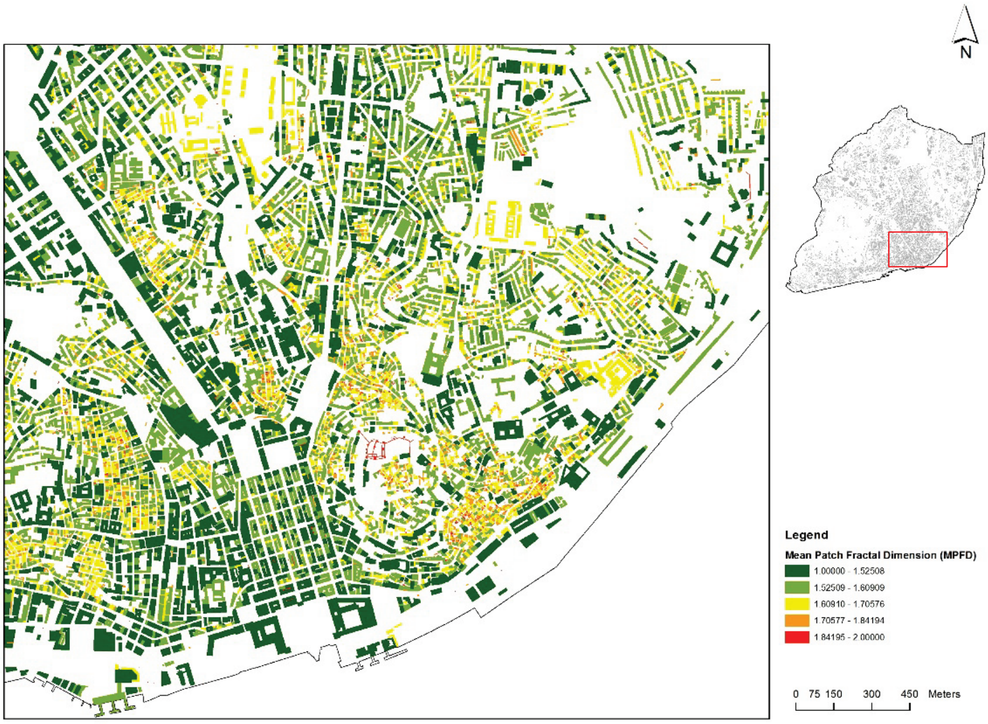


Figure 107: Lisbon built environment and Lisbon Fractal Dimension – high fractality

Figure 108: Lisbon built environment and Lisbon Fractal Dimension – low fractality

The Edge Density (ED) metric was used to measure the complexity of the buildings form, through the account of the number of edges per area, and the results both for the higher value and for the lower ones show a similar pattern compared to the MPFD values, indicating that more regular forms tend to present lesser edges and more irregular forms tend to present a higher number of edges. Alfama typology (T1E1) showed again the highest value, and the lowest was obtained in the typology of Avenida do Brasil (T4E2) mainly because of the existence of a large state laboratory (Figure 109).

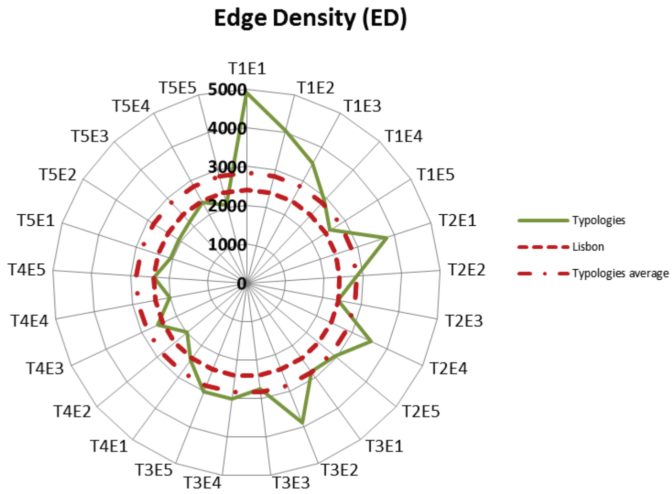


Figure 109: Edge Density results for each case

To note that despite the MPFD and ED metrics share many similarities, in what regards the values for Lisbon the MPFD was more in line with the "1920-1945" typologies while in the case of ED it is more aligned with the "1971-1990" typologies, and that can be related by the fact that while the first metric takes into account the ratio between area and perimeter the later only accounts for the number of edges, and therefore the high number of large equipment's and infrastructure in Lisbon, with more regular forms, tend to decrease this value (Figure 110).

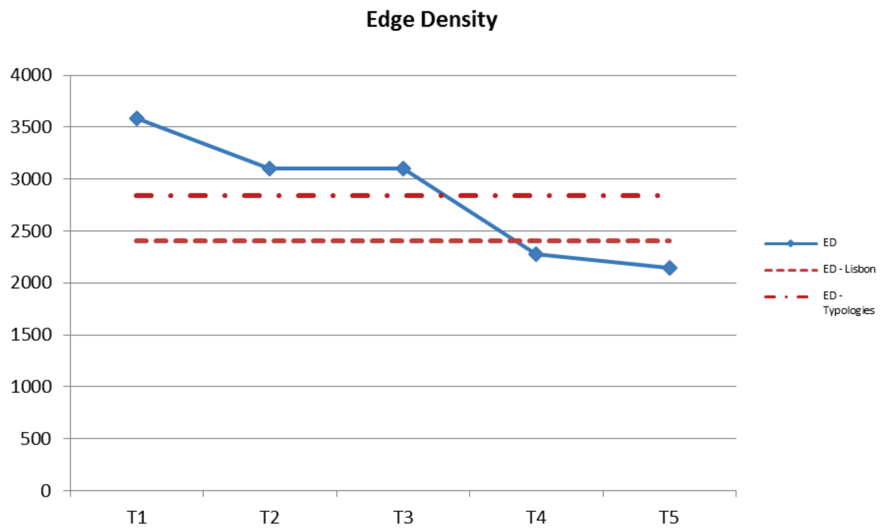


Figure 110: Edge Density results for the selected typologies and Lisbon

Regarding the Surface to Volume ratio (SVRatio) metric (Figure 111 and Figure 112), a high surface to volume ratio (0.3-0.45) is normally associated with urban configurations with important areas of detached housing (LSE, 2014), that is the case for instance of the typological samples T3E2 (Alvalade) and T2E4 (Arco Cego) as it will be seen further ahead. Also elongated urban forms composed of adjoined buildings with medium to low densities tend to present a medium to high SVRatio (around 0.30). Urban configurations with apartment towers, high rise and medium density housing, with significant height, tend to present average to low values of surface to volume ratios (0.2-0.25), and that is the case of some of the typological samples of the “1990-present” typology that contribute to the relatively low value of this period when compared to the others. The increased volume, in this case through increased height, strongly contributes to theses low values. The fact that the average SVRatio of the typologies from before 1919 and 1920-1945 is high, can be partially explained by the fact that these are typologies with low height levels, thus increasing the ratio. Further ahead that relation is explained in more detail with the negative correlation that was found between SVRatio and the AvHeight metrics.

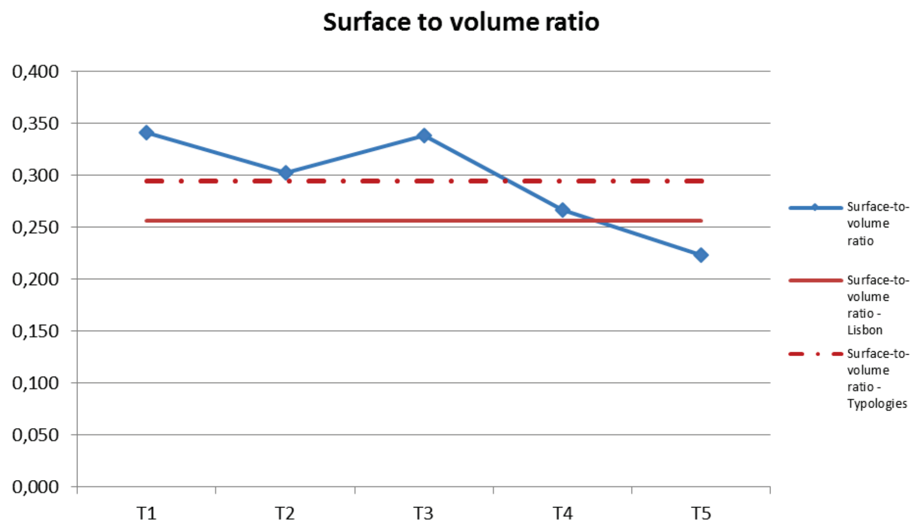


Figure 111: Surface to Volume ratio results for the selected typologies and Lisbon

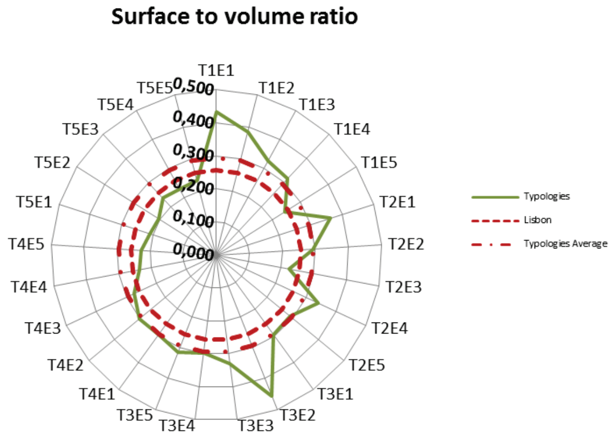


Figure 112: Surface to Volume ratio results for each case

Lisbon´s SVRatio is in line with the 1971-1990 typologies, which is a result of the increased height of buildings in more recent typologies that has strongly contributed to the increase in density and decrease in the surface to volume ratio (Figure 113).

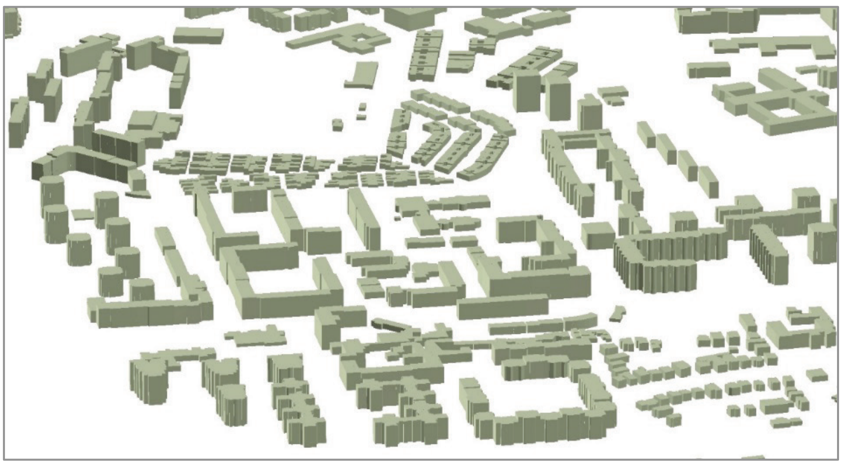


Figure 113: Example of a Lisbon area (Telheiras) with a Surface to Volume ratio similar to Lisbon´s average

- *Heterogeneity*

The metric Patch Size Coefficient of Variance (PSCoV) was used to analyze the coherence of the urban form in what regards the heterogenity of the buildings size. The PSCoV metric showed that the heterogeinity of the urban form is increasing until 1970´s-1990´s, and then decreasing in more recent typologies (Figure 114).

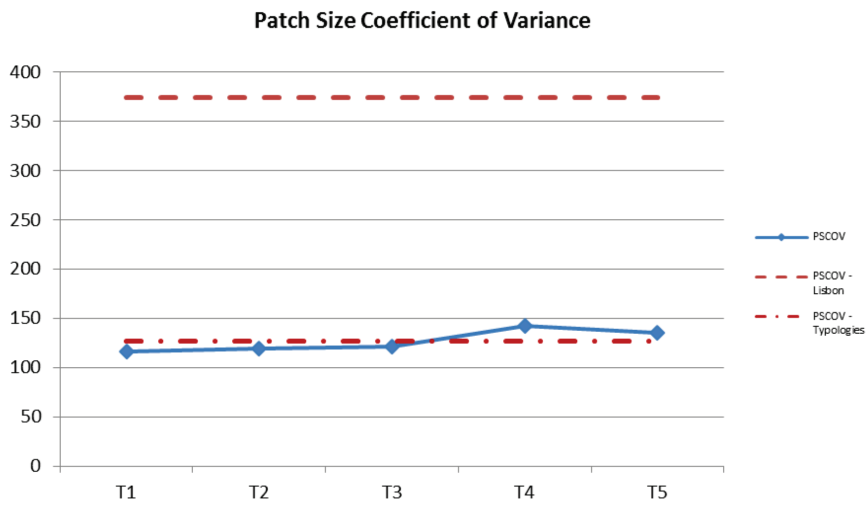


Figure 114: Patch Size Coefficient of Variance results for the selected typologies and Lisbon

The typology that presented the lowest value was the one of Mouraria (T1E2), a traditional neighborhood and together with Alfama and Castelo, also one of the oldest neighborhoods in Lisbon. The typology that presented the highest PSCoV, Av. Brasil (T4E2), is the one that corresponds to the period of 1971-1990, and is characterized by a large complex of buildings that are a state laboratory on the left, at the centre by a residential area, and on the right by social and and precarious residential buildings. This example ilustrate well the evolution of urban planning in the city of Lisbon, ranging from the left with the formal architecture with elements of the "Estado Novo" period, to the right and the expansion of the city of Lisbon in the 80´s and the explosion of social housing and precarious construction (Figure 115).

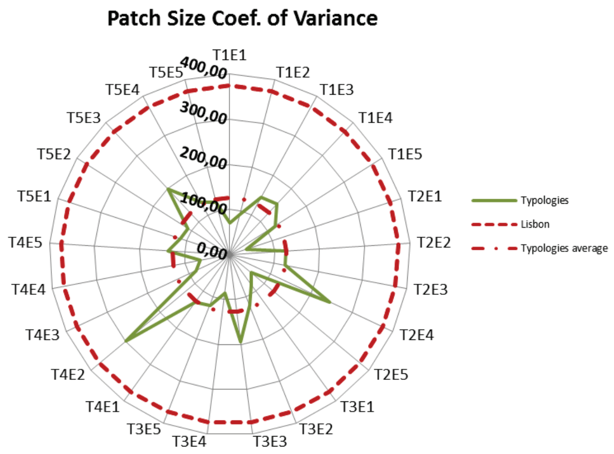


Figure 115: Path Size Coefficient of Variance for the selected cases

The value obtained for Lisbon is very high since it encompasses all of Lisbon´s buidling stock and therefore it measures a much higher stock of buildings from the oldest ones in Alfama and Mouraria, very small and irregular, to large infrastructure like the Lisbon airport for instance.

Figure 116: Patch Size Coefficient of Variance example similar to the Lisbon average result

- *Compaction*

The Patch Density (PD) metric was used to access the dispersion of the urban neighborhoods, and as it can be seen in the figures below, that correspond to the typologies with the highest and lowest patch densities respectively, the resulting urban form pattern is very different. The PD metric shows that the density of patches was diminushing until the 1970´s-1990´s but then stabilized in the 1990-present typologies (Figure 117).

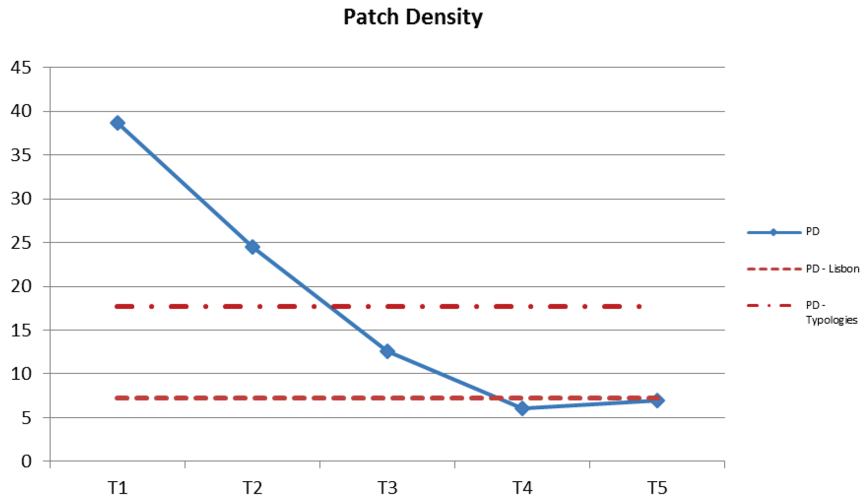


Figure 117: Patch Density results for each typology and Lisbon

Once again Alfama (T1E1) is the typology that has the highest value since the way that the buildings are arranged throughout a very narrow road network, without large public spaces and with very small buildings allows a great concentration of buildings. On the contrary, the Marvila typology (T4E1), with larger buildings, displayed geometrically and with space between them and through large avenues, resulted in a low density of buildings per hectare. Overall there is a huge contrast between the 1970-present urban forms with the ones before 1919 and even from 1920-1945. Lisbon´s value is more in line with the latest typologies, that can be explained by the importance of the last 40 year´s expansion pattern of the city in its periphery, that indeed was more fragmented and dispersed, but we cannot also overlook the contribution of large spaces to the decrease in the PD value, as are examples the Monsanto green area, and the Lisbon´s airport (Figure 118 and Figure 119).

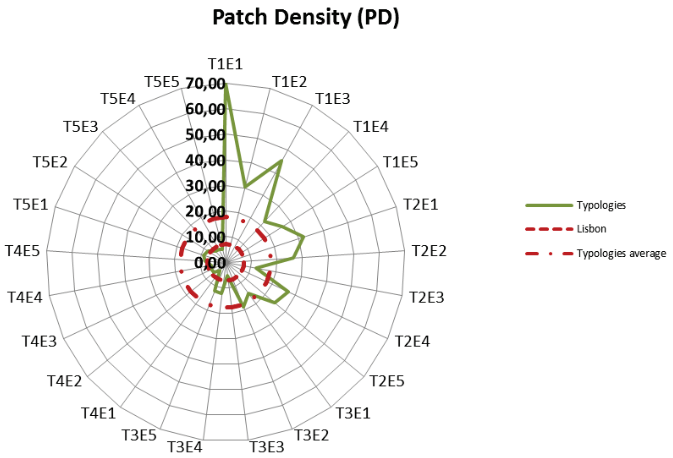


Figure 118: Patch Density results for each selected case

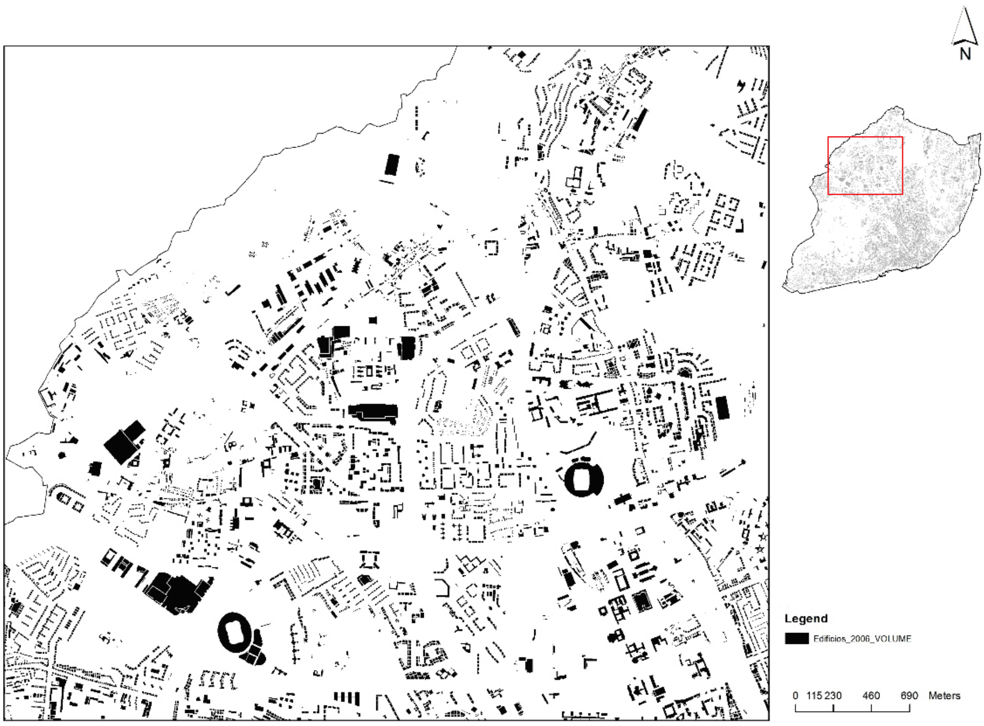


Figure 119: Patch Density example similar to Lisbon average results

The Average Nearest Neighbor (ANN) metric show a progressive tendency of clusterization (fragmentation) of the urban form in small centers. With the ANN metric, it is possible to identify what are the urban areas that are more clustered – with low values – (and thus fragmented if we take into consideration their overall form), and what are the urban areas that present a more dispersed but constant pattern of the buildings – with high values -, which indicates that the buildings are more evenly distributed across space and thus the urban form is more space filling and more connected (through the perspective of euclidean distances between buildings) (Figure 120).

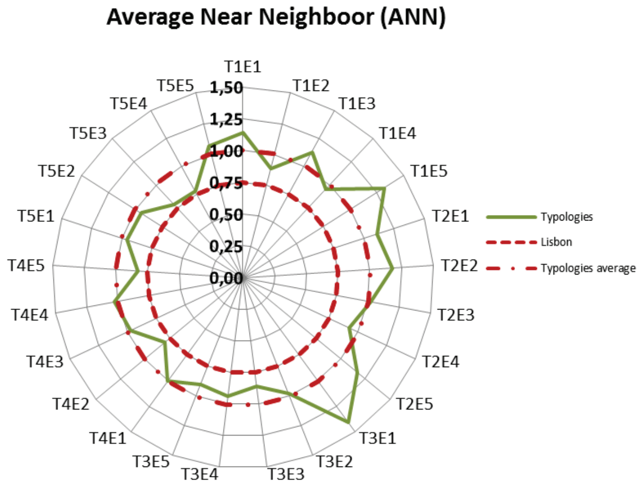


Figure 120: Average Near Neighbor results for each selected case

Low ANN values are also normally related to urban forms that are more enlongated, even when having a uniform distribution of buildings, since the distance between the buildings in the extremes of the form greatly increases the average value (e.g. the case of Mouraria). The highest value (more space filling and less fragmented) corresponded to an urban form of the 1950´s/1960´s (Alvalade-Campo Grande – T3E1), which presented a great homogeinity in the space distribution of the buildings. On the contrary, the lowest values (more concentrated in small centers and thus more fragmented) were registered in a 1990´s-present" urban form (S. Domingos de Benfica – T5E4), since buildings were disposed more densely around certain small centers, due to a larger road network and different configuration of public space (Figure 121 and Figure 122).

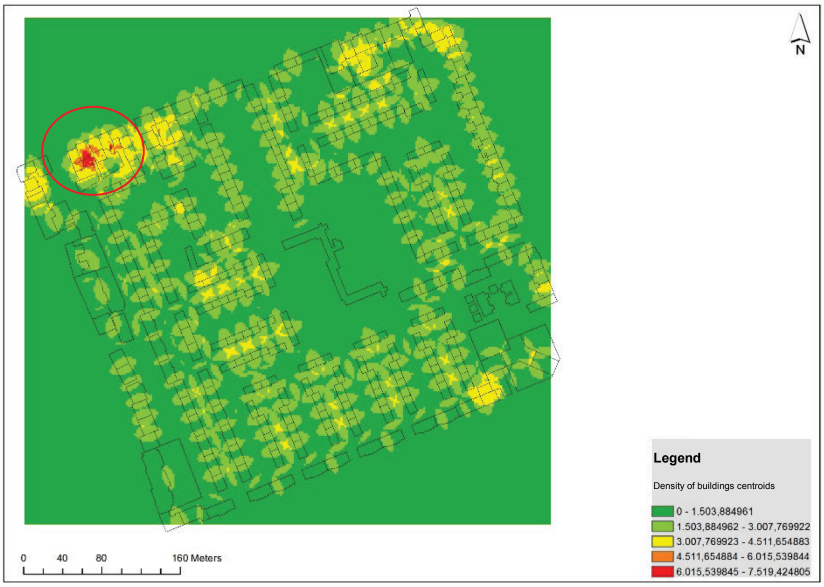


Figure 121 ANN example – Alvalade / Campo Grande typology with density of buildings centroids

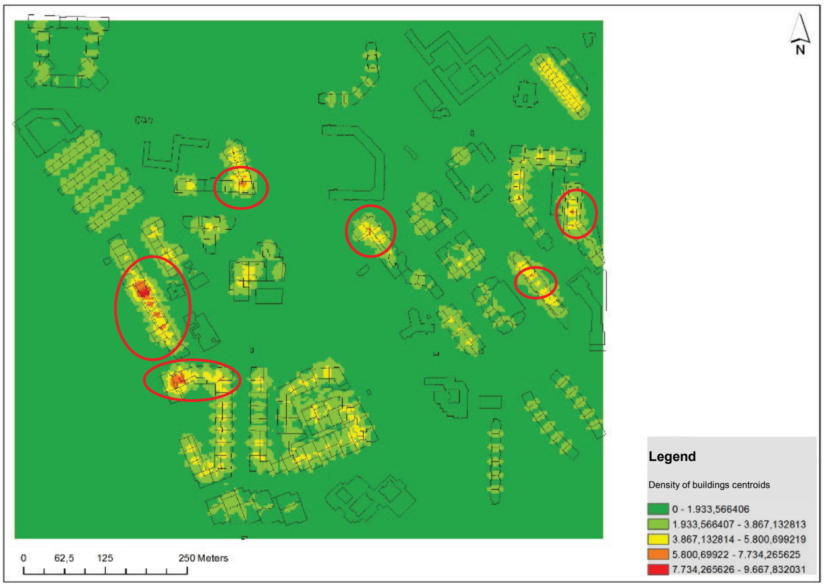


Figure 122 ANN example - Chelas typology with density of buildings centroids

The Lisbon value clearly demonstrates that the city, in its current urban form, is fragmented, mainly associated with typologies from the 1970´s – 1990´s as it can be seen in Figure 123 and Figure 124.

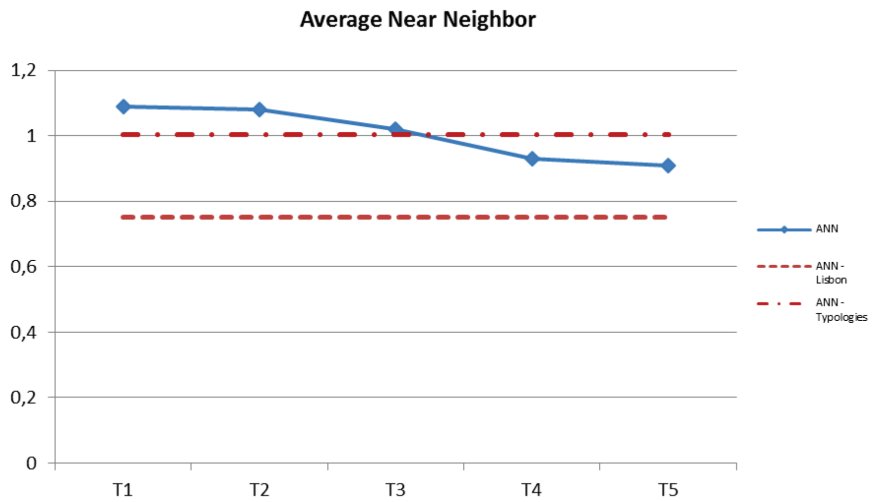


Figure 123: Average Near Neighbor results for each typology and Lisbon

Figure 124 Average Near Neighbor example similar to the Lisbon average results

In what regards the Coverage Ratio (CR), it is clear that older typologies, with a more space filling and intricate patterns tend to present higher ratios of coverage than more recent typologies. To note the reverse tendency of the 1990-present typologies when compared to the periods before, that can partially be explained by the introduction of an urban design that favors less larger avenues, streets to walk, buildings with a higher volume and in urban block configuration, which in general tend to result in less space between buildings (Figure 126).

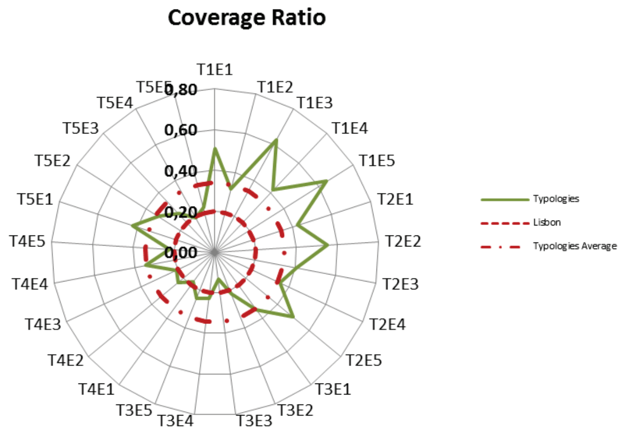


Figure 125: Coverage Ratio results for each selected case and for Lisbon

The coverage ratio for Lisbon is below many of the ratios obtained for the typologies, being closer to the 1945´s – 1990´s typologies which indicate a more disperse and fragmented configuration of the city´s urban form (Figure 126 and Figure 127).

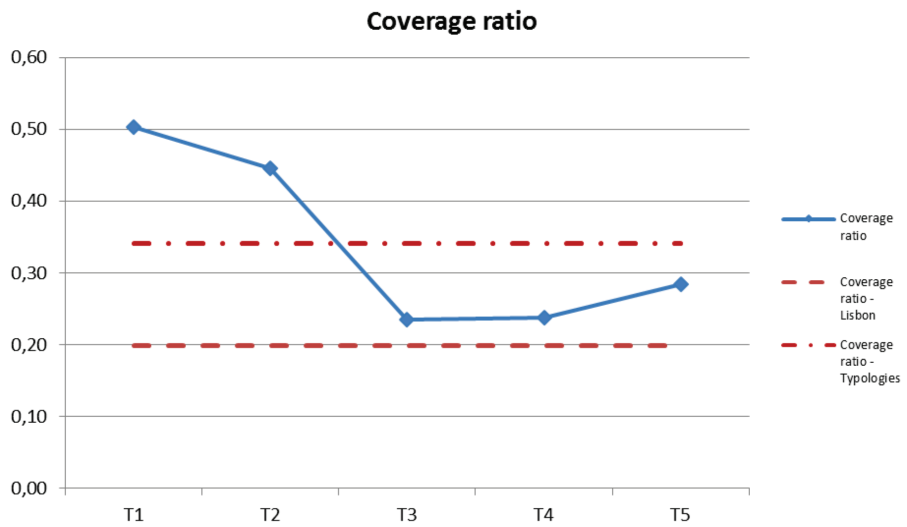


Figure 126: Coverage Ratio results for each typology and Lisbon

Figure 127: Coverage Ratio example similar to Lisbon´s average result

- *Density*

The Floor Area Ratio (FAR) metric is normally used to assess the density of urban areas. The typological samples until the 1945´s present very dense urban areas, that progressively became less dense with the incorporation of other design plans and models, which is specifically the case of the 1945-1970´s typology. Once again, a reverse tendency is observed in the more recent typologies, meaning that more recent urban areas are becoming denser (Figure 128).

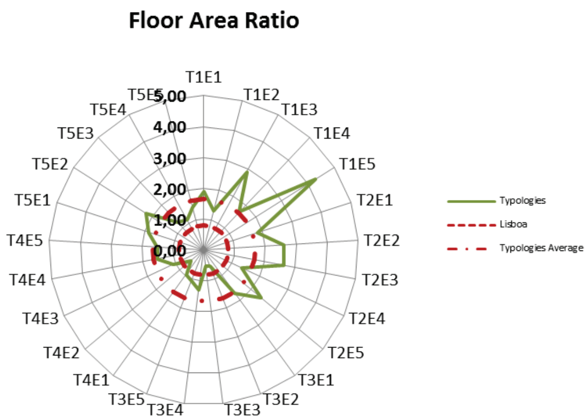


Figure 128: Floor Area Ratio results for each selected case and Lisbon

The value for Lisbon is again below many of the values registered for the other typologies, but also again closer to the 1945´s – 1970´s typology, indicating that overall Lisbon´s urban form is characterized by medium-to-low density, as it can be seen in the Olivais case (T3E3) (Figure 129 and Figure 130).

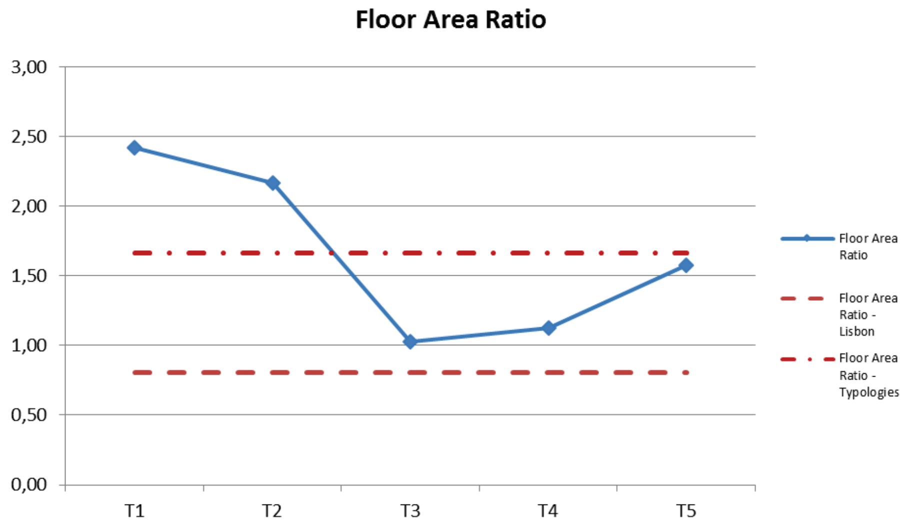


Figure 129: Floor Area Ratio results for each typology and Lisbon

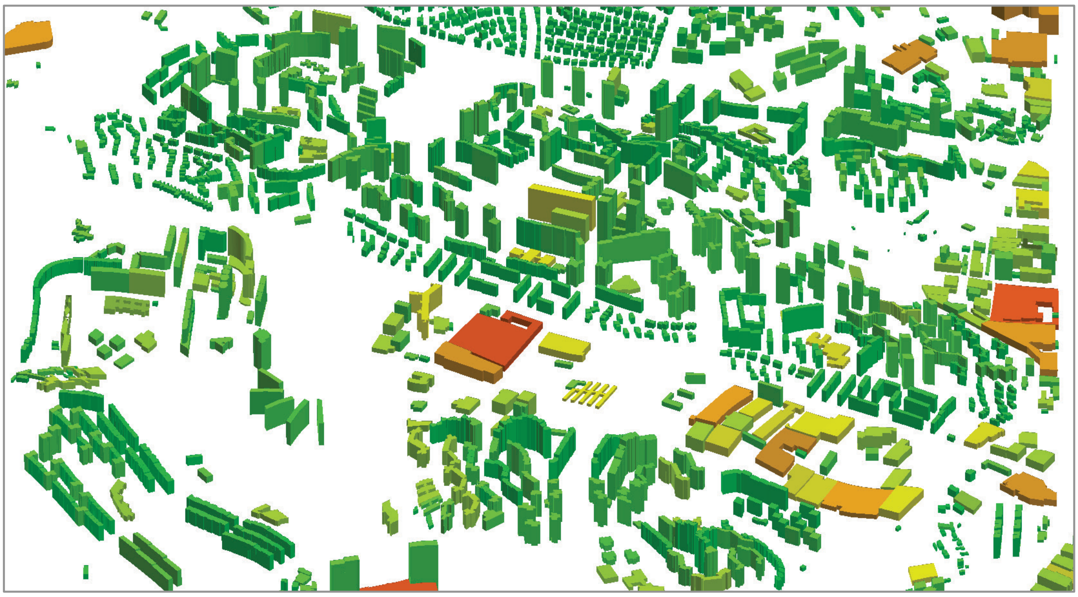


Figure 130: Floor Area Ratio example similar to Lisbon´s average result

The Average Height (AvHeight) metric shows a pattern that was predicted and that is that older typologies tend to have less height than more recent ones. To note that only from 1970´s onwards did the height of buildings increased significantly. That can be explained in part by the fact that there isn´t the tradition to build tall buildings in Lisbon, by the fact that the city is an active seismic zone, and also due to the orography of the city. As the city expanded outwards of the historic area, and to more plain areas, taller buildings began to be made as a response to both economic and demographic growth of the late 20th century (Figure 131).

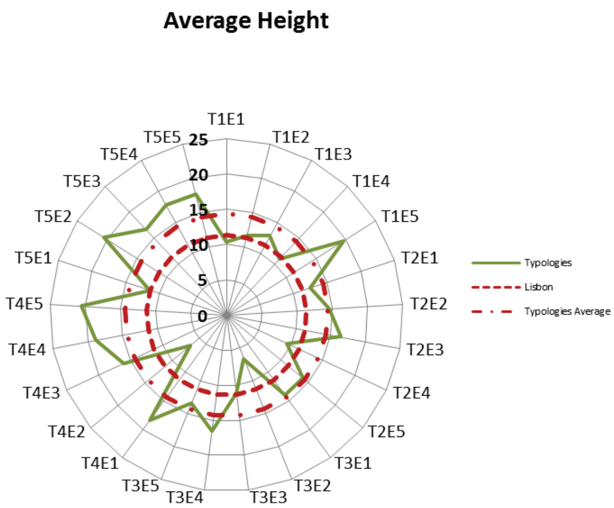


Figure 131: Average Height results for each selected case and Lisbon

The average height for the city of Lisbon is situated around 12 m. which gives a ratio of 4 floors/average per building. This result is strongly influenced by the more traditional urban areas that still have a large share of Lisbon´s building stock, as it is an example the urban area of Lapa/S. Bento (Figure 132 and Figure 133).

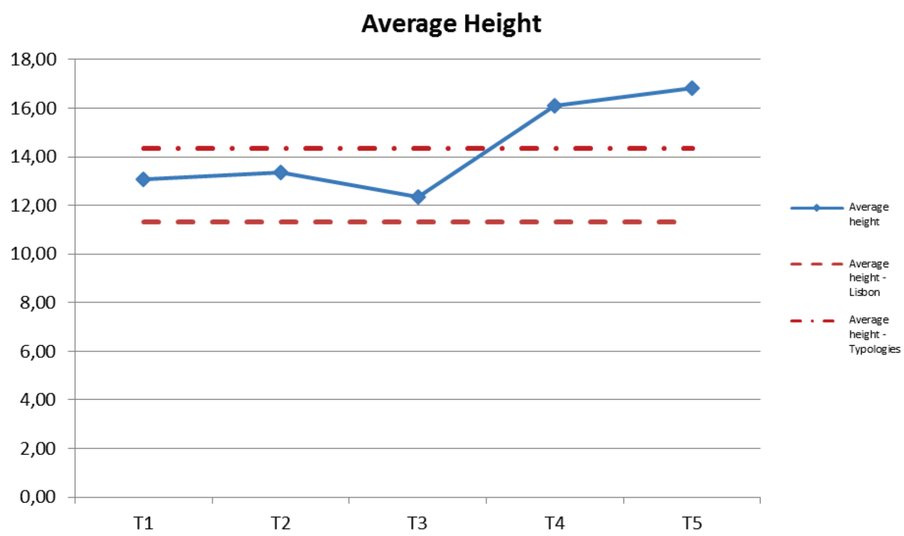


Figure 132: Average Height results for each typology and Lisbon

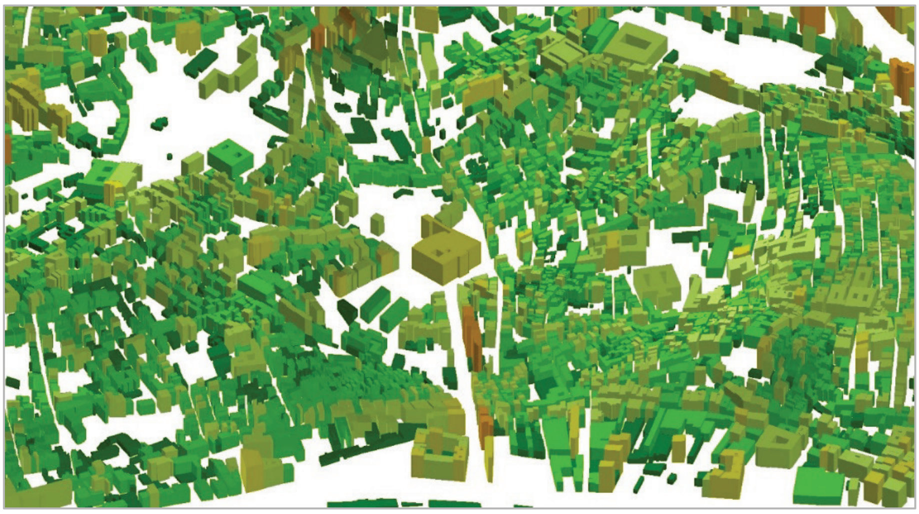


Figure 133 Average Height example similar to Lisbon´s average

The Road Density (RD) metric illustrates well the relation between the urban form configuration and buildings characteristics. The high values in the "before 1919"/ 1920-1945 and 1971-1990 typologies have however different causes: in the first case it is due to the very close and complex network that is characteristic of historic neighborhoods with small buildings, with small public spaces, and a network that was designed to walk and therefore associated with streets; the latter was due to urban forms which are not compact, made of separated and high density buildings, and configured for the use of automobile – associated with roads. Detached housing tends to have lower values of road density (e.g. samples T3E2, T3E3, T4E2) (Figure 134 and Figure 135).

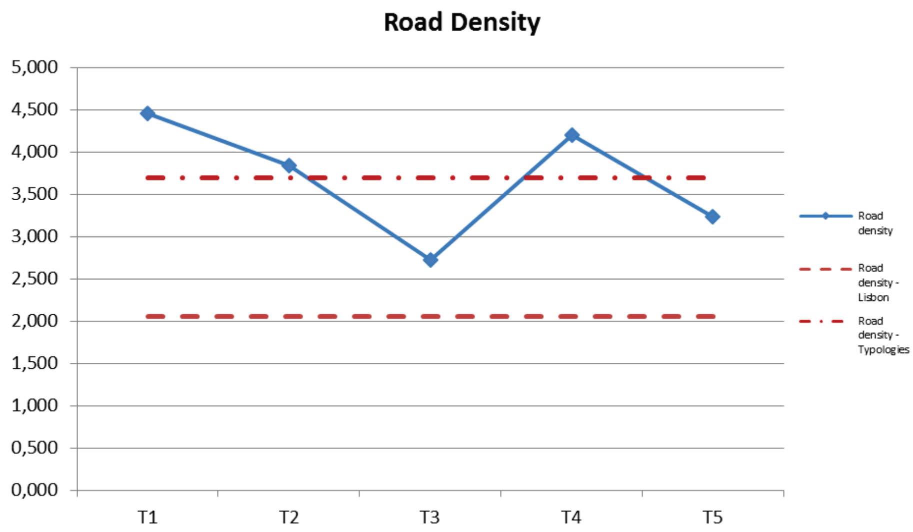


Figure 134: Road Density results for each typology and Lisbon

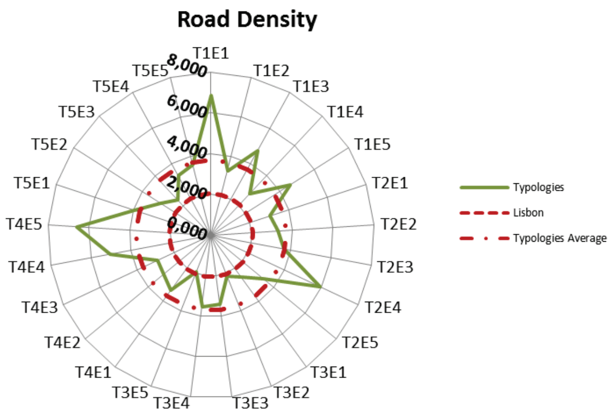


Figure 135: Road Density results for each selected case and Lisbon

The value obtained for Lisbon is closer to the detached housing typologies (more common in the 1945-1970 period). To note that this value is strongly influenced (negatively) by the fact that there are large areas in Lisbon that are naturally not covered by a dense street network, as it is the case of the Monsanto forest park and the airport, to name the two most important (Figure 136).

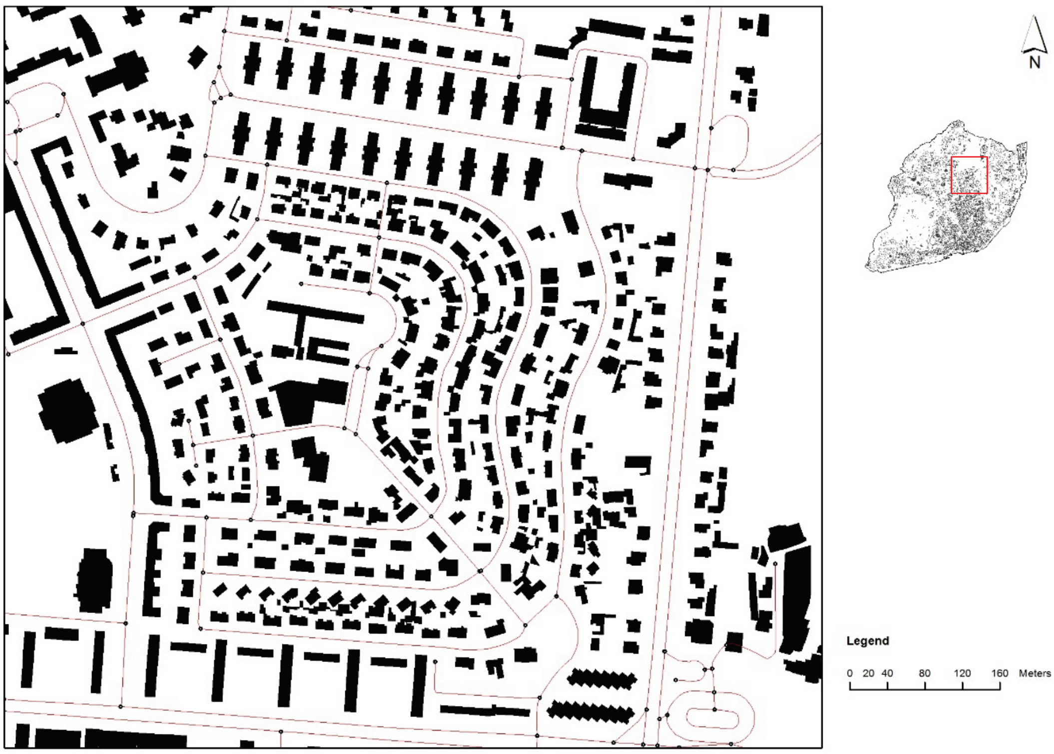


Figure 136: Road Density example similar to Lisbon´s average result

8.1.2 Intra-typologies analysis

Looking specifically into each typology it is possible to understand the differences between the urban form configurations of the same period and therefore understand why there are cases of typological samples of the same period that have different performances. The results that will be presented next for each typology were calculated taking into account the proportion of the typological sample value regarding the average of that indicator for the typology category of that sample, in order to understand if the performance of that specific typology sample is above or below the average for all typologies of the same period.

Looking at the "before 1919" typology (Figure 137) we can see that the T1E5 sample (Baixa) is the one which has the biggest discrepancies when compared to the "before 1919" typology average, namely in the FAR and average height indicators, presenting values above average, and below average in case of the surface-to-volume ratio. This can be explained by the fact that this was an urban area that was completely re-constructed from zero due to the Lisbon earthquake, and with a progressive urban plan for the time which focused on the development of an orthogonal street layout with urban blocks, large streets and a central avenue, and buildings with a considerable height (average of 6 floors) and volume compared to the existing stock in Lisbon. The T1E1 typology (Alfama) is the one with the highest road density due to its narrow streets configuration that was a result of the defense characteristics from the Moorish presence from before the 12th century, to the small buildings size that led to a short distance between streets, and to facilitate mobility that was made by foot or carriage. Both the T1E3 (Bairro Alto) and T1E5 (Baixa) present coverage ratios above the average, mainly due to their orthogonal display, and the lack of great public spaces and large avenues that lead to a short distance between buildings and a compact urban structure. The "before 1919" typology, Alfama (T1E1) stands out both in terms of the PD and the ED, which is a result of its extremely dense and compact urban form. Due to the existence of large elements (ISEG university and green area) in the case of Lapa (T1E4) lower values of PD where registered. The Baixa sample (T1E5) due to the regularity of its street network and building design presents a low share of ED when compared to the other samples. To note the uniformity in the MPFD values.

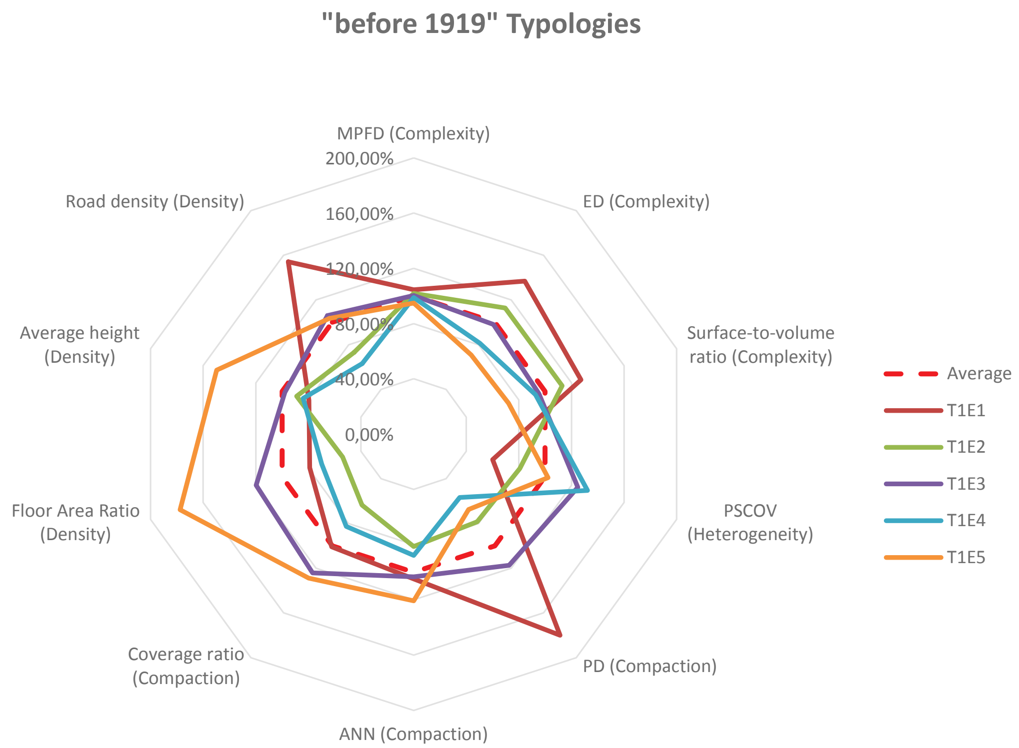


Figure 137: “Before 1919” typologies urban form results

The T2E4 (Arco do Cego) typological sample is clearly the example that is more unaligned with the average for the “1920-1945” typology (Figure 138). Mainly in terms of road density (above), but also in the FAR and Average Height (below), which give support to the idea that its configuration resembles still the patterns of the first group of typologies (close grid, small and short buildings) more than the actual urban design that was being implemented in the 1920-1945 period. The T2E3 (Avenidas Novas) sample presents a SV Ratio below the average, since it has large buildings (both volume and height) when compared to the average size of that period, which is reflected in the FAR metric that is the highest in the typological samples of this period. The Arco do Cego (T2E4) sample stands out in the case of PSCOV, due mainly to the size of a school and of an hotel that really outsize when compared with the residential houses dimension. Both Anjos (T2E5) and Penha de França (T2E1) samples present significant levels of uniformity in its building stock and thus the low value registered. The low values of PD in case of the Avenidas Novas (T2E3) typology is due to the large size of the buildings that have a great volume and many dwellings per floor.

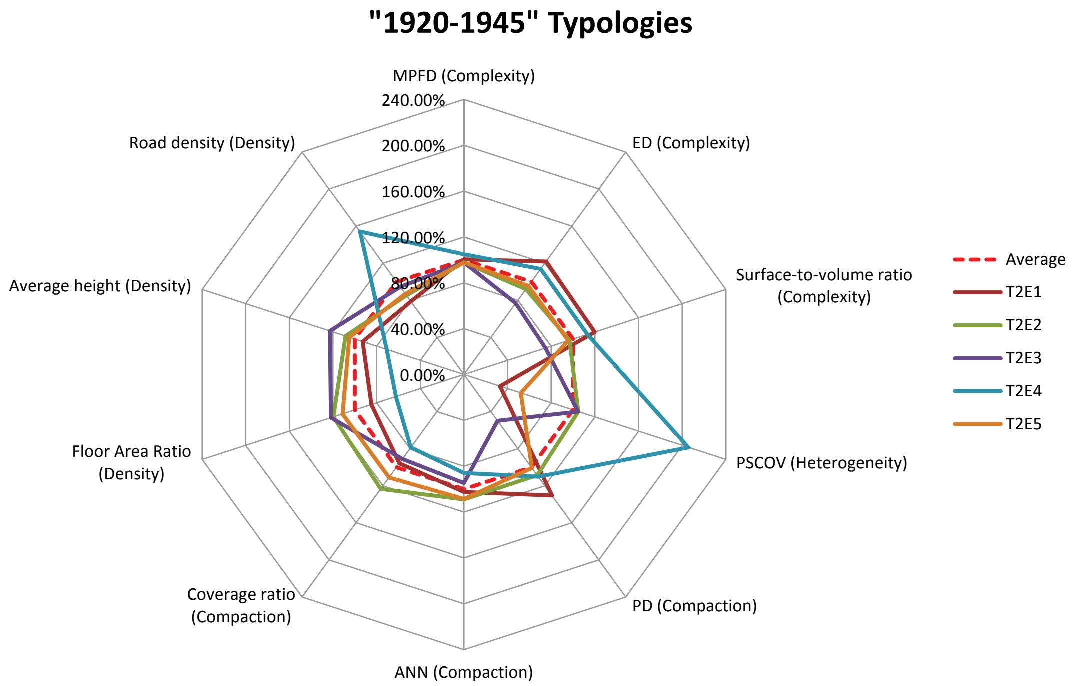


Figure 138: "1920-1945" typologies urban form results

In the case of the "1946-1970" typologies (Figure 139), we can see that the T3E1 (Campo Grande/Alvalade) was the typology that presented the highest difference concerning the average in what regards the FAR, and the Coverage Ratio, a very compact urban block of the Alvalade neighborhood, that presents a geometric organization of the buildings and streets, being that the buildings are of medium height but with a high volume due to their elongated shape. The T3E4 sample (Benfica), presents high values regarding the road density and average height, since this is an urban area with buildings mainly from the late 60´s, that have a considerable height (8 plus floors), and designed taking into account the automobile as the main mode of transportation. That can be seen in the streets layout that has a linear display, with few intersections and squares. Benfica is a neighborhood with a strong dependence on the automobile being mainly residential but well served in terms of services. The typology T3E2 (Alvalade) present a very high surface-to-volume ratio, mainly because it's a detached housing neighborhood, and thus the lower values of road density, FAR, and average height. Regarding the T3E3 (Olivais) sample, some of the features identified before in the analysis of the Olivais plan, namely the densification of the residential areas, the structuring of the buildings around a civic center of great dimensions (three schools and a church), and the abandon of the concept of neighbor unit, can be assessed through the metrics. That is the case of the low coverage ratio result since buildings are not displayed in a compact way but scattered in space, which influences the low FAR result, together with the existence of detached housing in the south-west corner. The high road density that was observed in this sample is also a characteristic of these types of urban forms. In what regards the Chelas sample (T3E3), it stands out in the case of PSCOV, since it has both detached housing, high-rise apartments, and then large equipment's as are a football field and a school, and has a low value of PD since buildings have medium-to-large areas separating them, an urban display of which the causes where already addressed before in the analysis of the Chelas plan. The Alvalade sample (T3E2) is a very different sample when compared to the others since it is mainly composed by detached housing, which contributes to the high value of PD, since each detached house counts as a building and therefore there is a huge concentration of buildings in a relatively small area, since a detached house occupies less space than an apartment building for instance. The ED value of this sample is also evident since each detached house as is own unique format, they are not exactly equal and that contributes to a more irregular pattern overall. To note also the important uniformity of the building stock in the case of the Benfica sample (T3E4), which is a consequence of the construction of the same building design in the same period, and the maintenance of that pattern until the present.

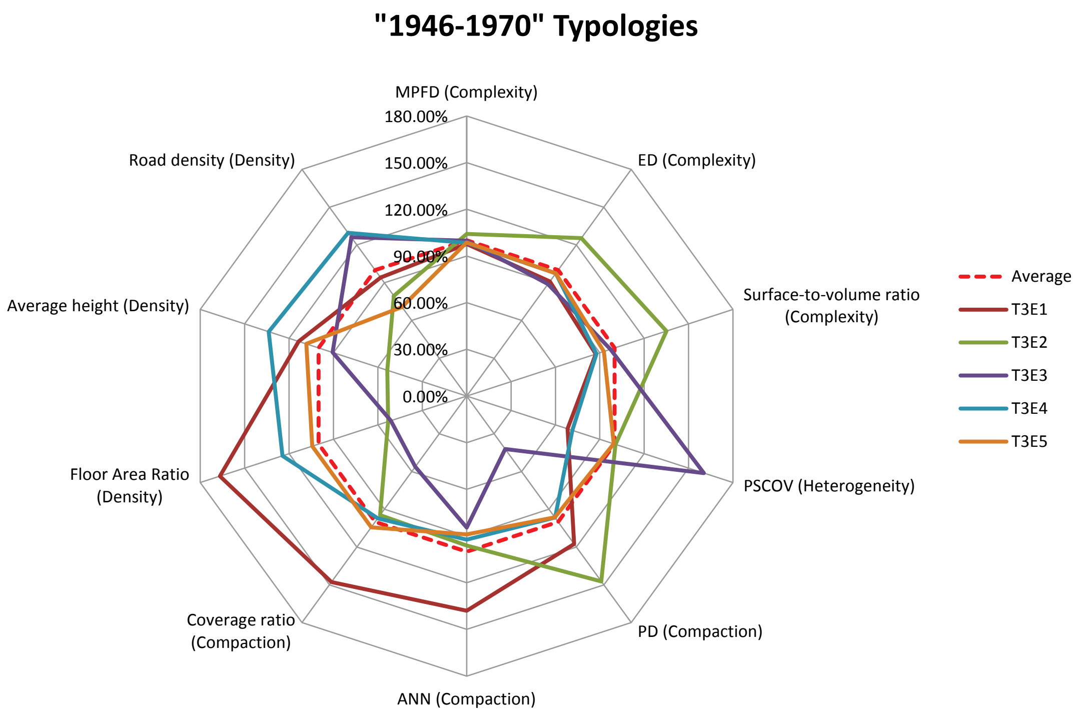


Figure 139: "1946-1970" typologies urban form results

The "1971-1990" typology (Figure 140) is a typology with great contrasts in their urban forms, and those are reflected in the samples. It was a period of experimentation and of transition from early urban models based in the modernist school, to urban configurations that re-introduced some traditional principles, but mainly on urban areas that lack the coherence of previous configurations. It was also the transition, in Lisbon, from a city model that was based in public transportation to one that was based in the automobile, which increased, generally, the fragmentation of the urban form. The T4E5 typology (S. Domingos de Benfica 1) has a high FAR due to its high-rise buildings, and its value of high road density its due to the fact that has a very important highway (2ª circular) that goes through the neighborhood. The T4E2 typology (Av. Brasil) has a high surface-to-volume ratio once again because of the high presence of detached housing, mainly shanty housing or precarious housing, and that explains also the low values concerning the average height, FAR, and road density. The T4E4 typology (Carnide) presents a very high coverage ratio since buildings display uniformly around the sample area, but this is also because all the other typologies from the same period have very low values. In the case of the T4E2 sample (Av. Brasil) it clearly presents the biggest difference in what concerns the PSCOV, since as it was addressed before, it is characterized by both large buildings (National Laboratory) and shanty housing. The low values in PSCoV of both the T4E3 and T4E4 samples (Chelas and Carnide) underline again the fact that these where planned neighborhoods since their conception which contributed to a certain homogeneity in their buildings design. In case of PD to note the high values of PD in case of the S. Domingos Benfica 1 (T4E5) sample, since this neighborhood is mainly composed by high-rise buildings, with relatively short streets (with the exception of the highway), and the low value of the Marvila (T4E1) sample, due to the separation of the buildings by green and vacant spaces.

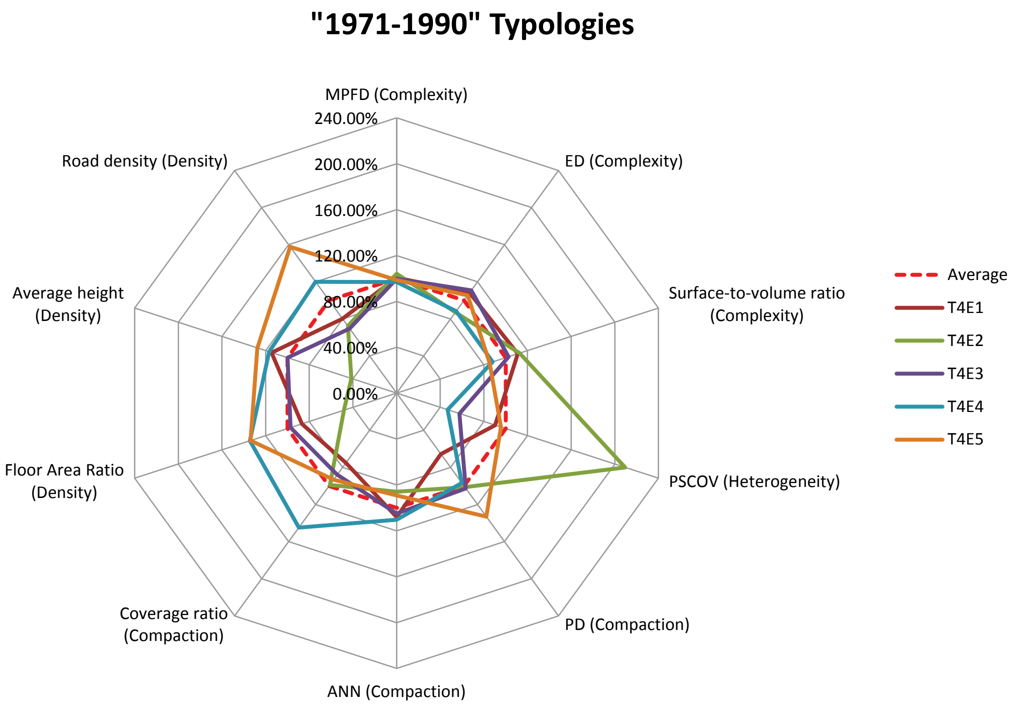


Figure 140: “1971-1990” typologies urban form results

In the "1991-present" typology (Figure 141), we can see that the T5E2 (Telheiras) typology has the highest FAR, this is due to the fact that this typology is almost fully composed of high-rise buildings, with an average of 6 floors and with a great volume. The fact that it has a high coverage ratio, together with the T5E1 typology (Parque das Nações), gives strength to the idea that the late 20th century, and beginning of the 20th century was characterized in Lisbon by the incorporation of sustainable urban design principles, namely the importance of urban design and the coherence of the image of the neighborhood, streets with large sidewalks to walk, green areas, public space for leisure, between others. The Lumiar 1 (T5E3) sample clearly has a higher value in the heterogeneity of its buildings size since it has both large buildings as are the Metro infrastructure and schools, together with mid-rise and high-rise apartment buildings and even detached housing, clearly remnants of the old urban structure associated with a rural occupancy. To note the differences of the two Lumiar samples (T5E3 and T5E5) that are of the same period and located in the same district but have completely different forms mainly in terms of heterogeneity of its buildings forms, and also in terms of their fragmentation (T5E5 less fragmented and T5E3 more fragmented) as it is clear in the ANN metric values. To note the high compactness of the Parque das Nações (T5E1) sample when compared to the other samples, the result of an urban design that is more associated with the urban block, denser structure, closed network with smaller width of streets.

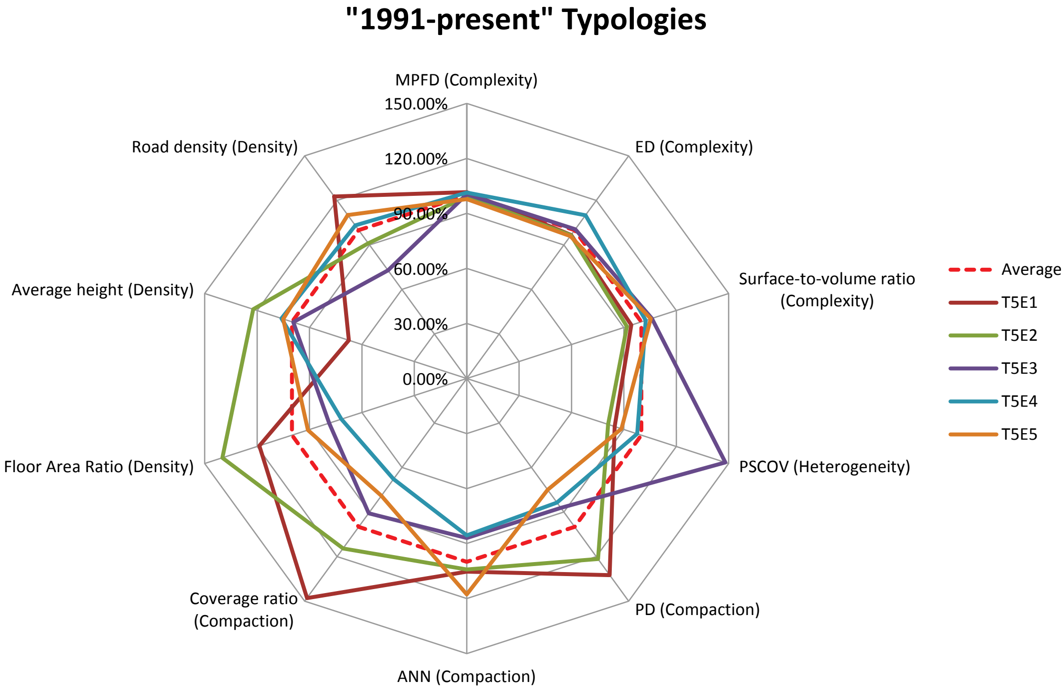


Figure 141 "1991-present" typologies urban form results

8.1.3 Correlations between metrics

To better understand the relation between metrics a Person Correlation analysis was made. Various correlations were found (Table 23 and Appendix x).

Table 23: Correlations found between urban form dimensions and metrics

Correlation type	Urban form dimension	Positive	Negative
Correlations inside dimensions	Complexity	MPFD-ED; MPFD-SV. Ratio	-
	Heterogeneity	-	-
	Compaction	PD-Coverage; ANN-Coverage; PD-ANN;	-
Correlations between dimensions	Complexity-Compaction	MPFD-PD; ED-PD; PD-SVRatio	-
	Complexity – Density	-	MPFD-AV. Height; ED-AV. Height; SV.Ratio-Av. Height
	Heterogeneity – Compaction	-	ANN-PSCOV;
	Compaction – Density	PD-FAR; ANN-FAR; ANN–Coverage; Coverage-FAR; PD-Road Density;	-

A strong positive correlation (at the 0.01 level) was registered between the MPFD, ED, PD, SV Ratio. In the case of the first three correlations, it indicates that as the value of one of those metrics increases the values of the other also increase, which gives support to the differences identified between compact (high complexity of the built environment, with smaller and irregular forms, and thus high building density) and disperse (low complexity of the built environment with regular and large forms and thus low building density), and thus the association between more space filling and traditional forms and less space filling and modern forms (Figure 142). The strong positive correlation between MPFD and SVRatio indicates that as the buildings forms became more complex – small and irregular so the SVRatio increases, and as they became less complex – large and linear –so the SVRatio decreases. This can be observed also in the work of Ratti et al. (2005:766) in which a Berlin urban sample (with larger and more regular buildings) has a lower SVRatio than London and Toulousse (with smaller and complex buildings). A strong negative correlation (at the 0.01 level) between MPFD and the Av. Height of buildings was also registered, indicating that buildings with a low height are more common in complex forms than taller buildings.

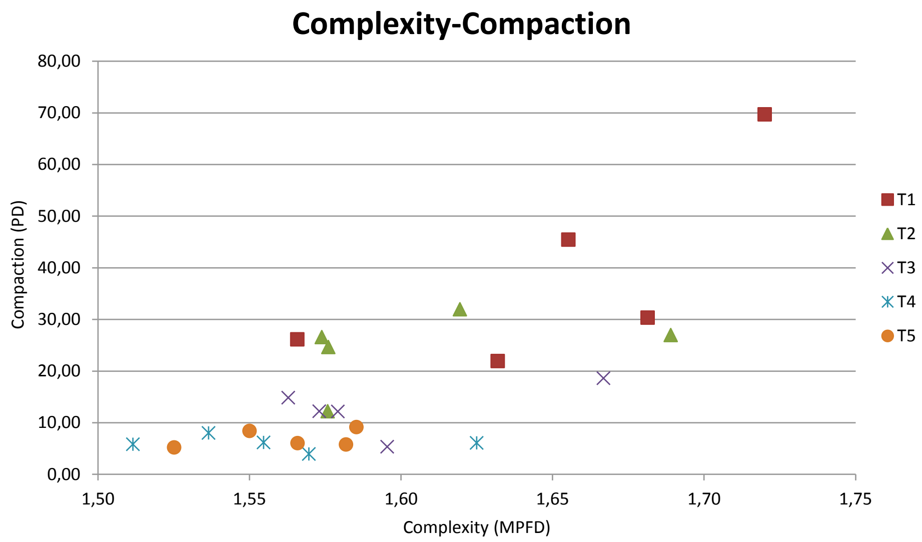


Figure 142: Complexity and compaction relation

A correlation at level 0.01 was found between ED, PD, Av. Height and SVRatio. The positive correlation between ED and PD shows that as the number of edges or the number of buildings increases the other variable also increases, which indicates that compact forms tend to be more complex, intricate, since there is less space available, and low densities tend to have less complex forms since there is more space available for larger buildings. The negative correlation between ED and Av. Height points out to the fact that as urban forms became more complex so their height tends to decrease. The positive correlation between ED and SVRatio indicates that as the complexity of buildings increases so the SVRatio, and this tendency can be related to the dynamics that were already analyzed in the case of the relation between the MPFD and SVRatio metrics. A positive (0.01) correlation was also found between SVRatio and PD. There is also a very significant negative correlation between the ANN and the PSCOV metrics, which indicates that as the variance of patches increases (heterogeneity), the ANN metric decreases, and vice-versa, which indicates that typically typologies with very different building sizes tend to be more fragmented (Figure 143).

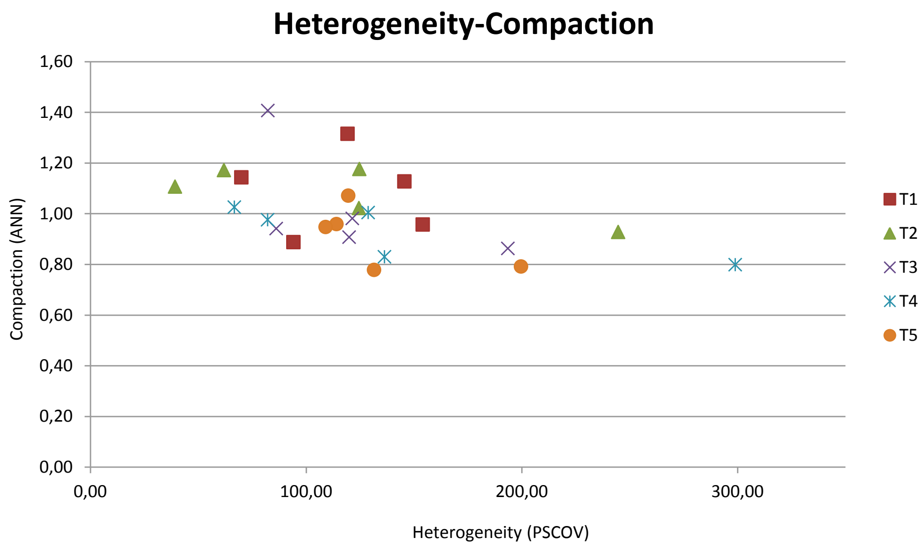


Figure 143: Heterogeneity and compaction relation

A strong correlation (0.01 level) was found between PD and Coverage, which indicates that more dense areas are also more compact areas. There are also important positive correlations (0.05 level) between PD, ANN, FAR and Road Density, which indicates that as the number of buildings per hectare increases their distribution in space becomes more compact and dense, as well as the corresponding street network. The strong correlation between ANN and Coverage points out to the same conclusion, while the other significant correlation between ANN and FAR, indicates that space filling urban forms are also the ones that have the highest density, this is also observed in the positive correlation between Coverage and FAR (Figure 144).

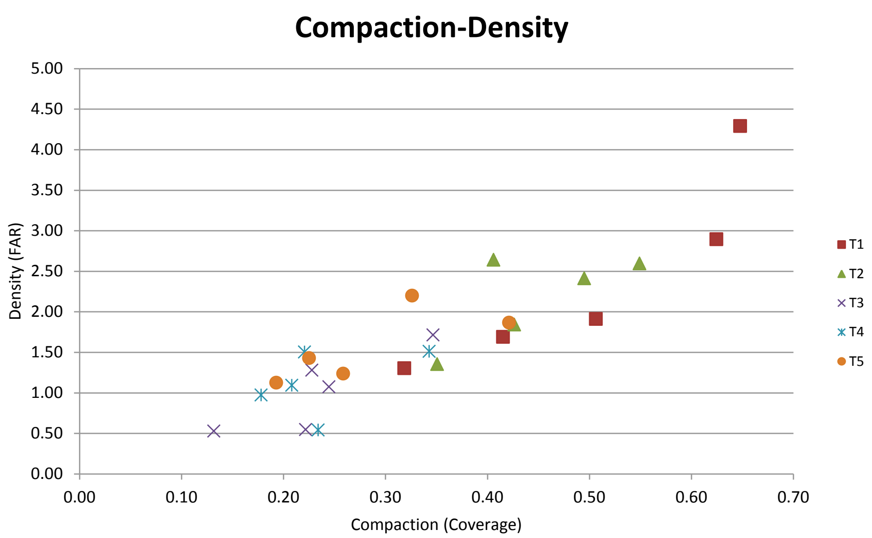


Figure 144: Compaction and density relation

A negative correlation was found between the SVRatio and Av.Height, indicating that smaller buildings tend to have higher SV Ratios, corroborating the idea of more elongated buildings and better insolation that was described before (Figure 145).

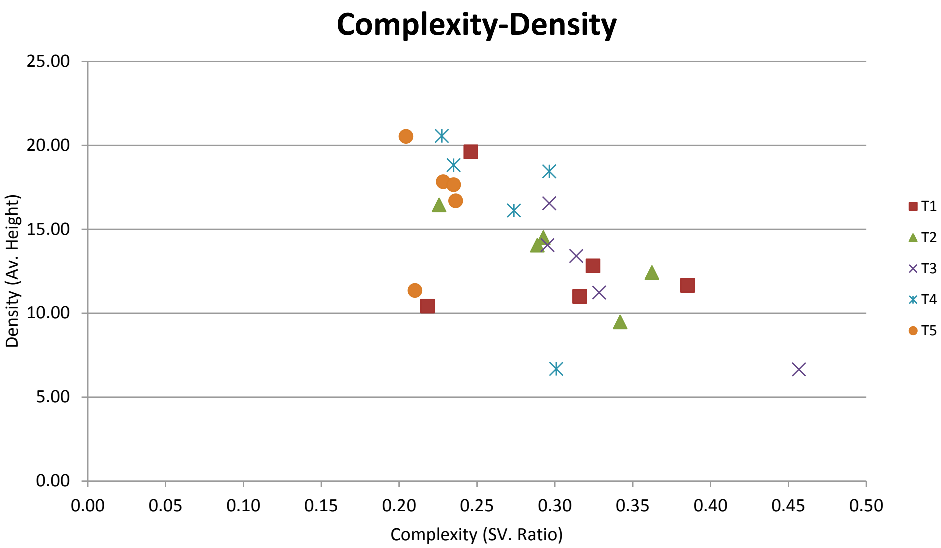


Figure 145: Complexity and density relation

8.1.4 Cluster analysis

The hierarchical cluster analysis was made to understand how the typologies would group if we took into consideration the urban form metrics results. This way similarities and differences can be extrapolated between forms and possibly different coherent urban patterns can be obtained for further analysis. The resulting typology cluster dendogram and membership table can be observed in Figure 146 and Table 24. More information on the calculated clusters can be found in the Appendix xi and Appendix xii.

Table 24: Cluster membership distributed according to 5 clusters

C4	C3	C2	C5	C1
T2E3	T1E3	T1E2	T2E4	T1E1
T3E4	T1E5	T1E4	T3E3	
T3E5	T2E2	T2E1	T4E2	
T4E1	T2E5	T3E2		
T4E3	T3E1			
T4E4				
T4E5				
T5E1				
T5E2				
T5E3				
T5E4				
T5E5				

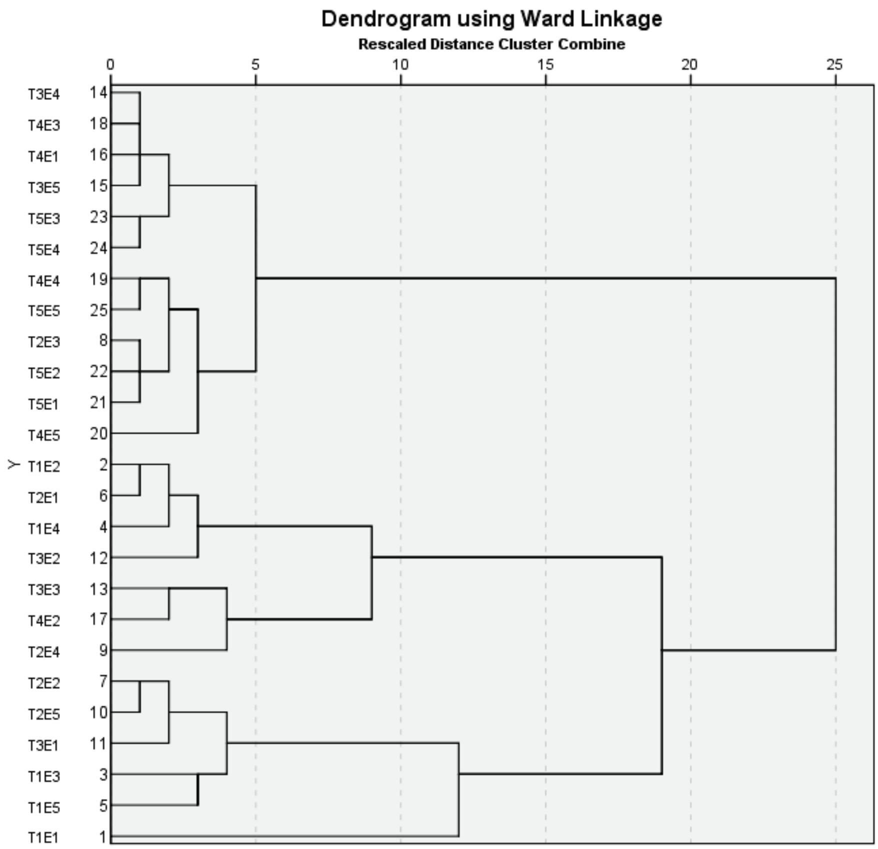


Figure 146: Dendogram using Average Linkage (Between Groups)

The analysis of the cluster membership was made through 4 dimensions for metrics analysis that were previously identified in the methodology section. A ranking was made in which the average values for each metric were analyzed by urban form dimension and cluster, and then all metrics ranks were averaged by urban form dimension in order to access the position of each cluster (Table 25).

Table 25: Ranking of clusters based on urban form metrics performance

Cluster	Complexity	Heterogeneity	Compaction	Density
C1 – Complex urban areas	1,00	5.00	1.67	2.33
C5 –Heterogeneous urban areas	3,33	1.00	4.67	4.00
C2 –Elongated urban areas	2,00	4.00	3.00	4.00
C3 – Compact urban areas	3,67	3.00	1.33	2.00
C4 – Modern urban areas	5,00	2.00	4.33	2.67

The cluster with the most extreme values (cluster 1) had only one typology, and it was the one of Alfama. This a cluster which comprehends a traditional typology that maintain (almost) intact their original form. It has a very high complexity of the buildings urban forms, low heterogeneity of buildings size, with high compaction and with a high density.

Cluster 5 is constituted by typologies from 1920-1945 (1), 1946-1970 (1), and 1971-1990 (1). Above all this cluster is characterized by urban forms that have a significant presence of detached housing together with large buildings and infrastructure that contribute to a high heterogeneity of their building stock. Influenced by this characteristic, it is a cluster that presents average levels of complexity and low levels of both compaction and density.

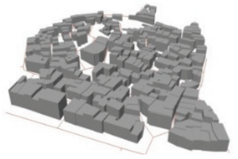
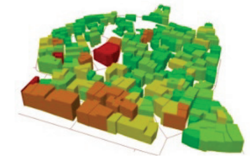
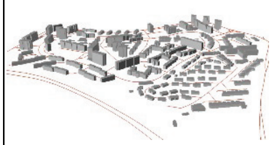
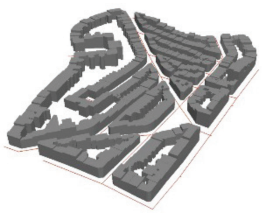
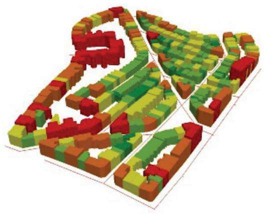
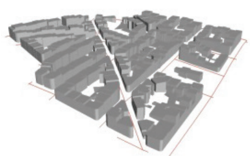
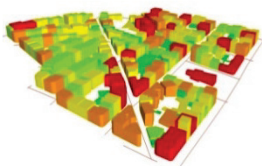
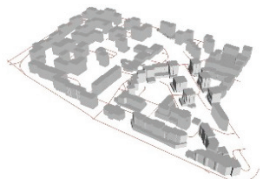
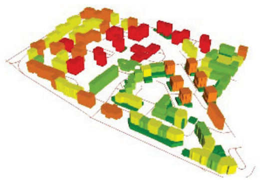
Cluster 2 is composed by typologies from "before 1919" (2), 1920-1945 (1), and 1946-1970 (1). This is a cluster that has elongated urban forms, with a very high Surface-to-Volume ratio. The metrics values are averaged when compared to the other clusters. To note high values in what regards MPFD and ED metrics, which indicate that the buildings in theses typologies have complex forms, and a relatively homogeneous urban form, indicated by the low levels the PSCoV metric. In what regards density these are forms with relatively low density values, as indicated by the FAR and road density metrics.

Cluster 3 is a cluster that has as a main characteristic the urban block configuration. It is composed by typologies from "before 1919" (2), 1920-1945 (2), and 1946-1970 (1). It is a cluster with urban forms that are very compact. Their buildings have medium complexity levels and low levels of heterogeneity in their size. Density levels are high, with a very high FAR and high building height when compared to the other typologies.

Cluster 4 encompasses mainly typologies that go from 1971 to nowadays: it presents 5 (all) typologies from "1990-present", 4 typologies from "1970-1990", 2 typologies from "1946-1970" and one from "1920-1945". The urban form of this cluster is more approximate to the modern urban planning with very low complexity in its buildings, medium heterogeneity in buildings sizes, low compaction and density.

In Table 26 the 5 types of urban configurations can be seen through 5 typological samples.

Table 26: 5 urban form clusters according to metrics performance, and examples on configuration, height and volume

Cluster	Metric	Configuration	Height	Volume
CLUSTER 1 Complex Urban Areas	++ (1.00) Complexity -- (5.00) Heterogeneity + (1.67) Compaction + (2.33) Density			
CLUSTER 5 Heterogeneous Urban Areas	= (3.33) Complexity ++ (1.00) Heterogeneity -- (4.67) Compaction - (4.00) Density			
CLUSTER 2 Elongated Urban Areas	+ (2.00) Complexity - (4.00) Heterogeneity = (3.00) Compaction - (4.00) Density			
CLUSTER 3 Compact Urban Areas	- (3.67) Complexity = (3.00) Heterogeneity ++ (1.33) Compaction ++ (2.00) Density			
CLUSTER 4 Modern Urban Areas	-- (5.00) Complexity + (2.00) Heterogeneity - (4.33) Compaction = (2.67) Density			

8.2 Analysis of the selected case studies

From the 5 identified clusters, 5 case studies were selected that exemplified best the main characteristics for each cluster. For cluster 1, characterized by the high complexity of its urban form, the typology of Alfama (T1E1), was the chosen one. Cluster 2, is characterized by its medium to low density and heterogeneity, and an urban form that is continuous with few intersections, being the typology selected Penha de França (T2E1). Cluster 3 is defined by its high levels of compaction and medium to high levels of density, being the typology selected Anjos (T2E5). Cluster 4 is characterized by its very low levels of complexity, being the typology selected Telheiras (T5E2). Finally, cluster 5 is characterized by its very high levels of heterogeneity and very low levels of compaction, being the typology selected Olivais Sul (T3E3) (Figure 147).

Figure 147: 5 selected typologies – Alfama, Penha de França, Anjos, Olivais Sul and Telheiras

According to the 2011 Census, and analyzing the statistic subsections that correspond to the typologies defined, the Telheiras typology is the one with the higher number of residents, followed by Olivais Sul. Penha de França and Anjos have generally the same population. Alfama is the typology with the lowest number of residents. Despite having the highest number of residents, Telheiras has a number of dwelling approximate to Olivais Sul, and is the typology with the lowest number of buildings, which indicates that has a high population density. Alfama, despite having fewer residents than the other typologies, presents a comparatively high number of both dwellings and buildings, which indicates that the number of residents per dwelling is not very high (Figure 148).

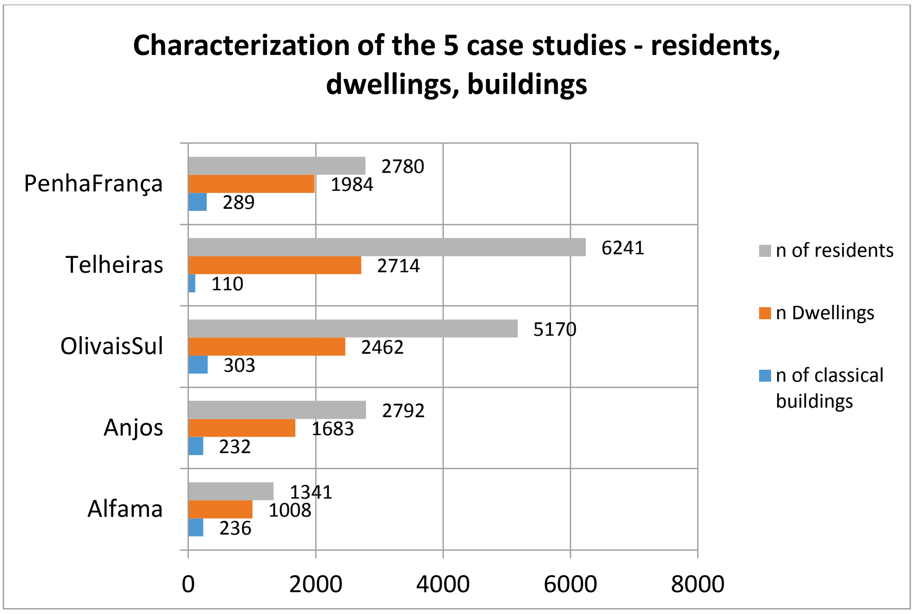


Figure 148: Characterization of the 5 case studies according to number of residents, dwellings and buildings

Making a brief characterization of the residents of the 5 typologies, it is possible to understand important specific characteristics in each typology. Telheiras is the typology with the highest share of young residents (28%), followed by Olivais Sul and Anjos (16-17% respectively), and Alfama and Penha de França (both with 13%) (Figure 149).

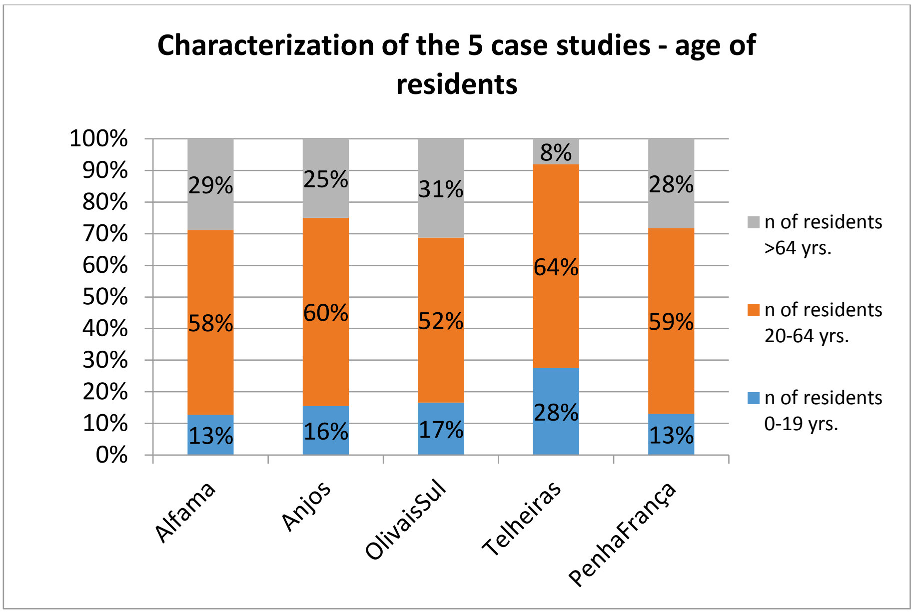


Figure 149: Characterization of the 5 case studies according to the age of residents

In what regards the education levels the most predominant one is the basic education, with the exception of Telheiras, that presents the higher education as the most predominant degree. This is a neighborhood which is characterized by a medium-high level of income of its residents, and preferred typically by people in qualified positions, namely in the higher education sector. To underline the similarity again between Anjos and Olivais Sul, now in what regards education levels, and also between Alfama and Penha de França, which is a tendency that is connected with the age of their residents already addressed below. Also to highlight the still large share of residents that don´t have any degree of education in Alfama that still represent 11% of the total population (Figure 150).

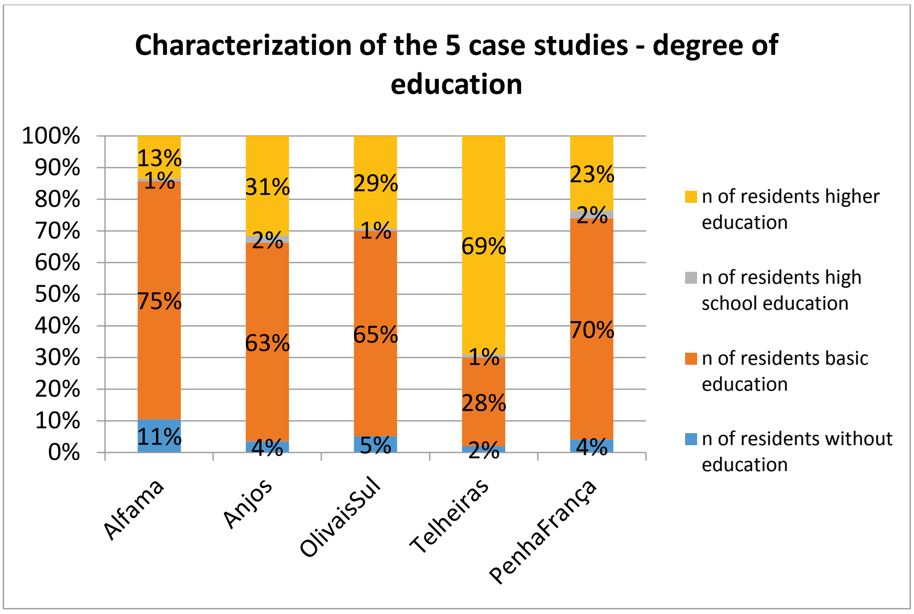


Figure 150: Characterization of the 5 case studies according to the degree of education

The share of residents with >65 years together with the young population and higher education students, contribute to the significant share of residents that don´t have a professional activity, either because they are retired (from 10%-27%) or simple don´t have an economic activity (from 28%-39%). The highest share of residents employed is in Telheiras, the lowest share in Alfama. The majority of the population in the 5 case studies works in the tertiary sector (87%-89%), followed by the secondary sector (10%-12%), almost no population works in the primary sector (Figure 151).

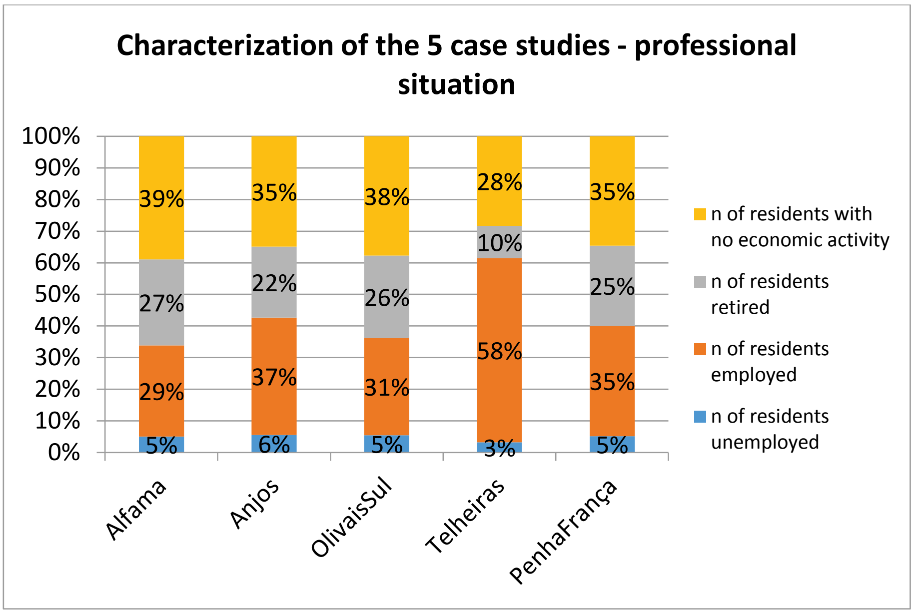


Figure 151: Characterization of the 5 case studies according to the professional situation

Regarding the workplace location, to highlight that almost 70% of the residents in Telheiras work in Lisboa, this can be explained by the more qualified activities that exist in a greater number in the city of Lisbon. On the other hand, in Alfama, nearly 55% of the residents that work, work outside Lisbon. Apart Anjos, where the majority of the residents work in Lisbon, in the other two typologies the majority of the residents work outside Lisbon (Figure 152).

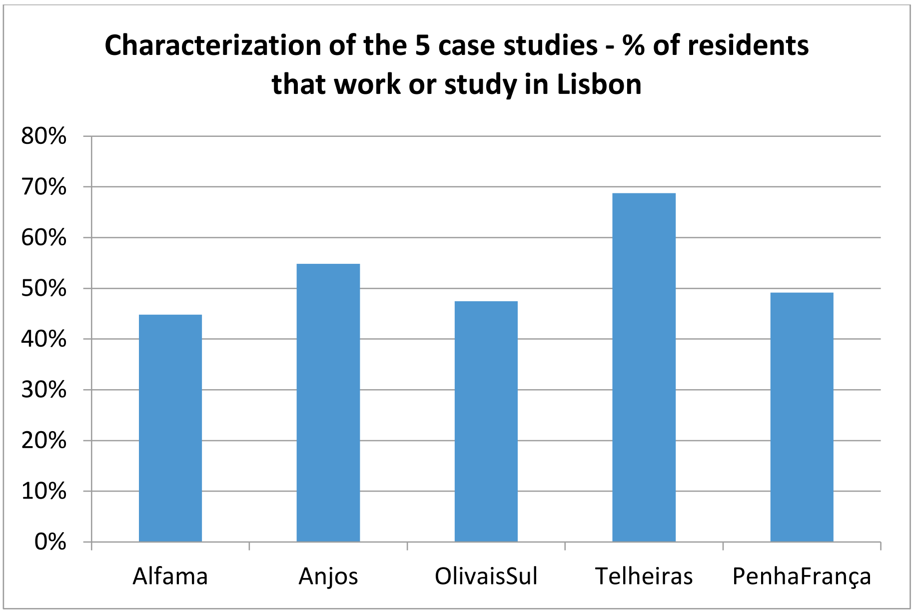


Figure 152: Characterization of the 5 case studies according to the % of residents that work or study in Lisbon

In what regards the building stock of the case studies and the predominant function of their buildings, Telheiras is the typology with a highest share of buildings that are mainly residential. This means that apart from the residential function, that is predominant, the buildings have other activity, which is an indicator of the diversity of the activities in a certain neighborhood. Olivais Sul is the typology which is more homogeneous in what regards its function, being the great majority of buildings exclusively residential buildings, which indicates that the commercial and services activity should be residual. Both Alfama and Anjos present a reasonable diversity in terms of functions, with around 33% of their buildings presenting more than one function. Penha de França has less diversity, being characterized mainly as a residential neighborhood, in the typology area that was analyzed (Figure 153).

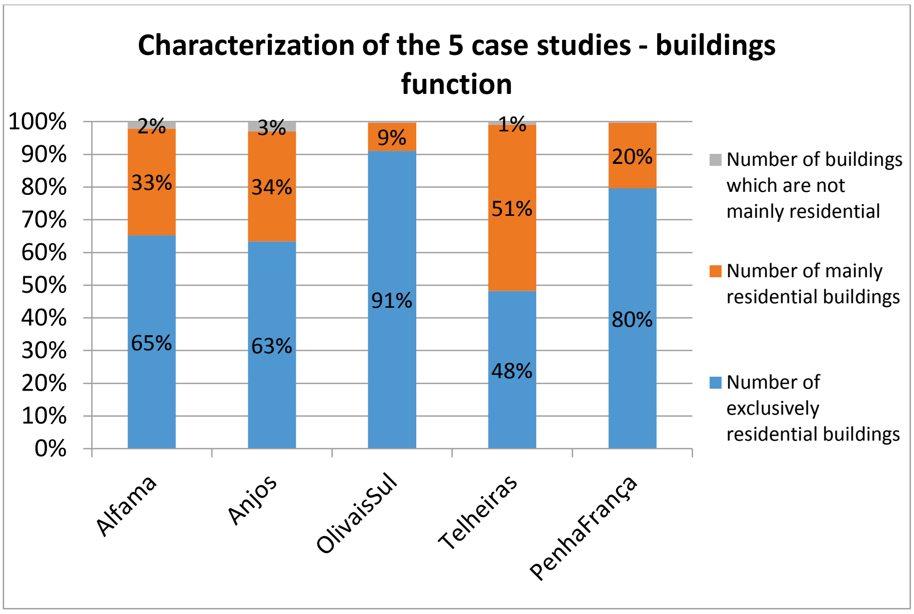


Figure 153: Characterization of the 5 case studies according to building function

Looking at the dwellings area, it is important to note the very small areas of the dwellings in Alfama, where 77% of the total dwellings have an area < 50 m^2, which can be related with the complexity levels identified in the chapter before. Penha de França presents a dwellings area slightly higher between 50-100 m^2. Both Anjos and Olivais Sul, despite having very different urban forms, present the very similar dwellings areas, having a mix of dwellings with 50-100m^2 and already an important share of dwellings with 100-200 m^2. Telheiras is characterized by dwellings with a much larger size, being the predominant the ones from 100-200m^2 , and having 12% of the dwellings with more than 200m^2 (Figure 154).

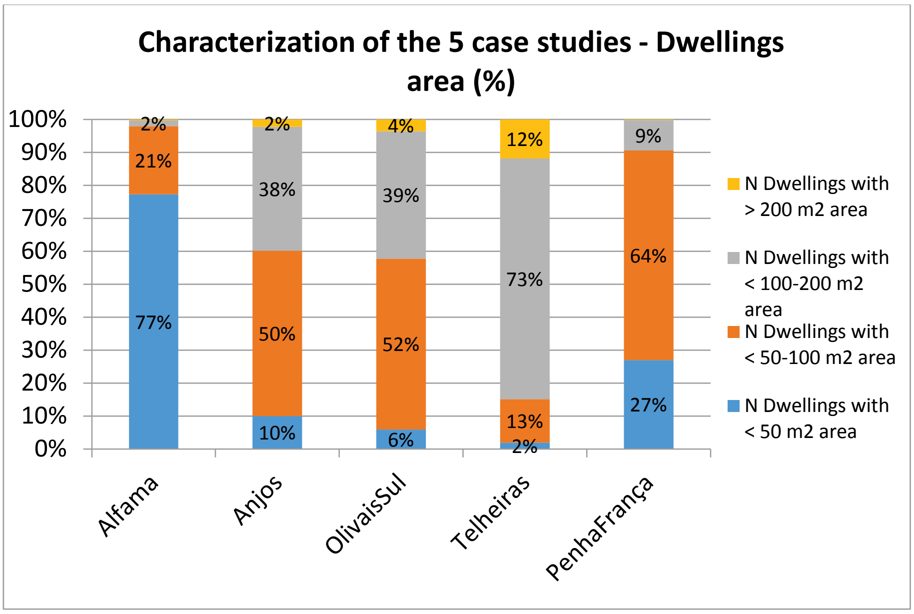


Figure 154: Characterization of the 5 case studies according to the dwellings area (%)

Despite having the larger dwellings with more than 200m^2, Telheiras is the typology with the larger population, and that can be explained by the importance of the buildings height and thus the vertical density of this typology, where 99% if the buildings have 5 or more floors. Anjos in this sense, is also a dense typology, presenting 62% of the buildings with 5 or more floors. Olivais Sul, despite having buildings with an important height is also characterized by an important share of detached housing, which lowers the share of buildings with 5 or more floors. Penha de França and Alfama, present a relatively low height for different reasons. In the case of Alfama it can be associated with the construction techniques that were available at the time most of the buildings were made, and their use and social origin, since they were made for the less wealthy population. Penha de França typology was designed to be predominantly residential, and that is why no more floors were added (Figure 155).

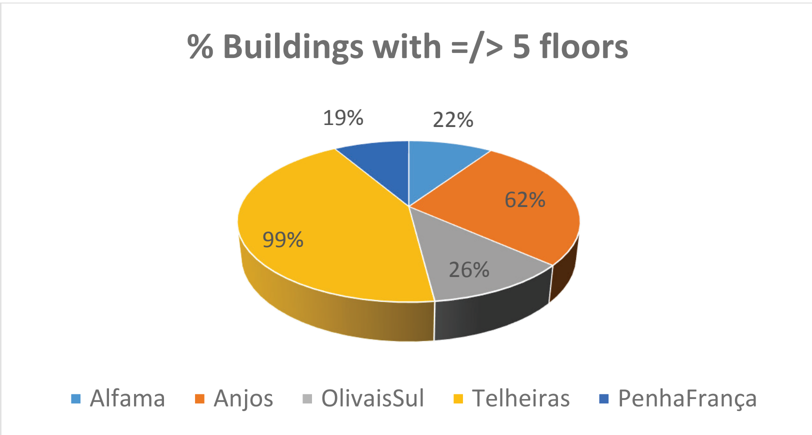


Figure 155: % of buildings with =/> 5 floors

In what regards the type of structure of the buildings in each typology, Alfama, the oldest typology of the 5, presented the majority of buildings without board, these are generally buildings which the structure is made of masonry, and the roof usually of wood and then ceramic roof tiles. To note also that Penha de França has a very large share of buildings without board. Anjos already presented an important share of buildings with board, these are buildings with the foundations, floors and roof made out of concrete, and became usual during the 1930´s in Lisbon. Both Olivais Sul and Telheiras present a majority of concrete buildings, Olivais Sul is a transition typology (as it was Anjos in what regards the transition from buildings without board to buildings with board), having still an important share of buildings with board (Figure 156).

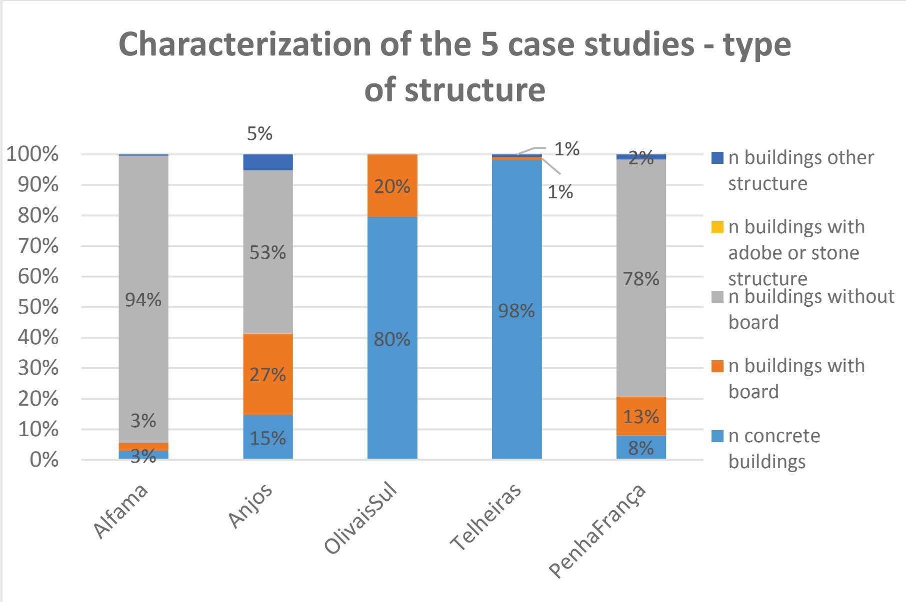


Figure 156: Characterization of the 5 case studies according to the type of building structure

9. Urban Energy analysis results

9.1 Passive and non-passive volume ratio

Passive and non-passive building zones are important since they "[…] *quantify the potential of each part of a building to use daylight, sunlight and natural ventilation*", being passive those that correspond to "[…] *all perimeter parts of buildings lying within 6 m of the façade, or twice the ceiling height* […]", and non-passive "[…] *all the other zones* […]" (Ratti et al. 2005:766). As it can be seen in the table below (Table 27 and detailed information in Appendix xiii), and if we eliminate the typology T4E2, that due to specific characteristics described before has a very low passive volume ratio, the passive volume ratios of the typologies that were identified tend to be lower in typologies with very large or large buildings, with squared or circular forms (less complex), than in typologies that are more complex, and with an intricate pattern.

Table 27 Passive volume ratio average results per cluster

Clusters	Average Passive Volume Ratio
Complex Urban Areas	99.37%
Heterogeneous Urban Areas	88.11%
Elongated Urban Areas	97.20%
Urban block	94.43%
Modern Urban Areas	90.60%

That tendency can be observed in the linear correlation that was made between the average footprint dimension of buildings across all typologies, and the corresponding ratios of passive volume, that resulted in a R^2 score of 0.53. Despite some outliers, the T1-T3 typologies present average footprint areas from around 100 to 250 m^2 and passive volume ratios of 95%. The T4 typologies are very dispersed in what regards their average building footprint areas ranging from around 300 – 600 m^2 and passive volume ratios of 90%. The T5 typologies are generally between 350 – 450 m^2 in average building footprint areas and with passive volume ratios of 85% (Figure 157).

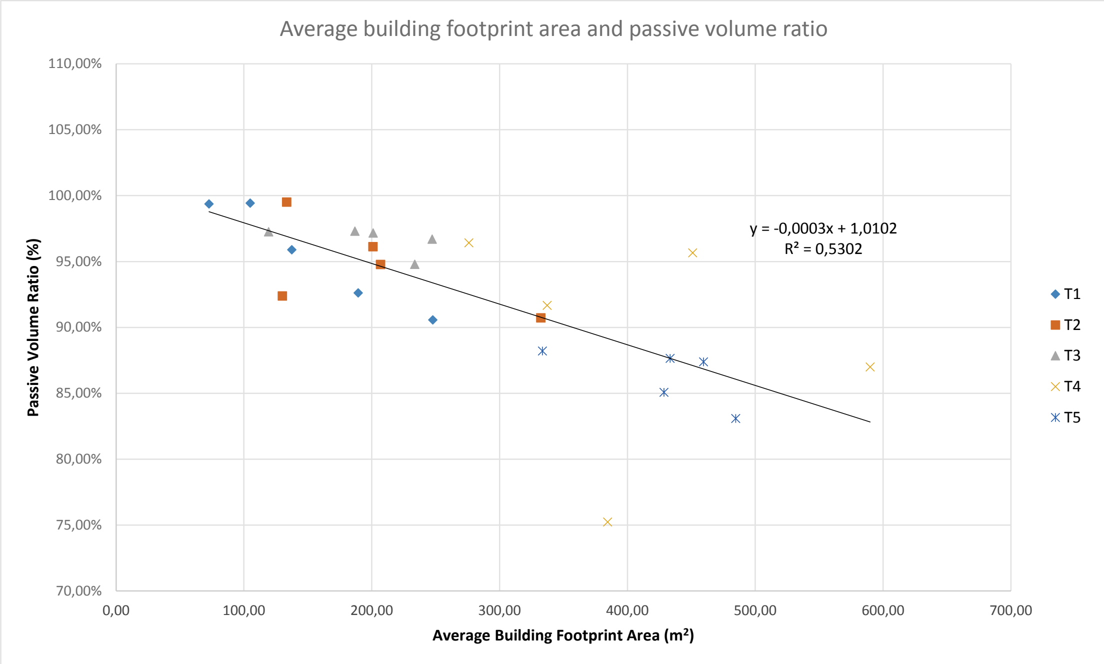


Figure 157: Average building footprint area and passive volume ratio relation

If we relate the passive volume ratio with average building volume no linear correlation can be found. This indicates that height does not influence passive volume, only area. To note that if we eliminate some non-aligned variables in each typology, that present values out of the average, we can understand a tendency for the T1-T3 typologies to group buildings average volumes from 1.500 – 2.500 m^3 and normally above passive volumes ratios of 95%; while in the T4 and t5 typologies the range in average volume ratios is higher from around 6.000 – 10.000 m^3, presenting the T4 typologies passive volumes ratios around 90% and the T5 around 86% (Figure 158).

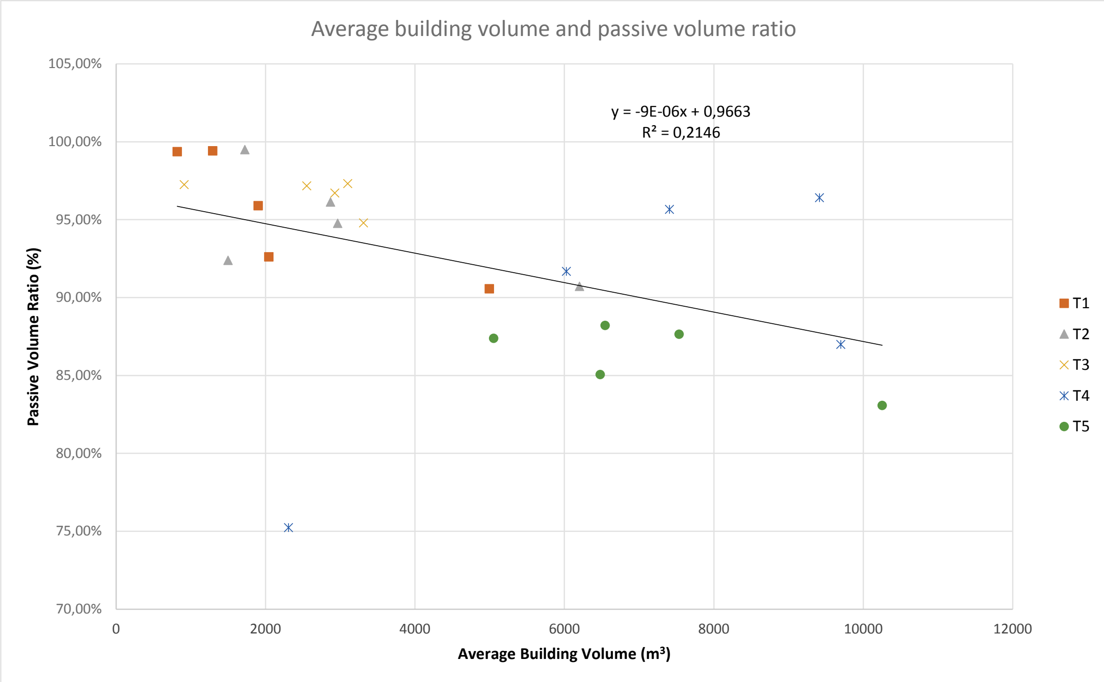


Figure 158: Average building volume and passive volume ratio

This tendency can be explained by the fact that the footprint area of a building is crucial in calculating the passive volume ratio, since as it was stated before, to understand what is a passive and non-passive energy building area a distance of 6 m from the façade to the interior of the building is considered. For instance, buildings with a diameter of 12 meters or less but with increased height don't have almost any non-passive volume, but have a very high volume. Thus a high volume can be registered both in typologies that have a low passive volume ratio or a high passive volume ratio, since what is important in defining this ratio is the area of the building, that is in a non-passive energy zone. That is the case for instance of the T4E5 (Benfica) typology with a passive volume of 96% and an average building volume of 9413 m3 when compared to the T4E4 (Carnide) typology that has a passive volume of 87% and average building volume of 9698 m^3 (Figure 159).

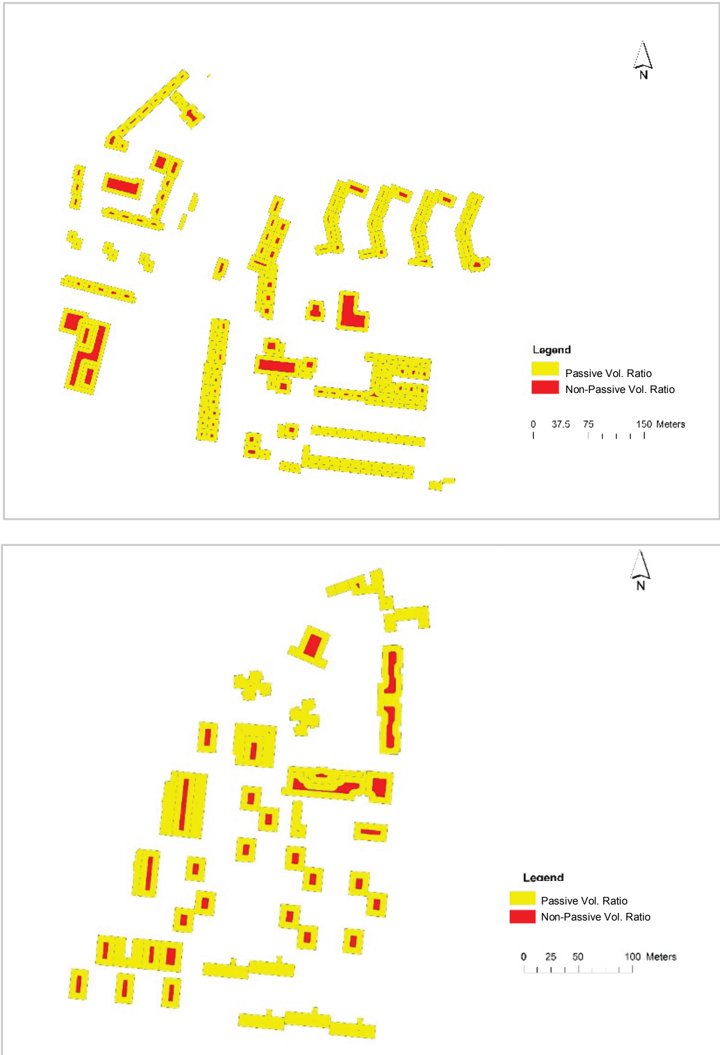
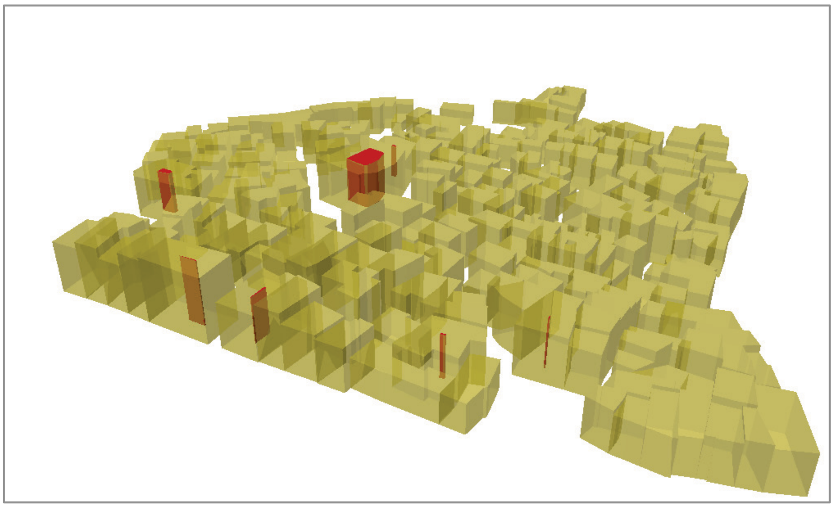


Figure 159: Passive and non-passive volume ratio of the T4E5 (top) and T4E4 (bottom) typologies

If look closely into the 5 typologies it be can easily understood the impact of passive volume ratio in each typology. 4 of the typologies present very high volume ratios, specially T1E1 (99,37%) and T2E1 (99,50%). These typologies have nearly no non-passive volume ratio (Figure 160).



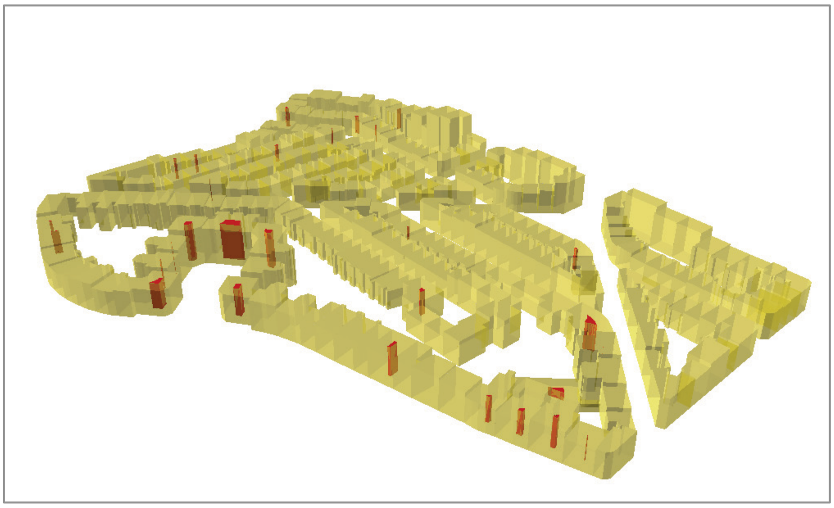


Figure 160: T1E1 and T2E1 typologies with a passive volume of 99% (Non-passive volume is represented in the areas in red, all the other areas are passive volume)

Both the T3E3 and T2E5 typologies present high passive volumes of around 96% (Figure 161), but the reasons of these results differ. While on the T3E3 typology the largest share of non-passive volume ratio is concentrated around very few buildings, in the case of the T2E5 typology the non-passive volume is much more dispersed, presenting the majority of buildings some expression of non-passive volume. This indicates that potentially the impact of a high share of passive volume is more present in the T3E3 typology, since it affects more buildings, and also because of the shading effect in this typology that is much less significant than the T2E5 typology, as it will be also seen in the urban daylight chapter.

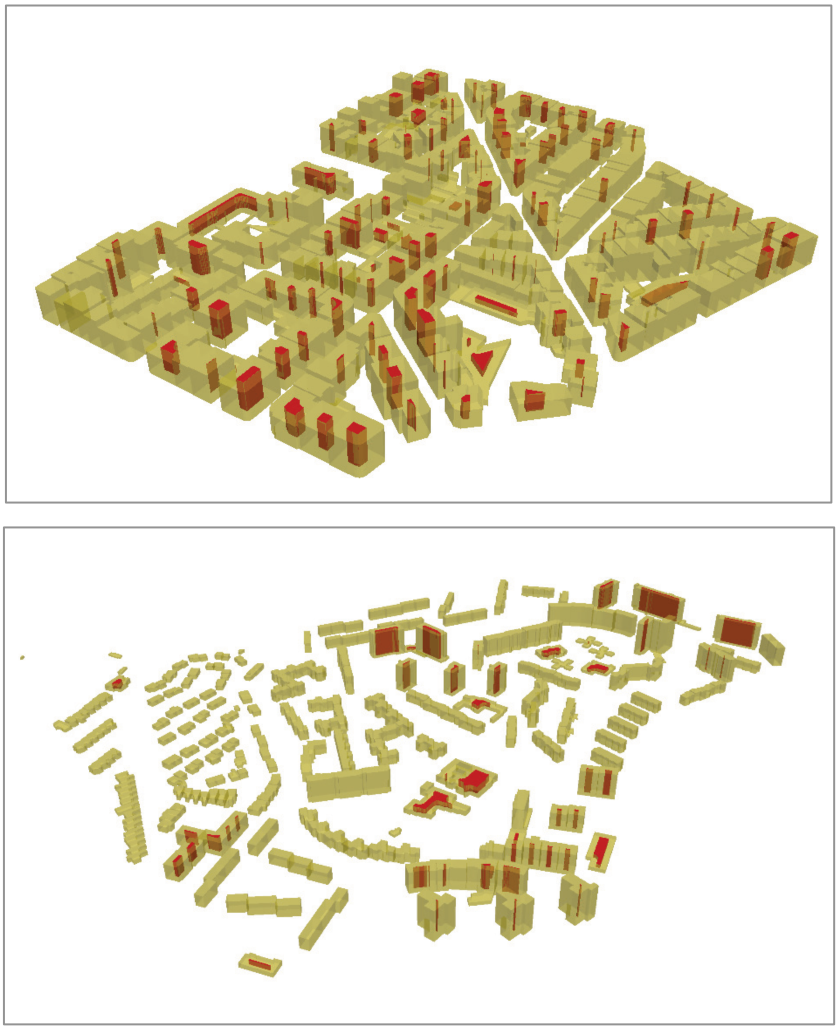


Figure 161: T3E3 and T2E5 typologies with a passive volume of 96% (Non-passive volume is represented in the areas in red, all the other areas are passive volume)

The T5E2 typology presents an average passive volume ratio of 83%. It is the typology from all the 25, who presents the lowest value. As it can be seen in Figure 162 nearly every building has non-passive volume, and this is due to the large footprint areas that characterize this typology.

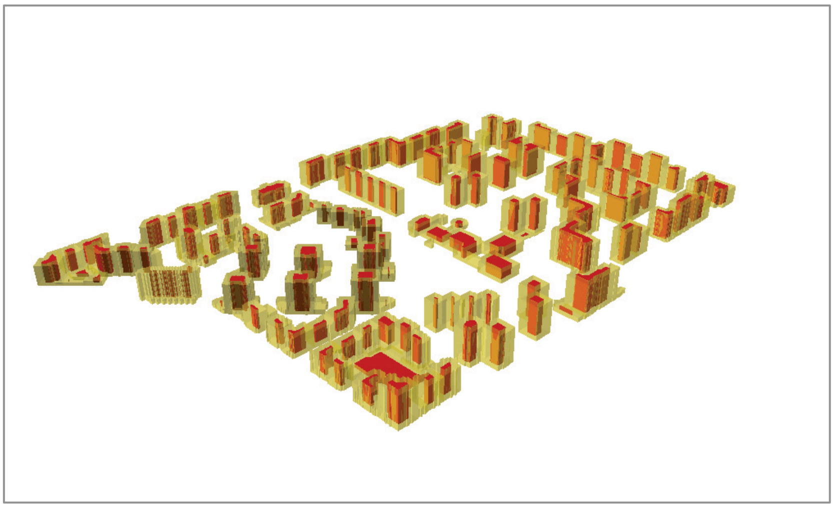


Figure 162: T5E2 typology with a passive volume ratio of 83% (Non-passive volume is represented in the areas in red, all the other areas are passive volume)

9.2 Urban daylight analysis

Apart from the built environment, that has a crucial impact in the shading conditions of a typology as it will be seen further ahead, elevation and the main orientation of the typology also contribute to the total solar radiation received and consequently the shading effect. Total elevation, average elevation, and elevation standard deviation were calculated for the 5 case studies; also average orientation was also calculated to understand the overall orientation of the selected cases buildings (Table 28). To calculate the elevation for each typology, information of the altimetry for the city of Lisbon (point shapefile for ArcGIS) was used, also a TIN was created with this shapefile in order to model the slope of the terrain. To calculate the main orientation of the buildings, the ArcGIS tool *Calculate Polygon Main Angle* was used. This tool calculates the dominant angles (from -90º to 90º) of input polygon features and assigns the values to a specified field in the feature class. The geographic option was selected, so the angle is calculated clockwise with 0 at top/north. Both T1E1 and T3E3 presented somewhat considerable slopes, which are more evident in T1E1 since the area is much smaller originating a higher inclination. This fact has conditioned the buildings characteristics, and is in part one of the reasons why this typology has been maintained as it is through time. Both T2E1 and T2E5 have an elevated area, but overall the typologies don´t have dramatic differences of elevation. T5E2 is the plainest typology (Figure 163). In what regards orientation, all typologies have good average solar orientations, which allow the maximum exposition to sun light, which in the particular case of Lisbon, Portugal, could not be entirely positive, due to climate conditions, which tend to be hotter than colder (Figure 164).

Table 28: Terrain elevation (total elevation, standard deviation, average elevation), and orientation properties (average orientation, and N-S orientation) for each typology

Typology	Total Elevation (Difference between highest and lowest point)	Standard Deviation Elevation	Average Elevation	Average Orientation	N-S Orientation
T1E1	50,738	16,09	18,51	-2,7	N-S
T2E1	29,182	7,40	84,26	-21,3	NW-SE
T2E5	36,137	9,25	47,57	-13,5	NW-SE
T3E3	61,298	13,43	89,18	-5,62	N-S
T5E2	21,943	3,85	107,35	-20,3	NW-SE

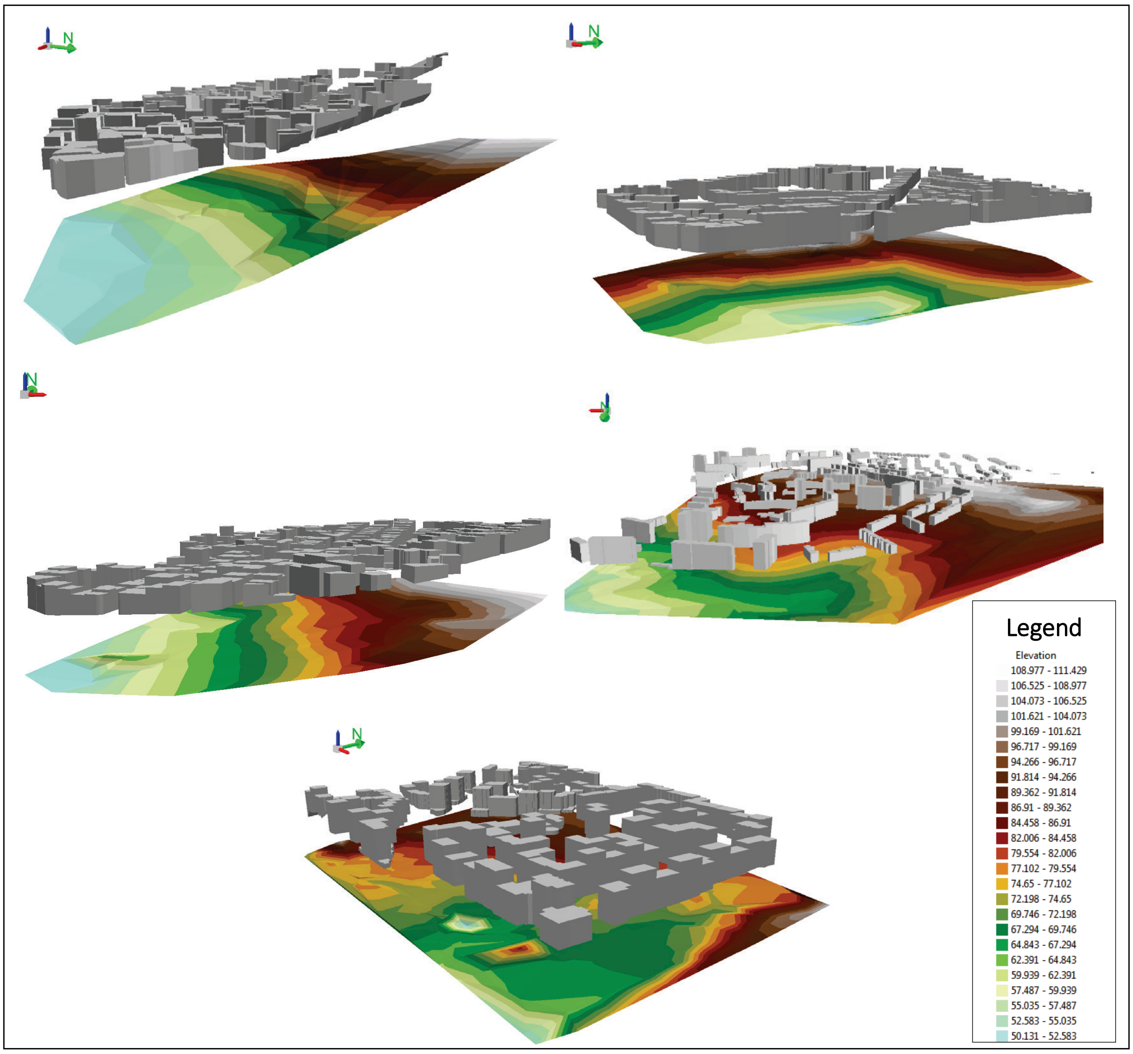


Figure 163: Terrain elevation for each typology

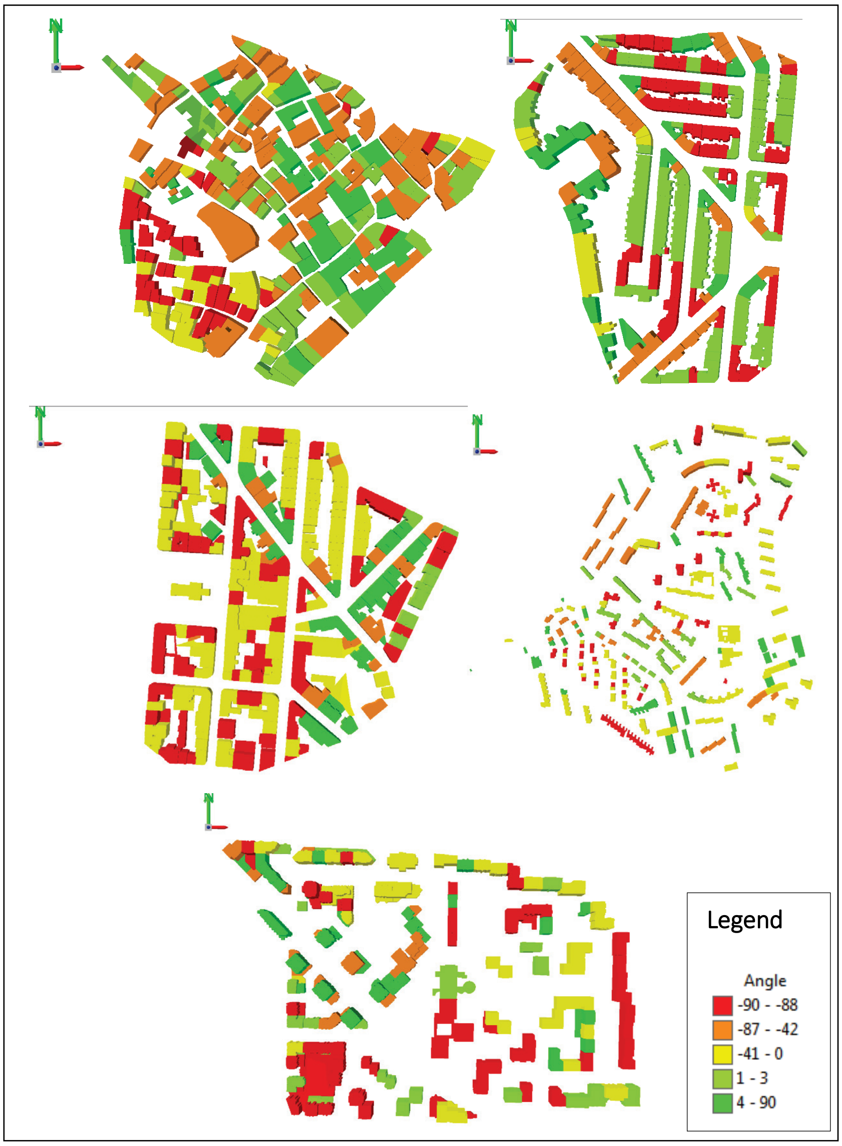


Figure 164: Predominant orientation the buildings facades (Red: West/ Yellow: North or South/ Green: East)

In what regards urban daylight metrics, the complete set of calculated metrics – CDA: Continuous Daylight Autonomy; DA: Daylight Autonomy; ER: Envelope Radiation - for each typology is presented in Table 29. Next each urban daylight metric results will be analyzed.

Table 29 Urban daylight metrics for each typology. CDA – Continuous Daylight Autonomy; DA – Daylight Autonomy; ER – Envelope Radiation

Typology	CDA (m2)	CDA (%)	DA (m2)	DA (%)	ER (Mluxh/t)	ER (Mluxh/t) / Total Envelope Area (m2)
T1E1	40411	58%	25770	37%	2379656	15,96
T3E3	256400	84%	221217	72%	8857655	21,52
T2E1	100302	66%	65747	43%	4126456	15,76
T2E5	160624	57%	93553	33%	5898791	15,06
T5E2	342903	59%	200881	35%	9576452	18,53

In what regards envelope radiation from the 5 case studies Olivais Sul typology (T3E3) presented the higher envelope radiation received with 21, 52 Mluxh/t (by Total Envelope Area – m^2), followed by Telheiras (T5E2) with 18,53 Mluxh/t (by Total Envelope Area – m^2). The remaining 3 case studies presented similar values around 15 Mluxh/t (by Total Envelope Area – m^2). Two positive Pearson correlations with some importance were found between ER (m^2) and both CDA (0,82) and DA (0,83), which point out to the fact that as the solar radiation increases so the daylight autonomy of the typologies. Both CDA and DA presented, as it was expected, strong significant Pearson correlations (0,99). No significant correlations were found between passive volume ratio and CDA and DA, an important negative but not significant correlation was found between ER (total) and passive volume ratio, which indicates that has the ER decreases so the passive volume ratio (Figure 165).

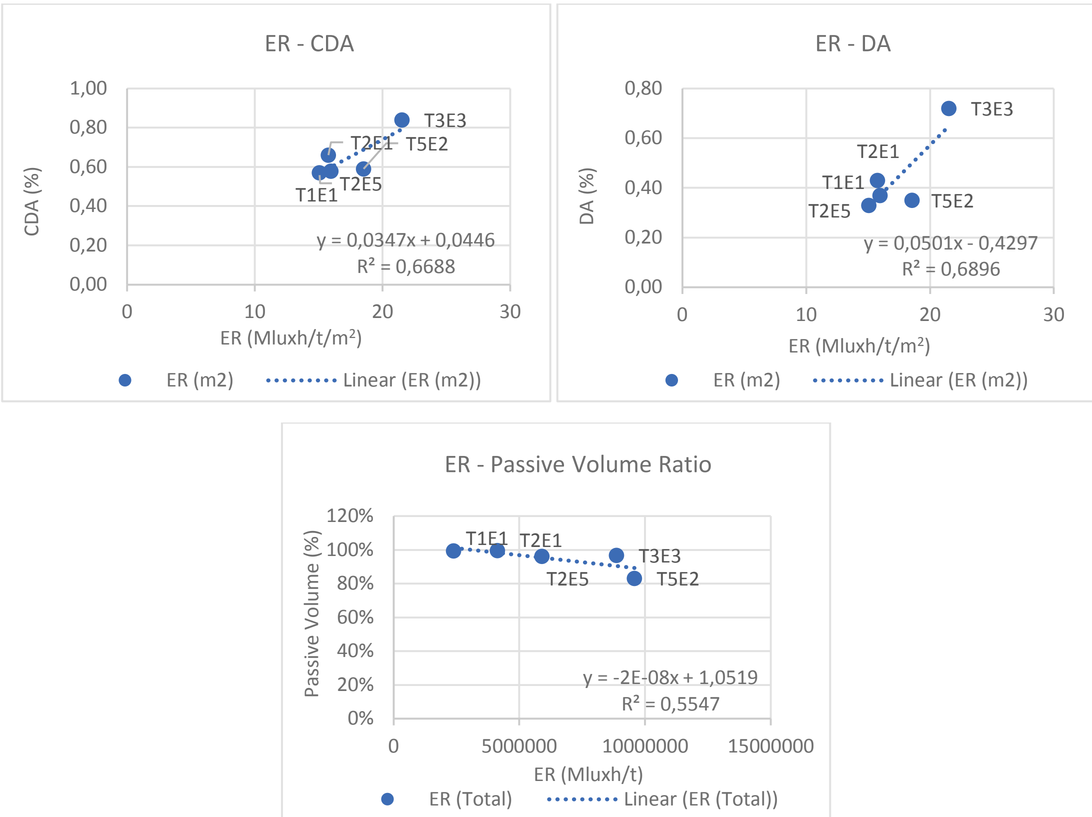


Figure 165: Linear regression between ER-CDA, ER-DA, ER-Passive Volume

Comparing the envelope radiation results with the urban form dimensions identified some important relations can be found. ER (total) presented important correlations with MPFD (-0,837) and SVRATIO (-0,844), and significant relation (at 0.05 level) with ED (-0,948) (Figure 166).

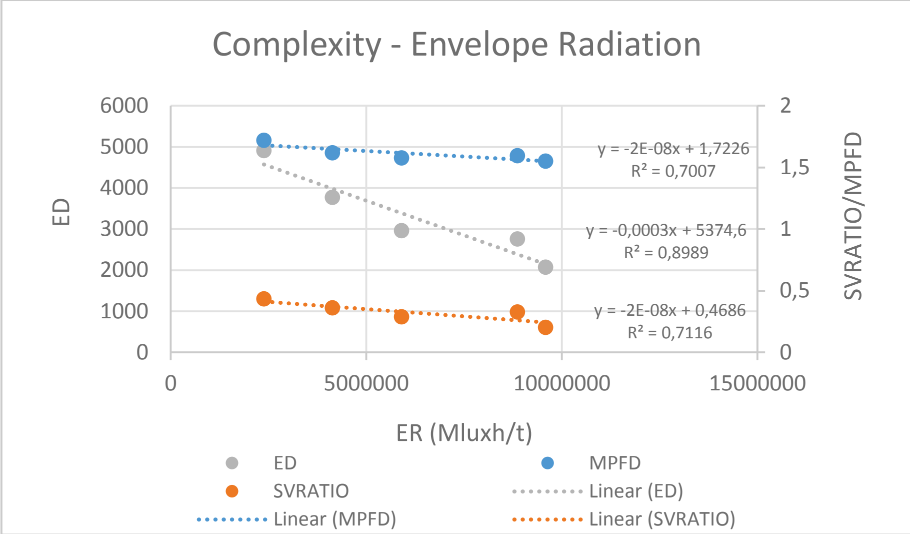


Figure 166: Linear regression between complexity and envelope radiation

Significant correlations were found between compaction (CR [-0,975 at 0.01 level], ANN [-0,976 at 0.01 level) and envelope radiation, and heterogeneity (PSCOV [0,967 at 0.01 level]) and envelope radiation. In what regards compaction, typologies which presented low values of compaction (T5E2, T3E3) – in buildings density, coverage ratio and average near neighbor – present high values of envelope radiation and vice-versa. It is therefore plausible to conclude that typologies which are more fragmented but also disperse have a higher exposure to the sunlight and therefore higher values of envelope radiation. Typologies which are more compact (T1E1, T2E1, T2E5), present higher levels of shading, buildings are closer to each other, and therefore, lower levels of envelope radiation (Figure 167).

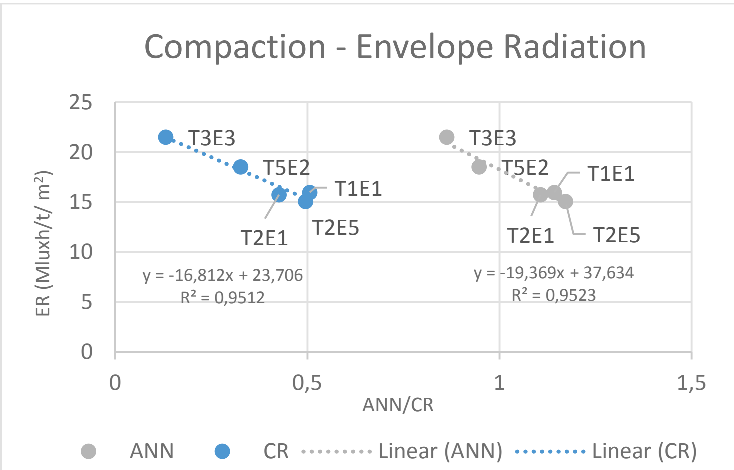


Figure 167: Linear regression between compaction and envelope radiation

In what regards heterogeneity, there is an important tendency to underline and that is as the buildings are more homogeneous between them, so the envelope radiation is lower, on the contrary, typologies which present a high heterogeneity between buildings forms, tend to present higher values of envelope radiation. The regularity of buildings sizes therefore seems to contribute actively to the shading effect that is observed (Figure 168).

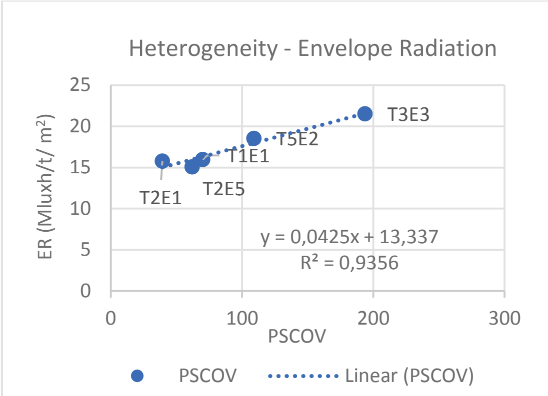


Figure 168: Linear regression between heterogeneity and envelope radiation

In what regards density there is an important correlation (-0,822) between Floor Area Ratio, and total envelope radiation received by buildings. The envelope radiation spatial distribution among the 5 typologies can be seen in Figure 169.

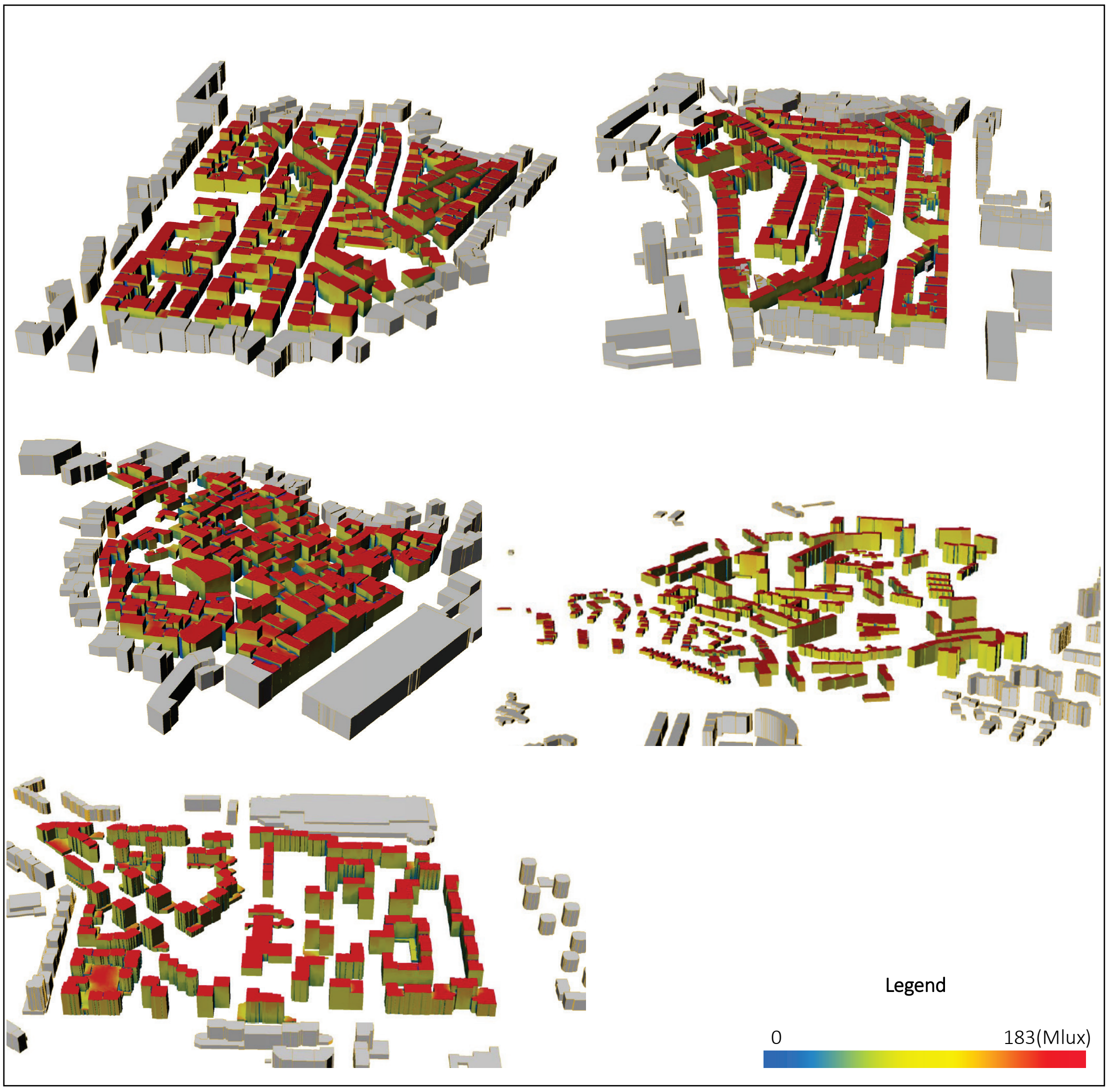


Figure 169: Envelope radiation distribution in the 5 urban typologies

While the envelope radiation metric explains the amount of radiation received by a determined typology (total or by m^2), the CDA and DA metrics are the measurement of the autonomy of each typology in what regards the necessary daylight for adequate lighting. This is an important difference, since a typology might not have the highest amount of total radiation received when compared to others, but can be auto-sufficient in what regards the daylight availability, and vice-versa. Three case studies present relatively the same values of CDA and DA – T5E2, T1E1, T2E5. The interesting fact in this case is that the T5E2 typology, that presented the second highest values of envelope radiation, is now a typology that presents a relatively low CDA and a low DA. The T2E1 despite presenting similar ER values than the T1E1 and T2E5, presented an overall higher radiation autonomy, and the T3E3 typology was the one which presented the lower the difference in importance between envelope radiation and CDA and DA, presenting the highest autonomy in terms of solar radiation (Figure 170).

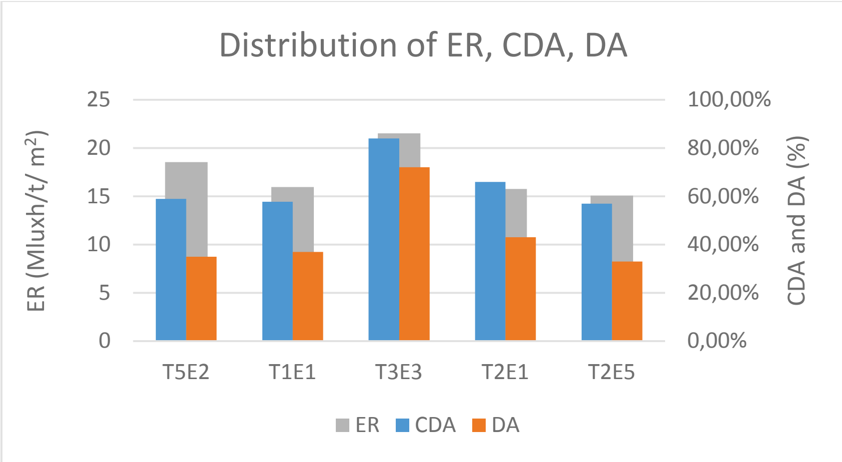


Figure 170: Distribution of ER, CDA and DA across the 5 typologies

While applying a Pearson Correlation to both CDA and DA, an expected strong relation between the two was obtained. Apart from that correlation a significant correlation was found with FAR (-0,969 at 0.01 interval level and -0,988 at a 0.01 interval level respectively); and between CDA and CR (-0,879 at a 0.01 interval level). Important correlations, but not significant, were found with ER, PSCOV and ANN. The correlation found between Floor Area Ratio (FAR) and both CDA and DA, indicates that as the FAR increases, thus density, so the daylight availability decreases (Figure 171).

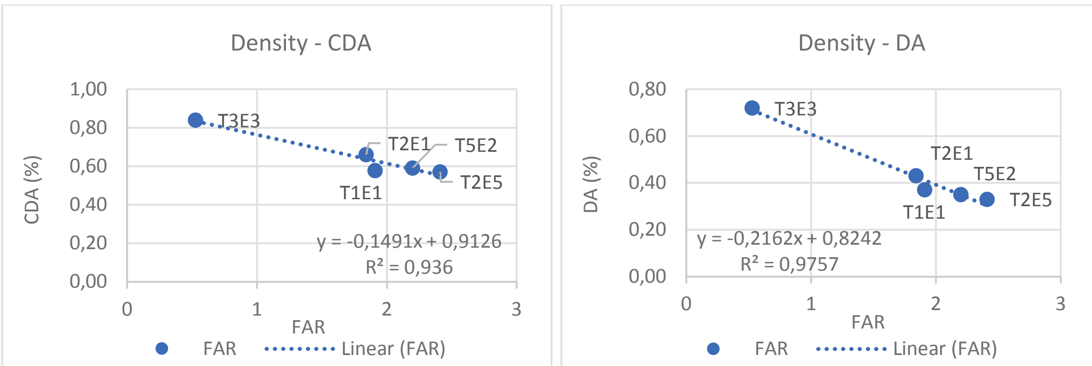


Figure 171: Linear regression between density and CDA and density and DA

The correlation found between compaction (CR) and CDA, indicates that has the compaction increases, so the daylight availability decreases. From these two correlations we can conclude that urban typologies which are very dense and compact tend to present low levels of daylight availability due to the shading effect of neighboring buildings, but also due to the large volume of the buildings that does not allow an adequate natural lighting (Figure 172).

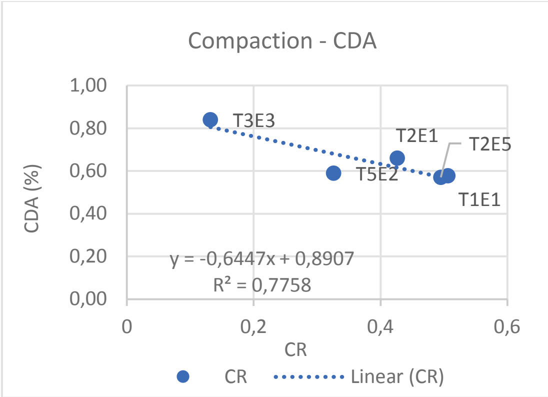


Figure 172: Linear regression between compaction and CDA

Regarding the T5E2 typology (Figure 173), the lower than expected CDA and DA values can be explained by the highest share of the envelope radiation received, which is concentrated in certain buildings (the tallest and narrowest), and therefore is not distributed in a uniform way; also, the radiation does not contribute actively to the daylight sufficiency of the buildings due to the buildings geometry – buildings have very large footprint areas which prevent the solar radiation to properly illuminate the buildings. This conclusion can be explained analyzing the PSCOV metric and the SVRatio metrics, that present low levels.

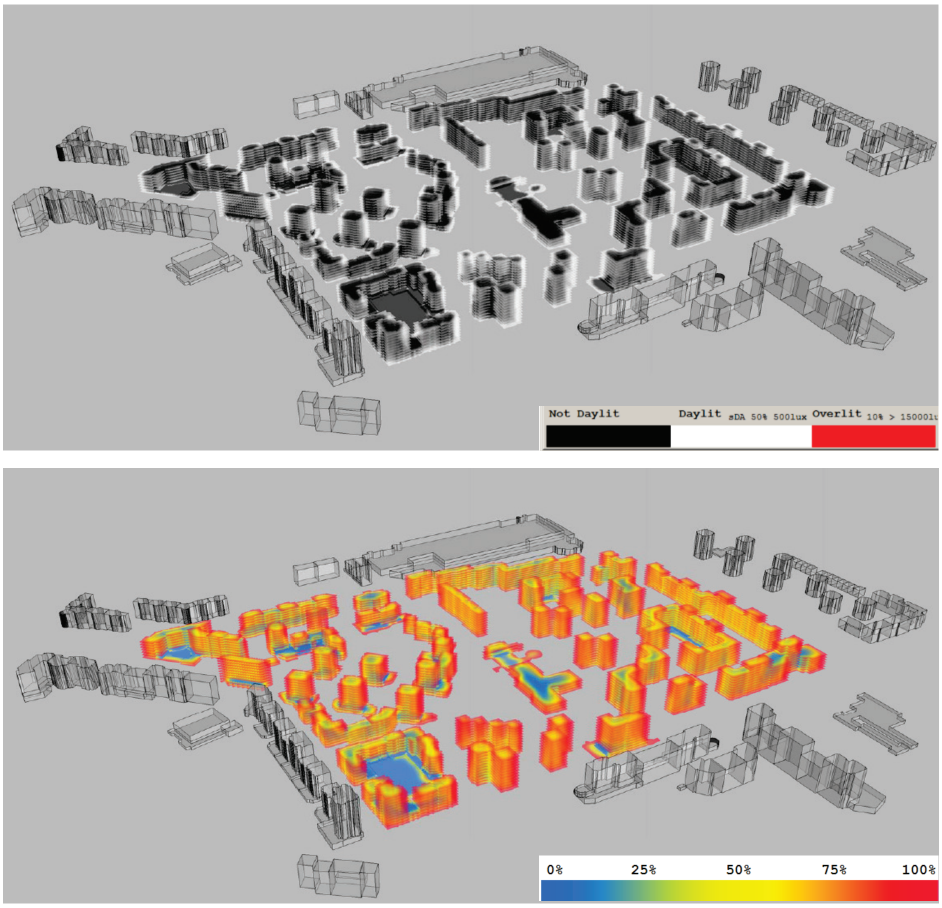


Figure 173: Spatial distribution of the DA (top) and CDA (Bottom) metrics on the T5E2 typology

The other two typologies which presented relatively low values of both CDA and DA were the T1E1 and T2E5. In the case of T1E1, the low daylight autonomy of the T1E1 typology is explained not by the characteristics of its buildings, but by the relation between them. If we observe the compaction metrics, it is easily understood that the fact that this typology have a significant compaction, with a very high building density, very short distance between buildings, and a very high coverage ratio, due to the narrow streets and small public spaces, highly contributes to the shading effect, as it can be seen in Figure 174.

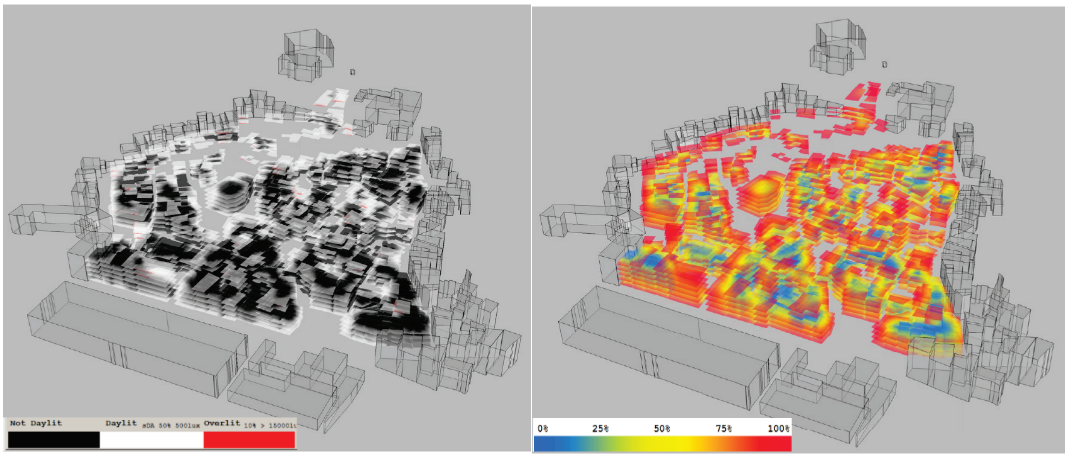
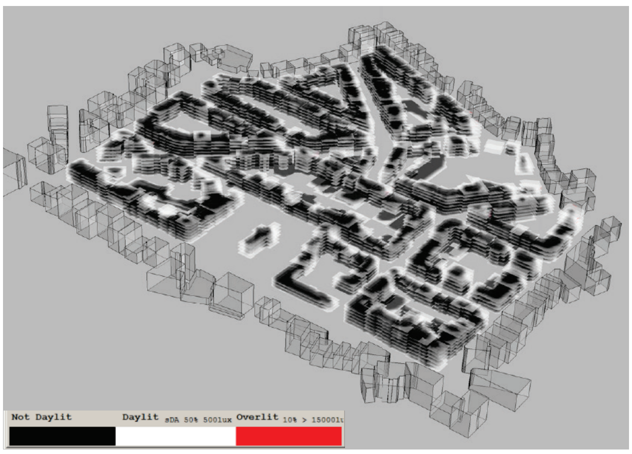


Figure 174: Spatial distribution of the DA (left) and CDA (right) metrics on the T1E1 typology

Regarding the T2E5 it does not have a highly complex geometry of its buildings, buildings are therefore more large and linear, which contributes to a lower internal radiation availability, it also presents high levels of compaction and density which end up creating a shading effect from neighboring buildings that contributes to the lower CDA and DA (Figure 175).



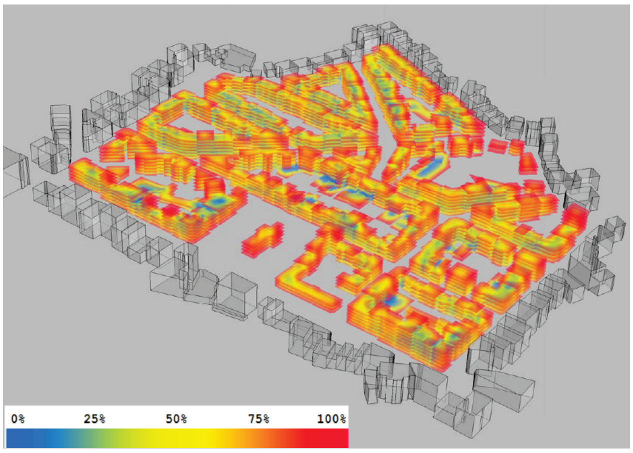


Figure 175: Spatial distribution of the DA (left) and CDA (right) metrics on the T1E1 typology

On the contrary, the T2E1 typology, that presented the second lower envelope radiation levels, is now the typology with the second higher CDA and DA levels. In the case of the T2E1 typology the fact that this typology has buildings that are very complex, with relatively small areas, and a linear urban form (low PSCOV), together with a medium compaction and density levels, all contribute to a higher levels of CDA and DA (Figure 176).

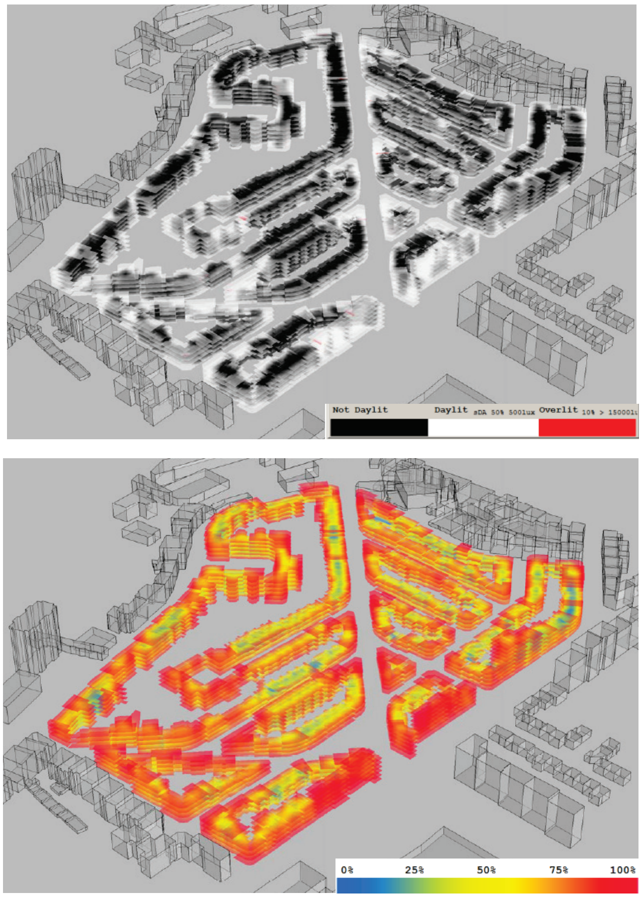


Figure 176: Spatial Distribution of the DA (top) and CDA (bottom) metrics on the T2E1 typology

Finally, the T3E3 typology, which presented the highest levels of envelope radiation, is also the one who presents the highest levels of both CDA and DA. This combination results, in the case of the buildings, from the fact that the buildings have a very large surface area, for relatively small areas. Is has also contribution from the fact that it is the most fragmented typology (buildings are situated far from each other decreasing the shading effect), together with low levels of density. The PSCOV metric which is very high, could indicate that some shading effect could occur from the difference of buildings sizes, however, the difference in buildings sizes in this case does not occur in the same area, the majority of buildings with low height are situated together in the same area does diminishing the shading effect (Figure 177).

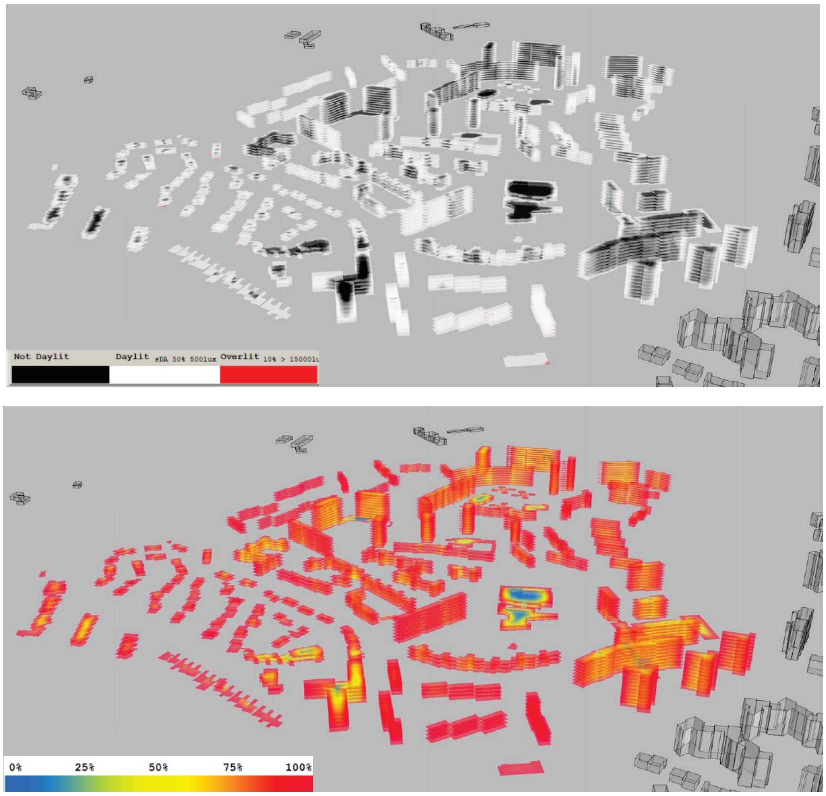


Figure 177: Spatial Distribution of the DA (top) and CDA (bottom) metrics on the T3E3 typology

9.3 Heating and cooling energy results

9.3.1 Analyzing the impact of urban geometry, context and local climate on a building´s thermal energy profile through UMI simulations

Model calibration was undertaken to access the validity of the simulation tool and also to understand the influence of urban geometry, context and local climate on the cooling and heating energy needs of buildings.

- **Buildings geometry and context**

- *Effect of neighboring buildings*

Comparing two different abstract sets of buildings, it is possible to understand the blockage effect of neighboring buildings. In case A (with neighboring buildings) the heating energy needs are of 17,14 kWh/m^2/year and cooling 1,59 kWh/m^2/year, in case B, the heating energy needs are of 15,56 kWh/m^2/year and cooling 1,67 kWh/m^2/year. It appears that the shadowing of neighboring buildings influences the amount of solar radiation received by buildings which explains the decrease of the heating energy needs from case A to B; on the other hand, without neighboring buildings and the corresponding shading effect the cooling energy needs also increase (Figure 178).

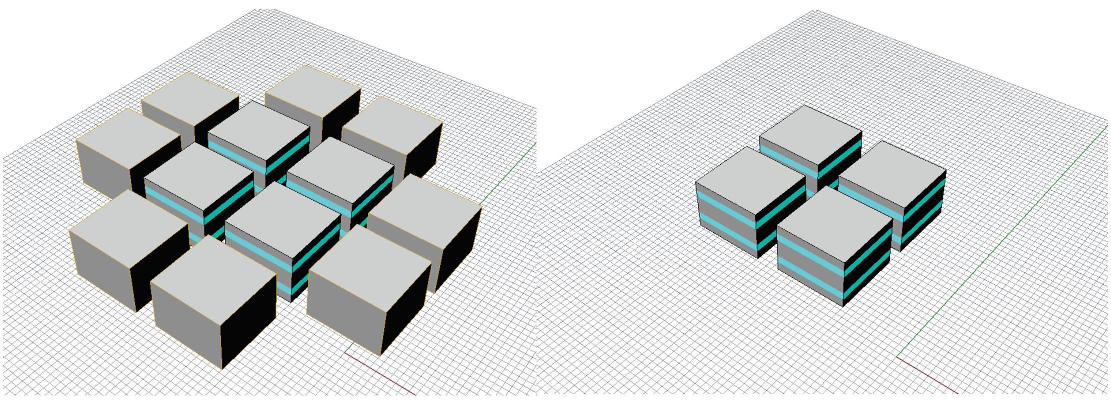


Figure 178: The effect of neighboring buildings Model A (buildings with context), and model B (buildings without context)

- Effect of orientation and terrain elevation

Regarding the effect of the buildings orientation to the sun, it is possible to conclude that different orientations result in different energy needs, despite the same building geometry. This means that buildings who are more exposed to solar radiation (buildings 3 with a east-south exposed façade) present higher cooling energy needs (479 kWh/year) than buildings who are not south oriented (building 1, with a west-north façade and cooling energy needs of 443 kWh/year). In what regards heating, buildings with predominant exposed north facades (buildings 1-2) present higher heating energy needs, with 4524 and 4580 kWh/year respectively, than buildings who are south oriented (3-4) with 4223-4269 kWh/year respectively (Figure 179).

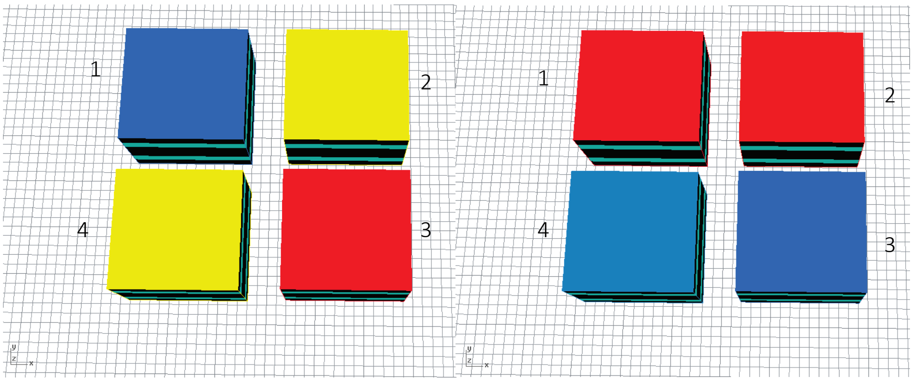


Figure 179: Energy needs for cooling (left) and heating (right) and the effect of solar radiation (blue indicates lower energy needs, and red higher energy needs; Y axis nearly represents North orientation)

In what regards the effect of terrain elevation, simulations indicate that at a lower ground spot buildings tend to have higher cooling energy needs (1915 kWh/year), than buildings located at a higher elevation (1652 kWh/year). In what regards heating there is a lower heating energy demand at a lower elevation than at higher elevation, however, the difference is not so pronounced as it is in the case of cooling (bottom series of buildings presented 17.433 kWh/year of heating energy needs vs. 17.607 kWh/year) (Figure 180).

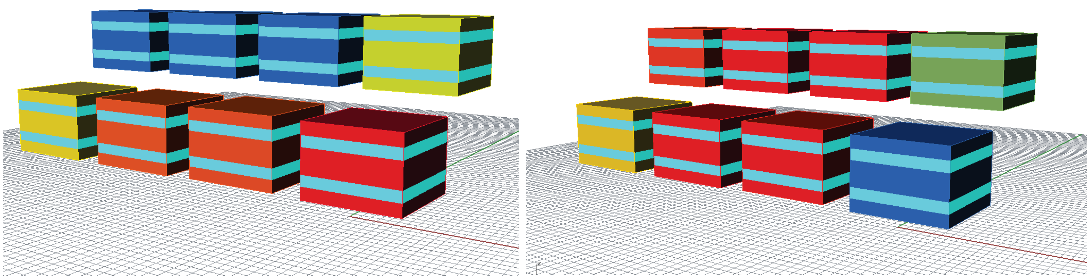
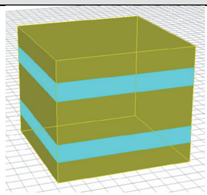
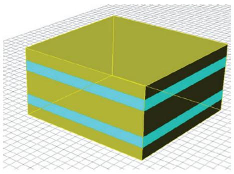
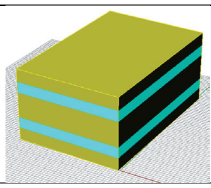
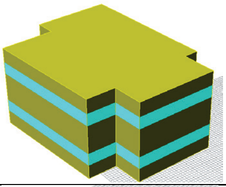
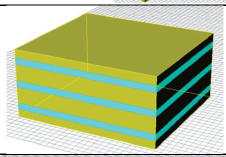
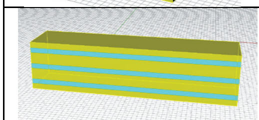
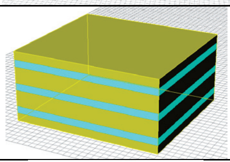
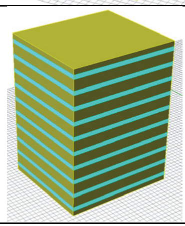


Figure 180: Energy needs for cooling and heating and the effect of elevation (blue indicates lower energy needs, and red higher energy needs)

- *Effect of buildings geometry*

Not only the urban context influences the performance of a determined building, but also the specific buildings characteristics also strongly contribute to a buildings thermal energy needs. As it can be seen in Table 30 the number of facades, floor area, area, height and overall shape of the building all contribute to different thermal energy needs. From the simulations results, the floor area is the buildings characteristic that strongly influence heating energy needs, both when increasing floor area through the area of the building or through the buildings height. When increasing the area of the building, passive volume ratio also increases which contributes to the higher heating energy needs. Increasing the height leads to more exposure to solar radiation, which in turn decreases the heating energy needs. Increasing the number of facades and also changing the shape of the building to a more elongated shape, also contribute to an increase in heating energy needs, but in a smaller proportion. In what regards the cooling energy needs, the floor area ratio, as it was the case with the heating energy needs, is also the building characteristic that strongly influences this parameter, but with different results. In the case of the increase of the floor area ratio through a buildings area, there is a decrease in the cooling energy needs in a building with a larger area (passive volume ratio influence), however, when the floor area ratio is increased through height, the buildings cooling energy needs also increase, because of the amount of façade that is exposed to solar radiation, that is considerably higher. Increasing the number of facades, and changing the shape of the building to a more elongated form, also contribute to an increase in the buildings cooling energy needs.

Table 30: Simulation of the impact of shape, number of facades, height, area, floor area in the heating and cooling energy needs of buildings

Building parameters	Shape	Facades	Height (floors)	Area (m^2)	Floor Area (m^2)	Heating (kWh/m^2)	Cooling (kWh/m^2)
= n facades ≠ floor area ≠ area = height = shape		4	2	98,5	197	15,16	1,93
		4	2	264,5	529	11,33	1,31
≠ n facades = floor area = area = height ≠ shape		4	2	118,5	237	8,17	1,46
		10	2	118,5	237	8,38	1,49
= facades +/- floor area +/- area = height ≠ shape		4	3	531,3	1594	7,50	1,31
		4	3	520	1560	8,33	1,34
= facades ≠ floor area = area = shape ≠ height		4	3	531,5	1595	7,50	1,31
		4	10	531,5	5315	4,05	1,99

- **Local climate effect on urban form**

To access the effect of local climate on urban form, three different climate files were used:

- INETI synthetic data series for Lisbon (2005) – based on spatially interpolation of public climatic data published by IPMA of 1951-80 combined with INETI owned data and other data sources. Ground elevation is of 71m.
- LNEG-DGEG synthetic data series for Lisbon (2013), used for the Portuguese Building Certification scheme (the reference year is 2011). Based on IPMA 1971-2000 climatology and 2015-2060 climate change predictions from emission scenarios RCP4.5 and RCP8.5 (ECEARTH website). Ground elevation is of 71m.
- LNEG-DGEG synthetic data series for Lisbon (2013) edited with SCE.METEO 1.0 tool (Aguiar and DGEG, 2016) in order to reflect a 1.5ºC temperature increase.

The 1.5 ºC increase is based on the two intermediate scenarios (RCP 4.5 and RCP 6.0) of the IPCC report (IPCC Synthesis Report, 2014:10) which indicates that "[…] g*lobal surface temperature change for the end of the 21st century (2081–2100) is projected to likely exceed 1.5°C for RCP4.5, RCP6.0 and RCP8.5 (high confidence)*". In Figure 181 it is possible to observe the temperature variations along the year for the 2005 and 2011 data series and for the 2100 projected climate scenario. Looking specifically into the 2005 and 2011 climate files, which are the ones based on real climate data, it is possible to understand that the average temperature has increased 0,6 ºC which is an important figure given the short time period. This increase in the average temperature was mainly due to the increase in the minimum temperature, since in what regards the maximum temperature it was registered a decrease of the average value, and also in the registered values throughout the year (in 12 months only 4 had a higher maximum temperature in 2011 than in 2005 and it were – January, February/ November, December).

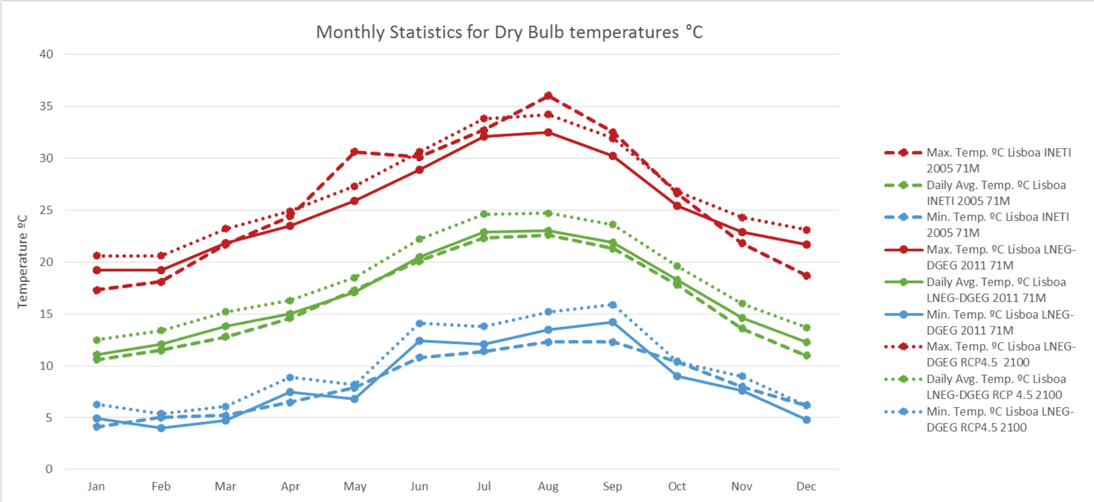


Figure 181: Monthly statistics for dry bulb temperature (ºC) for INETI 2005, LNEG-DGEG 2011 and LNEG-DGEG 2100 climate files

If we look into the hourly and monthly distribution of the temperature it is possible to observe this tendency, and also to understand that there is an increase in temperature also in the morning and night periods (Figure 182).

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	9,4	9,8	10,9	12,4	13,8	16,2	18,1	18,5	17,8	16	12,1	9,8
1:01- 2:00	9,2	9,7	10,7	12,1	13,3	15,7	17,5	18	17,3	15,7	11,9	9,6
2:01- 3:00	9	9,5	10,5	11,8	12,8	15,2	16,9	17,5	16,9	15,4	11,7	9,4
3:01- 4:00	8,8	9,3	10,3	11,5	12,4	14,6	16,3	17	16,4	15,1	11,5	9,2
4:01- 5:00	8,6	9,2	10	11,2	12,4	14,7	16,3	16,5	16	14,8	11,3	9
5:01- 6:00	8,4	9	9,8	11,3	12,6	15	16,7	16,7	16	14,5	11,1	8,8
6:01- 7:00	8,2	9	10	11,6	13,4	16	17,7	17,5	16,4	14,5	10,9	8,6
7:01- 8:00	8,4	9,3	10,6	12,4	14,7	17,4	19,2	19	17,5	15	11,1	8,7
8:01- 9:00	8,9	10,1	11,6	13,5	16,3	19,1	21,2	21	19,2	16,1	11,9	9,2
9:01-10:0	9,9	11,1	12,8	14,7	18,1	21	23,3	23,3	21,3	17,4	12,9	10,2
10:01-11:0	11,1	12,3	14,1	16	19,9	22,8	25,4	25,6	23,5	18,8	14,3	11,5
11:01-12:0	12,4	13,5	15,3	17,3	21,4	24,5	27,4	27,6	25,6	20,3	15,5	12,8
12:01-13:0	13,4	14,5	16,2	18,3	22,6	25,8	28,7	29,1	27,3	21,5	16,6	13,8
13:01-14:0	14	15	16,8	19	23,5	26,6	29,7	30	28,4	22,2	17,4	14,5
14:01-15:0	14,1	15,2	17	19,2	23,8	26,8	29,9	30,3	28,5	22,4	17,5	14,6
15:01-16:0	13,8	14,9	16,7	19	23,3	26,4	29,4	29,8	27,9	22	17,2	14,2
16:01-17:0	13	14,1	16	18,2	22,4	25,5	28,4	28,6	26,7	21,1	16,3	13,4
17:01-18:0	12,2	13,2	14,9	17,1	21	24	26,7	26,9	25	19,9	15,3	12,5
18:01-19:0	11,5	12,4	13,9	16	19,3	22,3	24,7	24,8	23,2	18,9	14,6	11,9
19:01-20:0	10,9	11,8	13,1	15	17,8	20,6	22,9	23	21,7	18,1	13,9	11,3
20:01-21:0	10,5	11,3	12,4	14,2	16,6	19,2	21,4	21,6	20,6	17,4	13,4	10,8
21:01-22:0	10,1	10,9	11,9	13,6	15,6	18,2	20,3	20,5	19,6	16,9	12,9	10,5
22:01-23:0	9,7	10,5	11,5	13,1	14,9	17,4	19,4	19,6	18,9	16,4	12,6	10,1
23:01-24:0	9,5	10,2	11,2	12,7	14,3	16,8	18,7	19	18,3	16,1	12,3	9,9

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	9,3	10,4	11,9	13,1	15,2	18,4	20,6	20,8	19,7	16,3	12,9	10,7
1:01- 2:00	8,7	9,7	11,2	12,4	14,5	17,7	19,8	20	18,9	15,7	12,3	10,1
2:01- 3:00	8,1	9,2	10,6	11,8	13,9	17	19,1	19,3	18,2	15,1	11,7	9,6
3:01- 4:00	7,7	8,8	10,1	11,4	13,5	16,5	18,6	18,7	17,6	14,6	11,3	9,3
4:01- 5:00	7,4	8,5	9,7	11	13,1	16,1	18,2	18,3	17,2	14,2	11	9
5:01- 6:00	7,2	8,3	9,5	10,8	12,9	15,9	17,9	18	17	14	10,8	8,8
6:01- 7:00	7,1	8,2	9,4	10,7	12,8	15,8	17,8	17,9	16,9	13,9	10,7	8,7
7:01- 8:00	7,5	8,6	9,9	11,1	13,2	16,3	18,3	18,4	17,4	14,4	11,1	9,1
8:01- 9:00	8,6	9,7	11,1	12,3	14,4	17,6	19,7	19,9	18,8	15,6	12,2	10,1
9:01-10:0	10,2	11,2	12,8	14	16,2	19,5	21,7	21,9	20,8	17,3	13,7	11,5
10:01-11:0	12	13	14,8	15,9	18,1	21,5	24	24,2	23	19,3	15,5	13,1
11:01-12:0	13,6	14,6	16,5	17,6	19,8	23,4	26	26,2	25	21	17,1	14,6
12:01-13:0	14,7	15,6	17,8	18,8	21	24,7	27,4	27,6	26,4	22,2	18,1	15,6
13:01-14:0	15,1	16	18,2	19,2	21,4	25,2	27,9	28,1	26,9	22,6	18,5	15,9
14:01-15:0	15,1	16	18,1	19,2	21,3	25,1	27,8	28	26,8	22,6	18,4	15,9
15:01-16:0	14,9	15,8	17,9	19	21,1	24,9	27,6	27,8	26,6	22,4	18,3	15,7
16:01-17:0	14,5	15,4	17,5	18,6	20,8	24,5	27,1	27,4	26,1	22	17,9	15,4
17:01-18:0	14,1	15	17	18,1	20,3	24	26,6	26,8	25,6	21,5	17,5	15
18:01-19:0	13,6	14,5	16,5	17,6	19,7	23,3	25,9	26,1	24,9	20,9	17	14,5
19:01-20:0	12,9	13,9	15,8	16,9	19	22,6	25,1	25,3	24,1	20,2	16,4	13,9
20:01-21:0	12,2	13,2	15	16,1	18,3	21,8	24,2	24,4	23,3	19,5	15,7	13,3
21:01-22:0	11,5	12,5	14,2	15,4	17,5	20,9	23,3	23,5	22,4	18,7	15	12,7
22:01-23:0	10,7	11,7	13,4	14,6	16,7	20,1	22,4	22,6	21,4	17,9	14,2	12
23:01-24:0	10	11	12,6	13,8	15,9	19,2	21,5	21,6	20,5	17,1	13,6	11,3

Figure 182: Annual hourly temperature (ºC) distribution for the INETI 2005 (top) and LNEG-DGEG 2011 (bottom) climate files

Relative humidity has also changed from 2005 to 2011, having been registered an increase in the minimum and average relative humidity, and a short decrease in the maximum humidity (Figure 183).

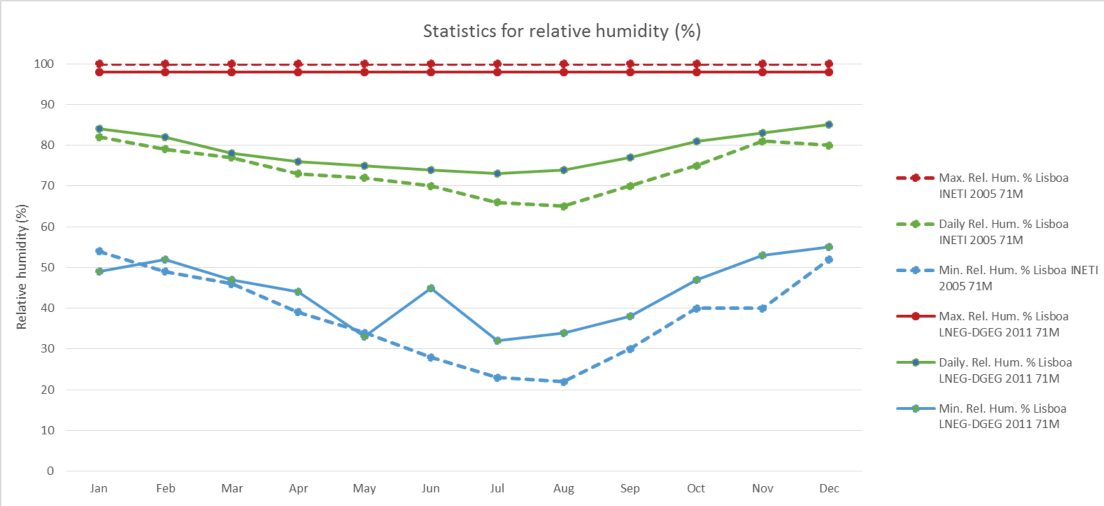


Figure 183: Statistics for relative humidity for the INETI 2005 and LNEG-DGEG 2011 climate files

In what regards solar radiation there has been an increase in the global average and direct average solar radiation and a small decrease in the diffuse solar radiation from 2005-2011 (Figure 184).

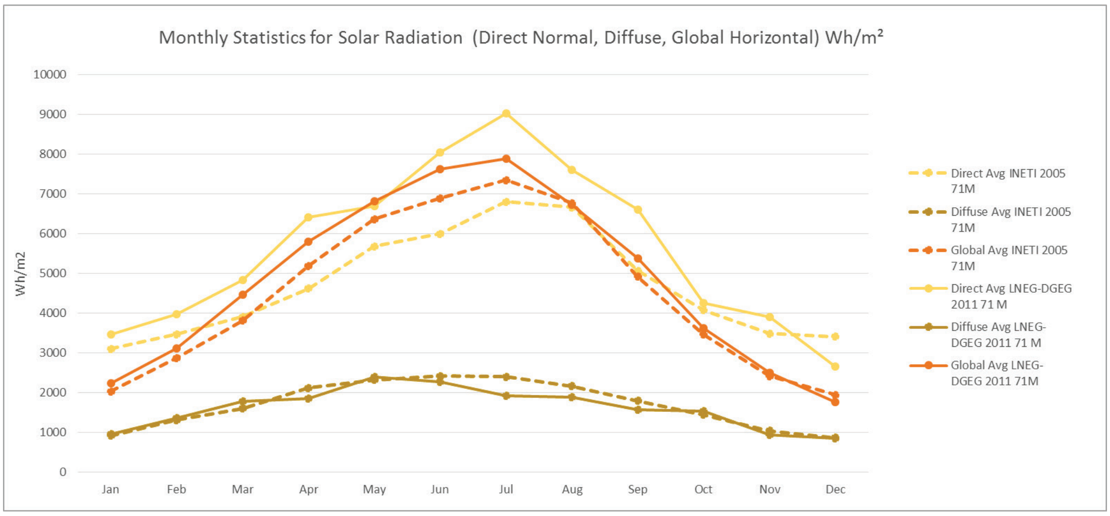


Figure 184: Monthly statistics for solar radiation for the INETI 2005 and LNEG 2011 climate files

Also important to mention is the increase in the average relative humidity from 74,09% to 78,42%, and mainly the increase in the total sky cover from 40,14% to 52,80%.

Comparing the same urban configuration as in Figure 178 model B but with different climate files, it is possible to understand the strong effect that local climate has in the energy needs of the buildings that were simulated (Figure 185). In what regards heating energy needs and comparing the INETI 2005 (27,98 kWh/m^2) and LNEG-DGEG 2011 data series (15,56 kWh/m^2) they reduce to nearly half, and comparing to the LNEG-DGEG 2100 (8,59 kWh/m^2) to a third of the 2005 value. When looking at the cooling energy needs there is the inverse tendency, since an increase in the cooling energy needs was registered, from 1,63 kWh/m^2 (INETI 2005) to 1,67 kWh/m^2 (LNEG-DGEG 2011) and to 2,42 kWh/m^2 in the LNEG-DGEG 2100 data series. Important to mention that in what regards the total thermal energy needs there is a decrease from 29,61 kWh/m^2 (2005) to 11,01 kWh/m^2 (projected 2100), and in the energy share, heating decreases from 94% to 78% and the cooling energy needs increase from 6% to 22%.

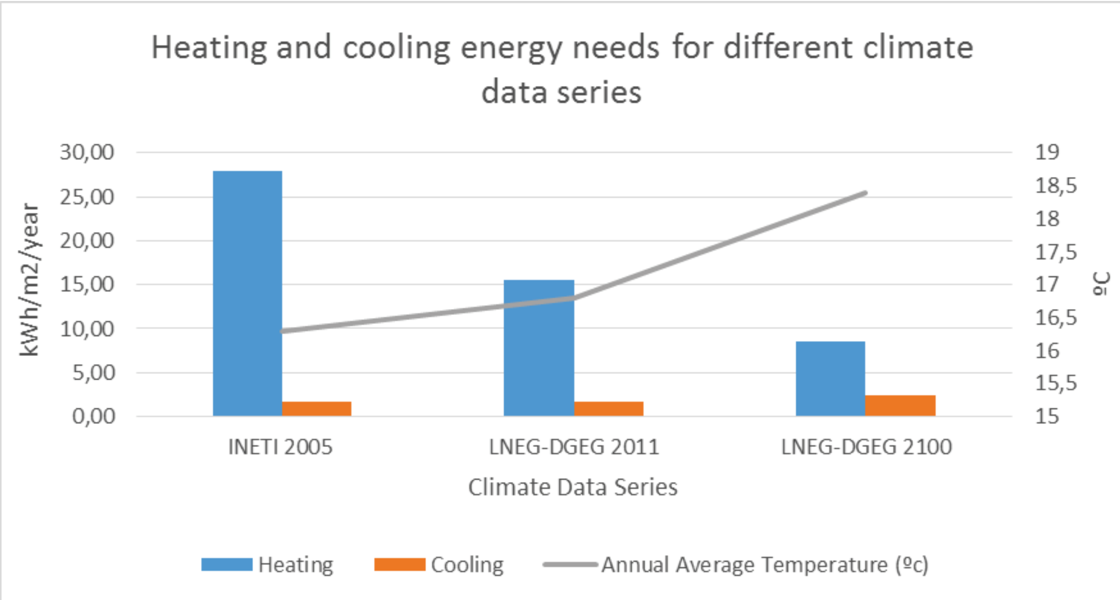


Figure 185: Heating and cooling energy needs for different climate data series

9.3.2 Heating and cooling energy results

When analyzing the heating and cooling energy needs (GWh/year) results from the 5 case studies (Figure 186), it is possible to understand that there is an increase on the total heating and cooling from typologies with a lower floor area ratio, envelope area and volume towards the ones with higher values of these parameters. From the typology which consumes less (T1E1) to the one which consumes more (T5E2) there is a more than 4 x difference; a 2 x difference between T2E1 and T5E2; and 1.5 x between T2E5 and T3E3 with the T5E2 typology.

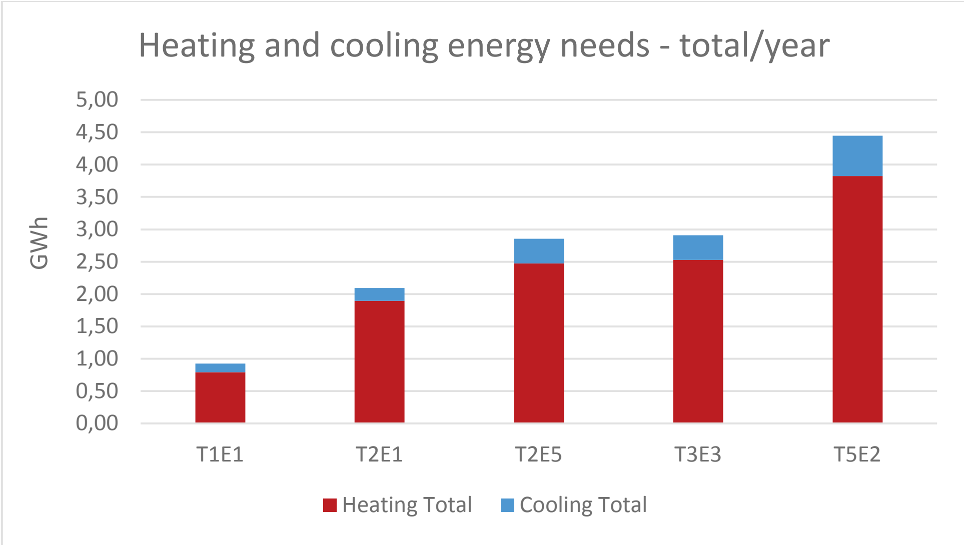


Figure 186: Total thermal energy needs (GWh/year) for the 5 typologies

When analyzing the operational energy by m^2 (kWh/m^2/year) (Figure 187), the order of the typologies changes. T1E1, the typology that presented the lowest heating and cooling energy (GWh), is now the typology that has the second highest heating and cooling energy needs (13,46 kWh/m^2/year), only lower than T2E1 (13,81 kWh/m^2/year), and higher than T2E5 (10,66 kWh/m^2/year), T3E3 (9,56 kWh/m^2/year), and finally T5E2 (8,21 kWh/m^2/year). When seen by m^2, the heating and cooling energy needs increase around 1.70x from the typology with the lower energy needs by m2 (T5E2) to the one with higher energy needs (T2E1), 1.77x if we consider heating energy needs, and 1.71x if we consider cooling energy needs, which is significant. The reasons that contribute to the different energy performances across typologies will be analyzed further ahead, comparing the energy needs results with the urban form and energy metrics.

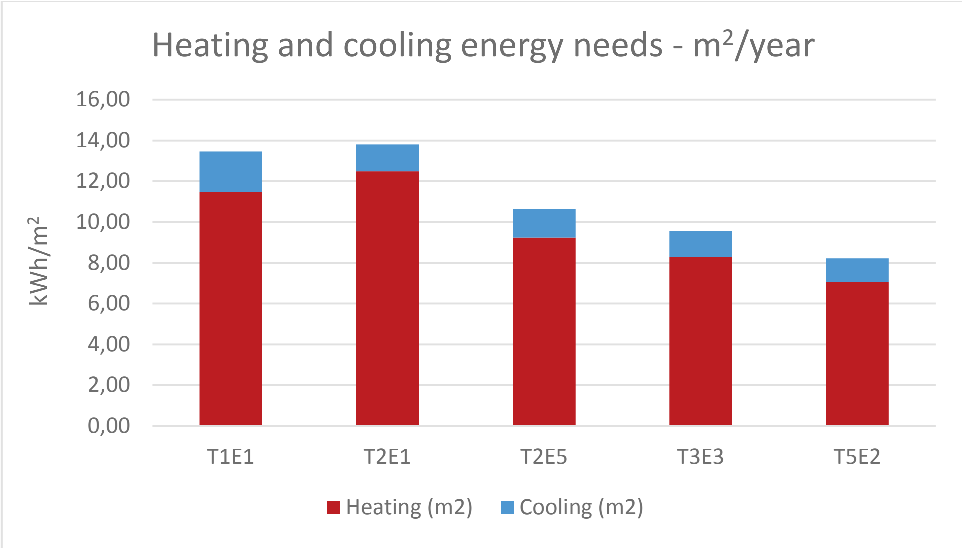


Figure 187: Total thermal energy needs (kWh/m^2) for the 5 typologies

Looking at the share of heating and cooling energy (Figure 188), it is clear that the heating energy needs are more important to the thermal energy needs of the 5 typologies, with a share always above 85%. Cooling energy needs share varies slightly from 10% to 15%.

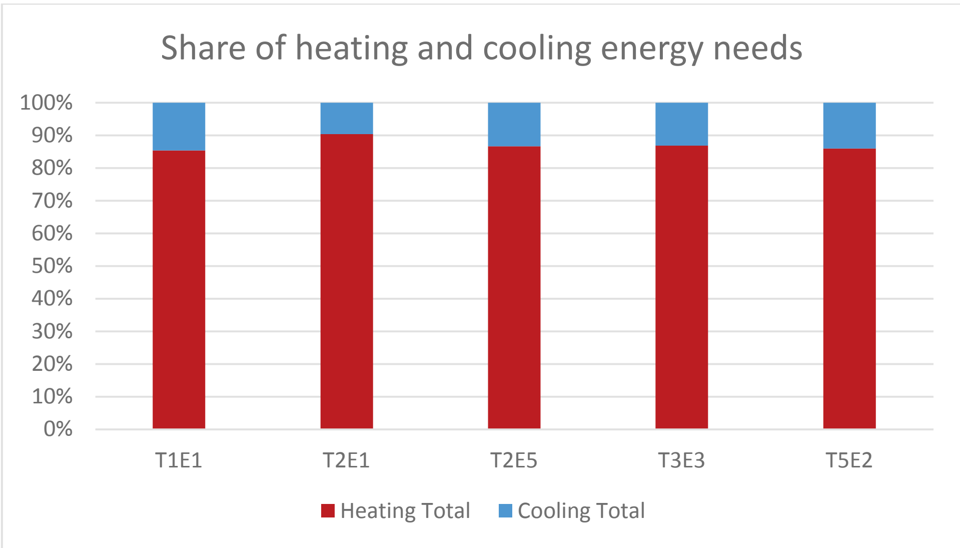


Figure 188: Thermal energy breakdown (kWh/m^2/year) in %

Next, the heating and cooling energy results will be analyzed both spatially and temporally in their distribution across the various buildings of the 5 typologies.

Looking at the energy profiles of the 5 typologies (Figure 196) and their spatial distribution (Figure 197, Figure 198, Figure 199, Figure 200) it is possible to register differences in the distribution of both the heating and cooling energy needs (kWh/m^2) throughout the typologies buildings which results in different heating and cooling energy total values. Typologies which presented the most significant intervals in their minimum and highest heating energy needs, tend to present a distribution that is pronounced in the end (T1E1, T5E2) or in the beginning (T3E3), they tend to have the highest heterogeneity in the results, presenting clearly 3 groups of buildings – in the lower side of the distribution the larger buildings in the typology, in the middle the most common buildings with average dimensions, and in the upper side of the distribution buildings that usually are very small and complex. The T2E1 and T2E5 are typologies with a higher regularity in what regards their urban form, and therefore buildings performance is more linear (Figure 189).

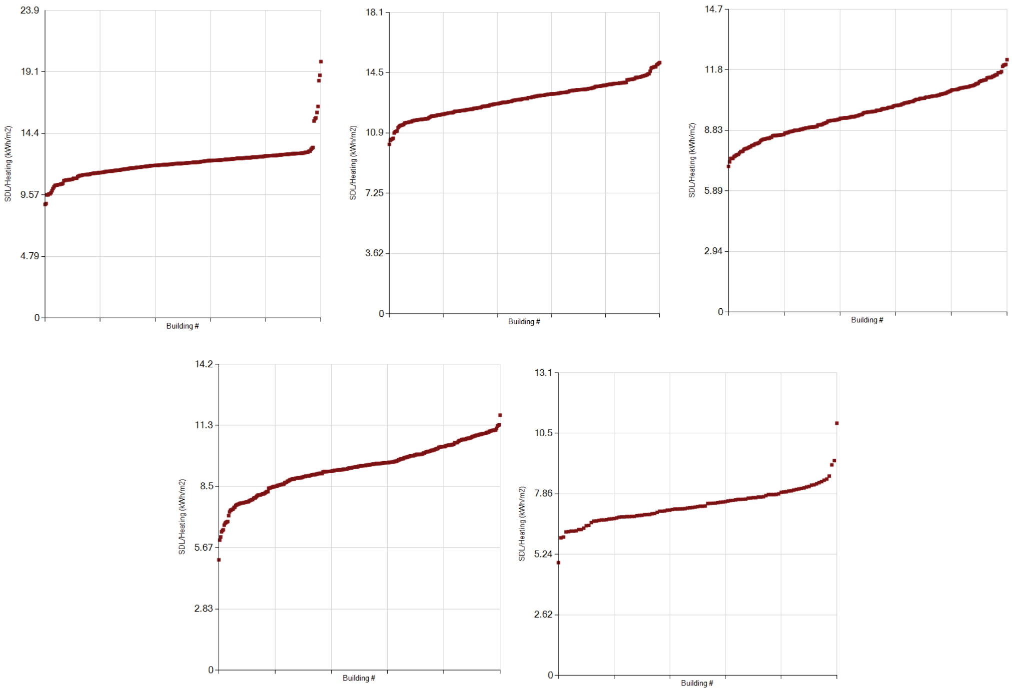


Figure 189: Heating energy needs (kWh/m²) for the 5 typologies: T1E1, T2E1 T2E5, T3E3, T5E2

Buildings that present a higher heating energy needs (>13 kWh/m²) are the ones which have less access to solar radiation, since they are surrounded by neighboring buildings, are positioned at a lower elevation, and have a low height and area (Figure 190).

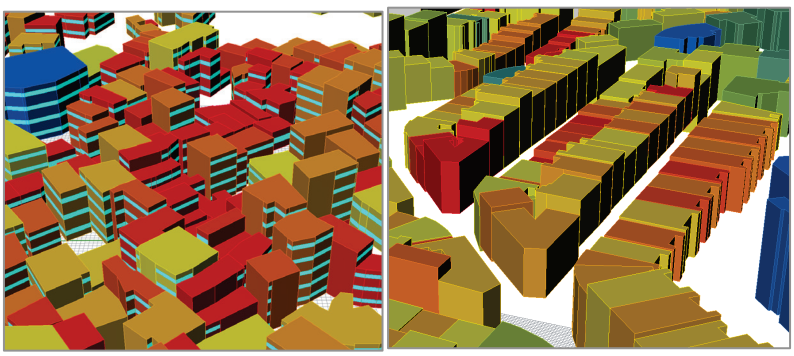


Figure 190: Examples of buildings that present higher energy needs in the T1E1 (left) and T2E1 (right) typologies (blue lines are representative of the glazing ratio that was taken into account)

Buildings which have all the properties as the ones indicated before but that have a higher solar radiation exposure still have a high heating energy needs but with lower values (10-11 kWh/m^2) (Figure 191).

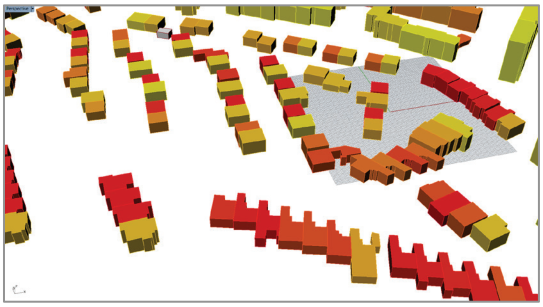


Figure 191: Example of buildings with high heating energy needs in the T3E3 typology

Whenever the area of the buildings increases, its height, and the regularity of its form, the heating energy needs decline as it can be seen in the example below of the T2E5 typology (around 8 kWh/m^2) and also the T5E2 (around 7 kWh/m^2) (Figure 192).

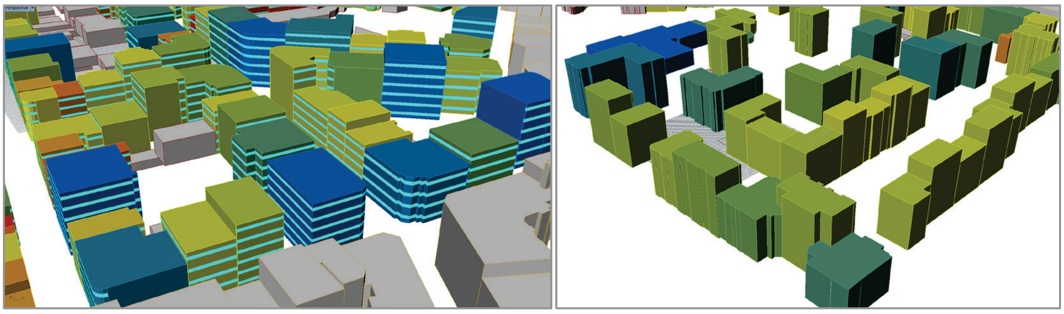


Figure 192: Examples of buildings with low heating energy needs in the T2E5 (left) and T5E2 (right) typologies (blue lines are representative of the glazing ratio that was taken into account)

In what regards the distribution of the cooling energy needs across the typologies buildings, T1E1 still maintains a nonlinear distribution together with T2E1, while both T3E3 and T5E2 now present a more linear distribution also in line with T2E5 (Figure 193).

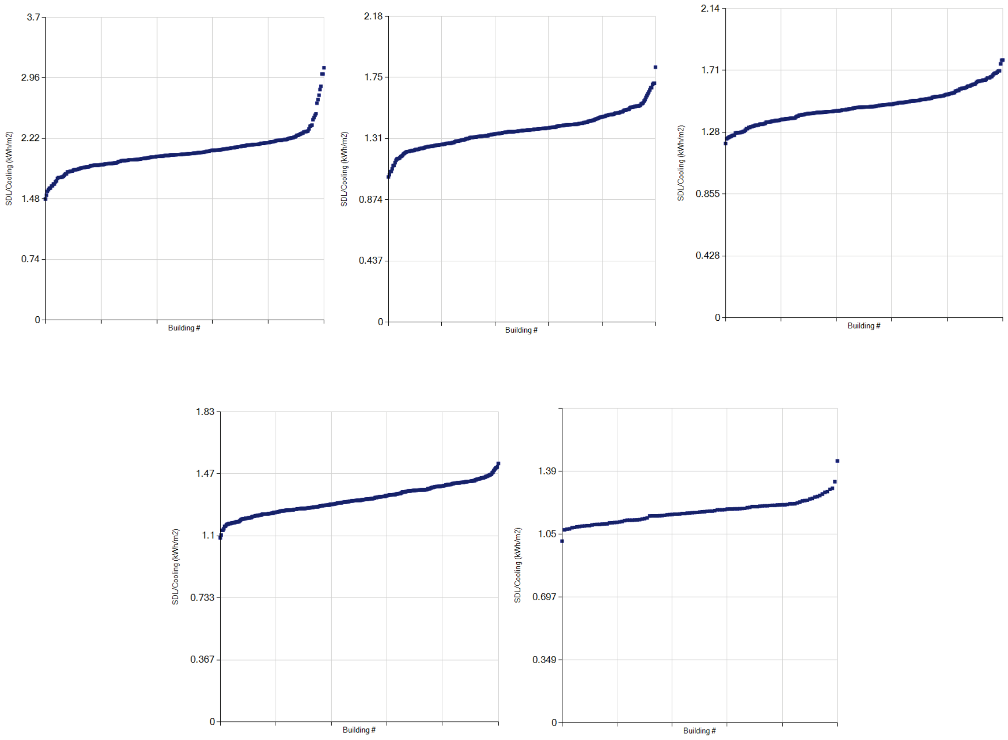


Figure 193: Cooling energy needs (kWh/m^2) for the 5 typologies: T1E1, T2E1 T2E5, T3E3, T5E2

Different shading availability as well as different ground elevations together with buildings with a small area complex or/and elongated contribute to the higher kWh/m2 of cooling energy needs in T1E1 and T2E1 typologies, being the buildings in the lower part of the distribution the largest (in terms of floor area ratio and area) and the buildings in the upper part of the distribution those that characterize these typologies (small and complex) but with a higher height than the average (Figure 194).

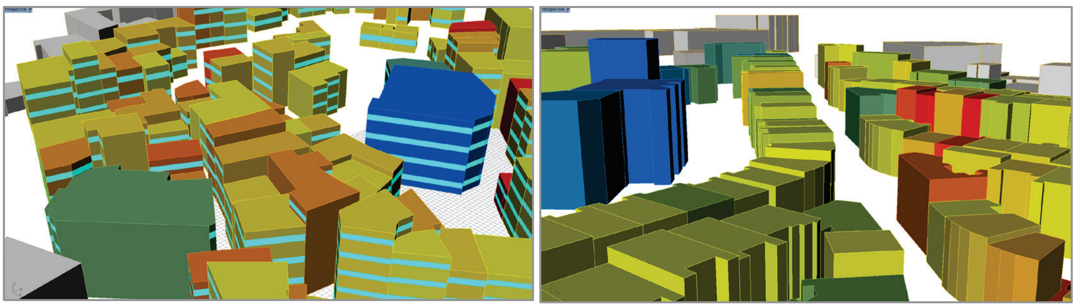


Figure 194: Examples of buildings with high cooling energy needs in the T1E1 (left) and T2E1 (right) typologies (blue lines are representative of the glazing ratio that was taken into account)

In what regards the typologies with the more linear distribution, this can be explained through different reasons. In the case of T3E3 the buildings who were expected to have higher cooling energy needs (the detached housing block), present a not so pronounced difference with the mid-size and large size apartment blocks (despite being still the buildings with higher cooling energy needs in the typology), because despite having low shading availability and small areas, they have also a low height, and that is one of the factors that contribute more to a decrease in the cooling energy needs as it was seen before. In the case of the T2E5 typology the high homogeneity of the buildings configurations (as it was seen before in the PSCOV metric) contribute to the linearity of their cooling energy needs distribution. The T5E2 typology is more heterogeneous (in what regards the PSCOV metric), but has less shading situations and the ground elevation is less important being the solar radiation more evenly distributed across the typology. Also, despite having a heterogeneity of their buildings sizes (in terms of area), the T5E2 presents the higher average building height across all typologies presenting the majority of buildings an average number of 6 floors, which greatly increases the façade exposure to solar radiation and consequently the cooling energy needs (Figure 195).

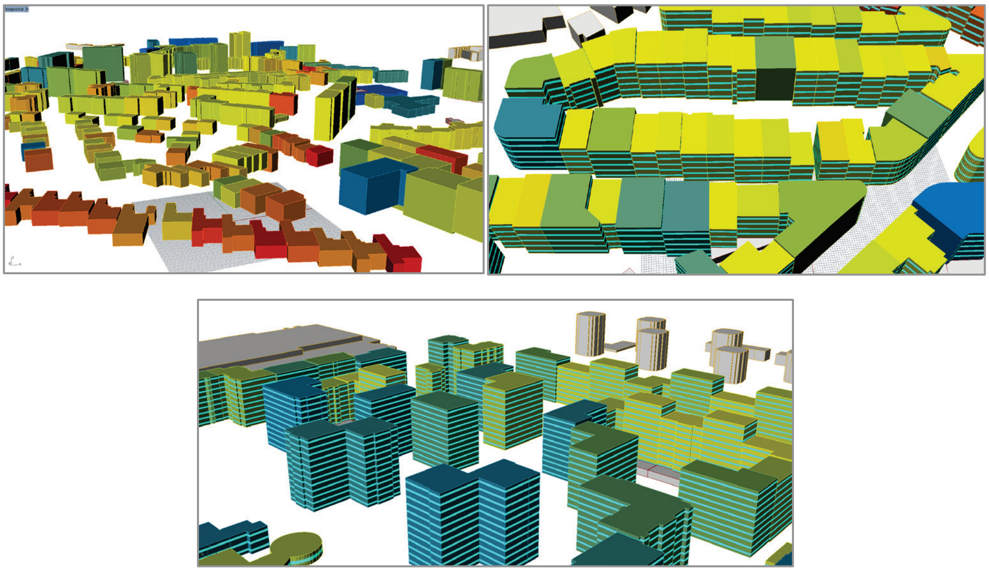


Figure 195: Examples of buildings with different cooling energy needs in the T3E3 (top-left) typology, and more homogeneous distribution of cooling energy needs in the T2E5 (top-right) and T5E2 (bottom) typologies (blue lines are representative of the glazing ratio that was taken into account)

Looking at the temporal distribution of both the cooling and heating energy needs, it is clear the tendency for a higher heating energy needs in the fall-winter months (specially December, January and February), and a higher cooling energy needs in the summer, especially in July-August. The distribution pattern in both the cooling and heating energy needs is similar across the 5 typologies and resembles the total energy needs distribution for heating and cooling explained before (Figure 196).

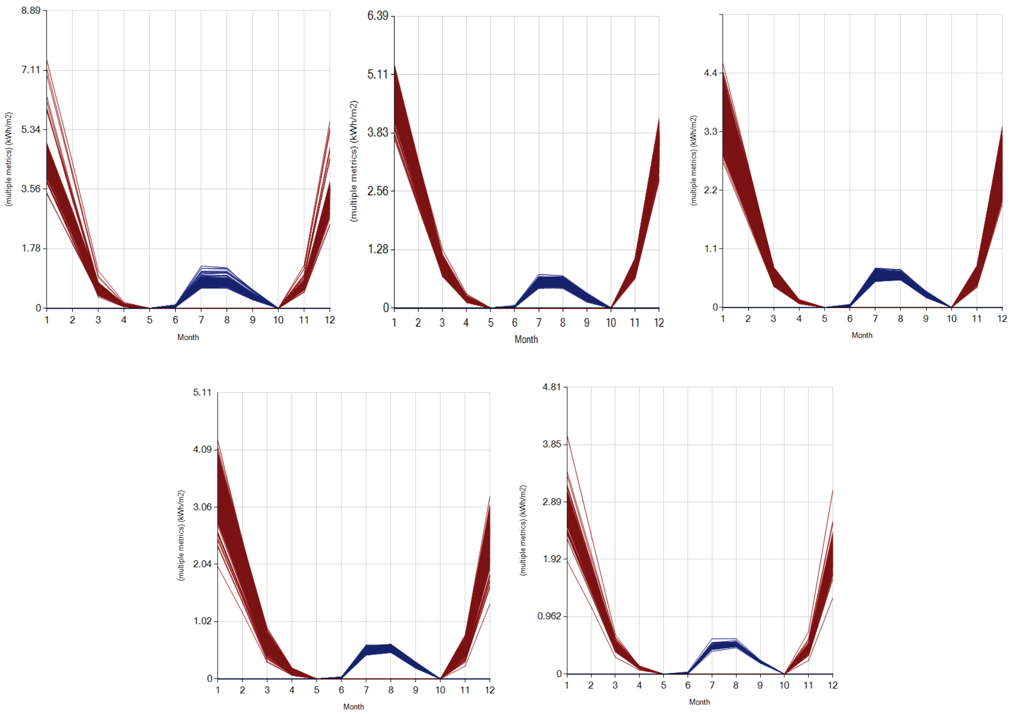


Figure 196: Heating and cooling energy needs (kWh/m²) during 1 year for the 5 typologies: T1E1, T2E1 T2E5, T3E3, T5E2

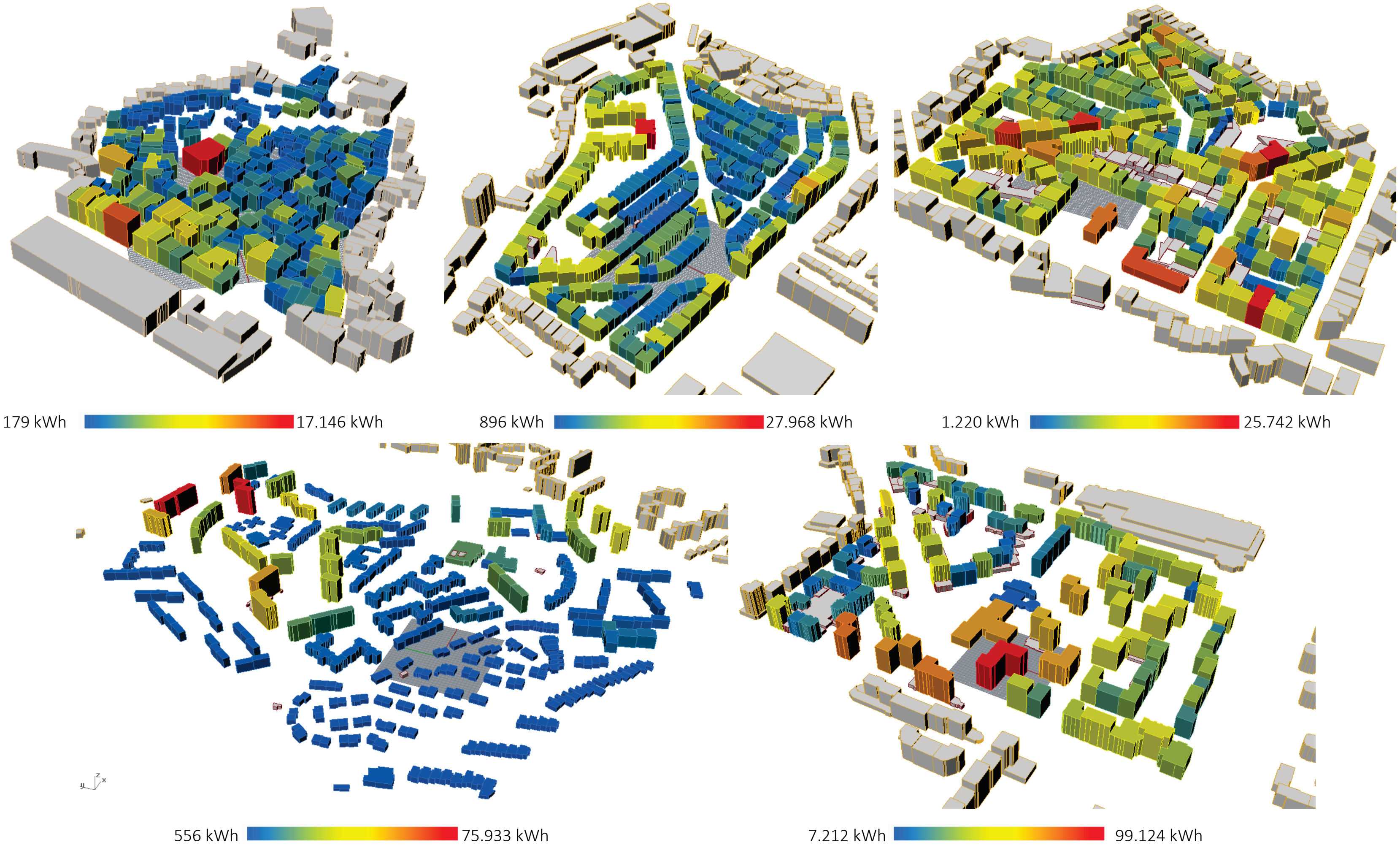


Figure 197: Heating energy needs spatial representation (kWh)

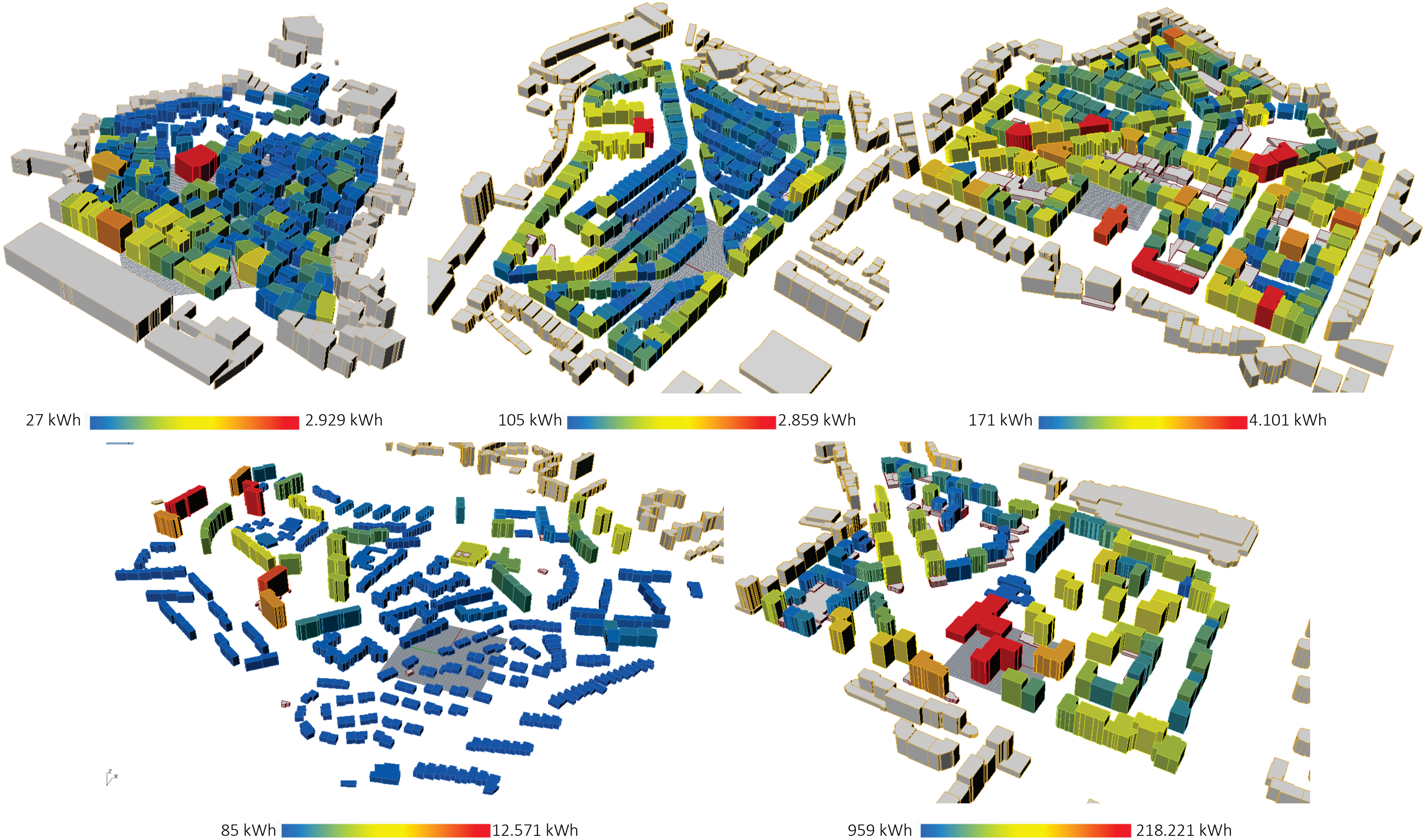


Figure 198: Cooling energy needs spatial representation (kWh)

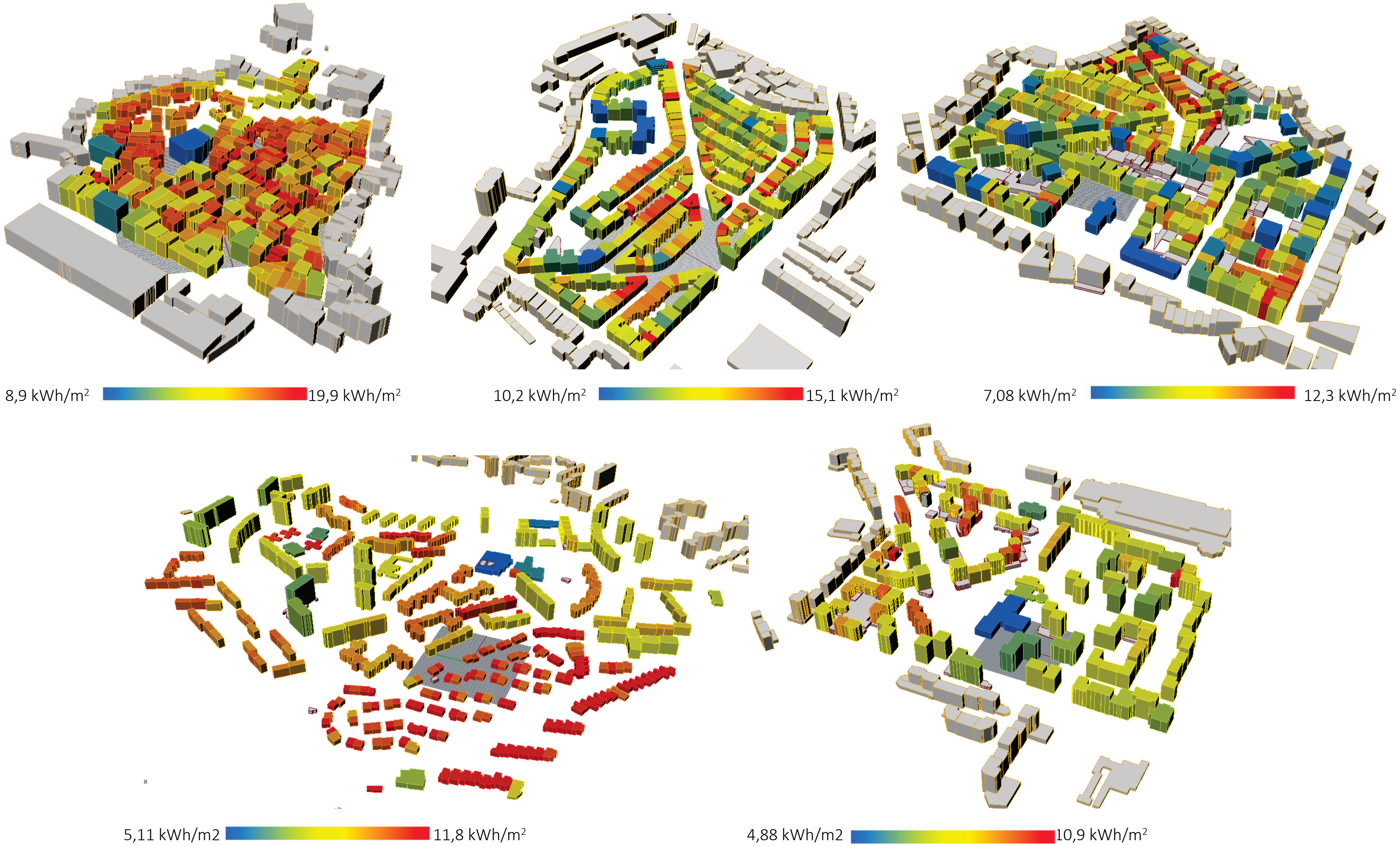


Figure 199: Heating energy needs spatial representation (kWh/m^2)

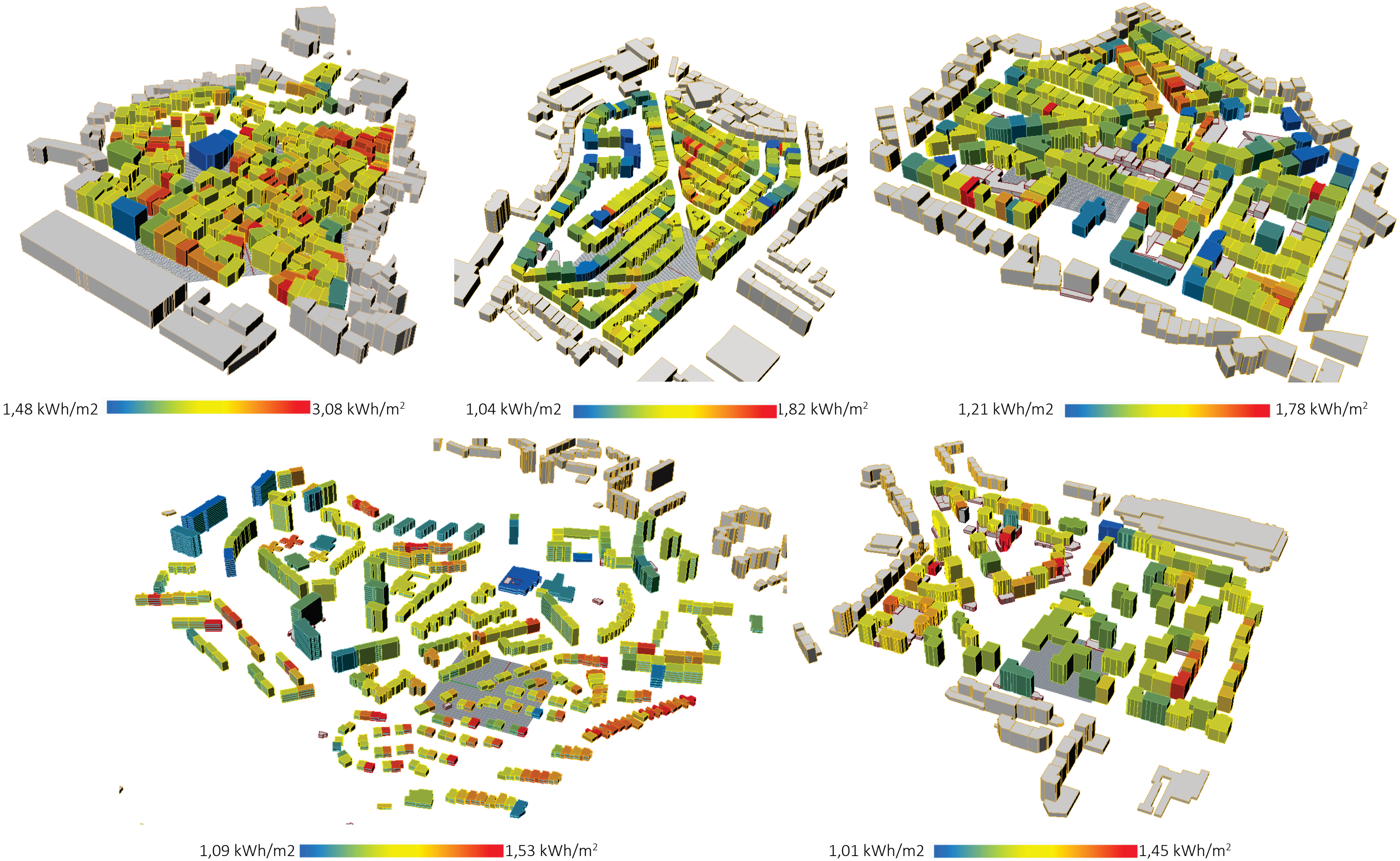


Figure 200: Cooling energy needs spatial representation (kWh/m²)

9.3.3 Relation between urban form and thermal energy

To understand the impact of volume, envelope area, and floor area on the thermal energy needs, a Pearson correlation analysis was made. All 3 variables presented strong correlations (0,98). To better understand the spatial distance between the typologies values when considering urban form and heating and cooling energy, and also to explain the differences between thermal energy needs in GWh and kWh/m^2 a linear regression was made (Figure 201). As it was observed before, robust R^2 results were obtained which proves the strong relation between thermal energy, volume, floor area and envelope area. Observing the distance between the typologies values and the trend line, some important conclusions can be drawn. First, the increase in volume, floor area and also envelope area all lead to an increase in the heating and cooling energy needs, but not proportionally. This means that to achieve a difference of almost 5x from the typology that has lower energy needs in GWh/year (T1E1) to the one with the highest energy needs (T5E2) volume and floor area must increase 7x, however, envelope area only 3x. Also, as a general tendency, whenever the thermal energy needs increase at a greater pace than the urban form variables (typologies that are situated to the left of the trend line) so the thermal energy needs by kWh/m^2, on the contrary, when the urban form variables increases at a greater pace than the thermal energy needs (typologies situated to the right of the trend line), so the thermal energy needs by kWh/m^2 slows its growth rate.

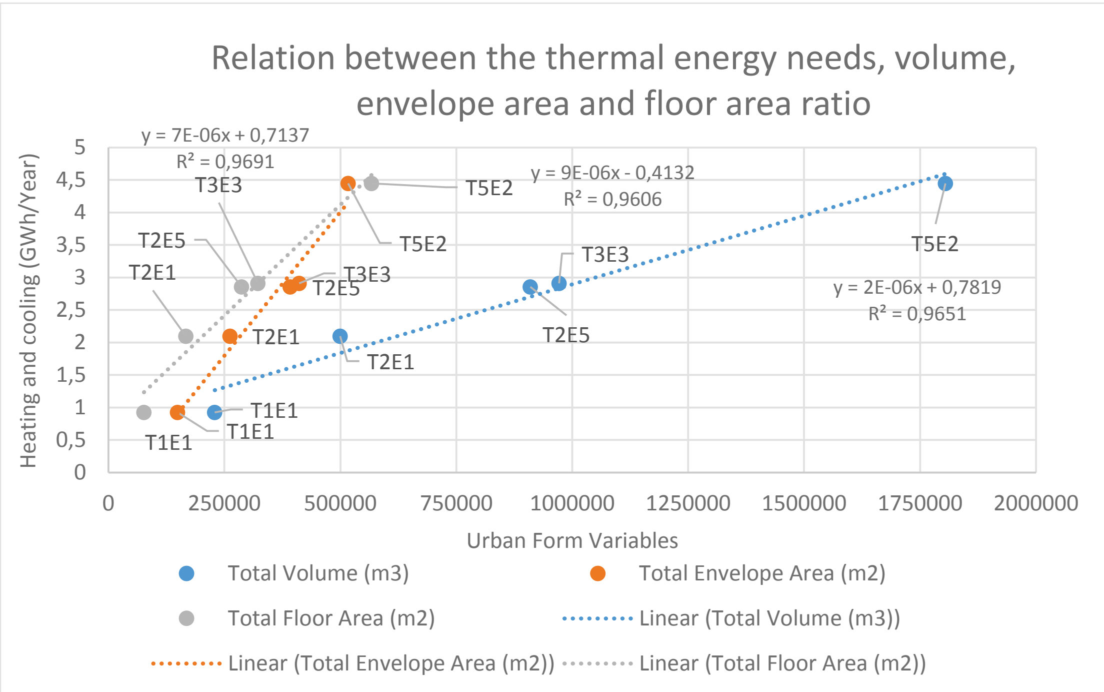


Figure 201: Relation between thermal energy, volume, envelope area and floor area

Analyzing the relation between thermal energy needs and the urban form metrics through a Pearson correlation (Appendix xiv), there is a strong relation between both complexity and thermal energy (GWh/year): MPFD presented a -0,931 correlation, ED a -0,975 correlation, and SVRatio with a 0,983 correlation. These results point out that has the urban form complexity increases, so the thermal energy (GWh) decreases (Figure 202). The same if we look into the correlations that exist if we divide thermal energy into the heating and cooling energy needs, presenting the heating energy needs correlations of -0,939 (MPFD), -0,976 (ED) and -0,981 (SVRATIO); and cooling energy needs correlations of -0,856 (MPFD), -0,939 (ED), -0,968 (SVRATIO). When looking to the correlations between complexity and thermal energy (kWh/m^2) it is registered the inverse tendency, which indicate that complex urban forms despite having an overall lower energy demand (and this is mainly due to the size of each urban form, being that the more complex urban forms that were analyzed were smaller), are less efficient.

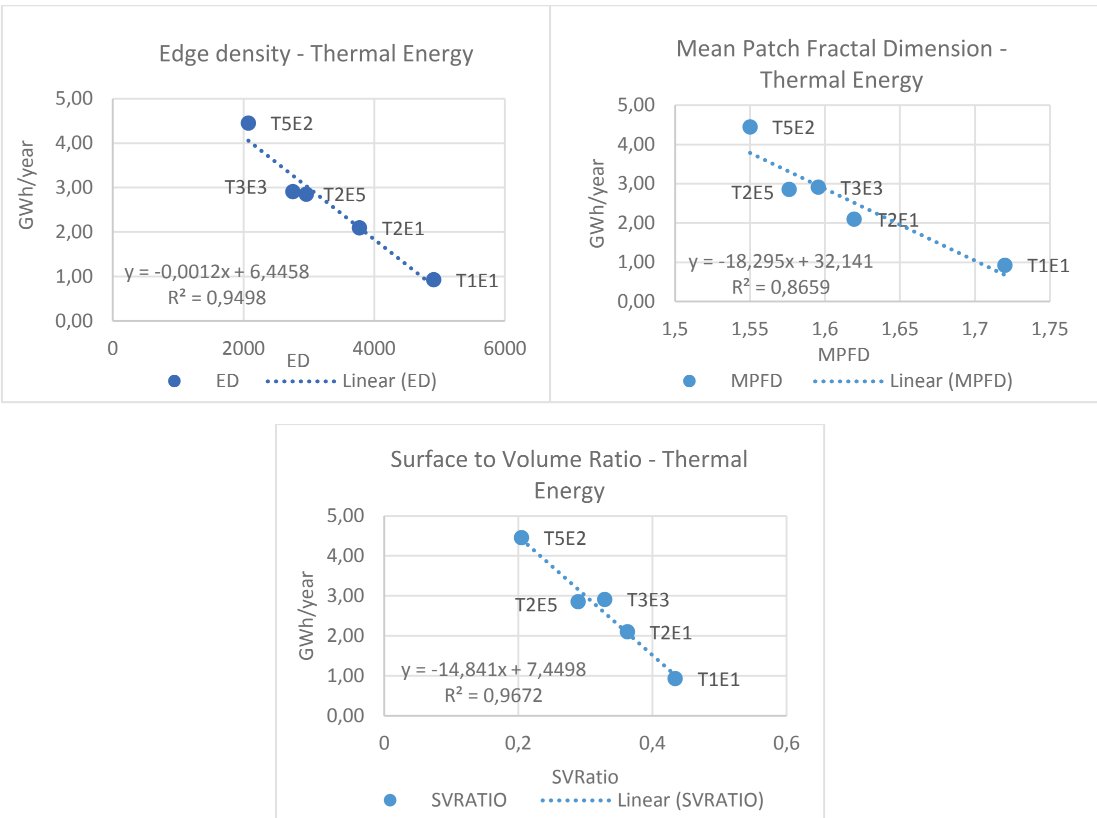


Figure 202 Relation between thermal energy (GWh/year) and complexity

In what regards compaction an important correlation was registered between patch density and thermal energy (-0,872), which indicates that has the typologies became denser so the thermal energy needs tend do decrease (Figure 203). However, looking into the thermal energy values by m^2 the tendency is inverse, with a strong positive correlation between the cooling energy needs and building density (0,951), and a positive correlation but not so significant in what regards the heating energy needs (0,737). This can be related with complexity, since compact urban forms tend to have a degree of complexity in their urban forms, which in turn increases the thermal energy demand. ANN and CR also contribute to the increase in both cooling and energy needs (kWh/m^2) but no so representatively.

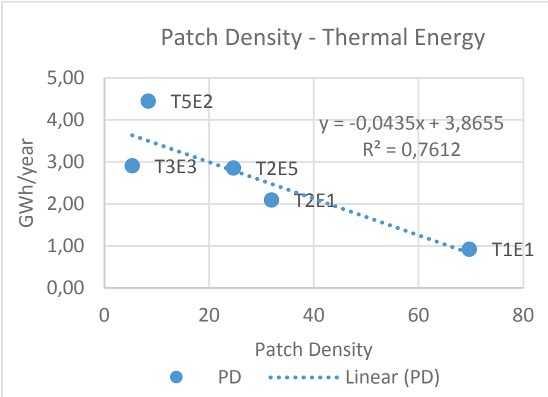


Figure 203: Relation between thermal energy (GWh/year) and patch density

In what regards density thermal energy (GWh) presented a correlation of 0,869 with AVHeight (-0,691 if correlated by kWh/m^2) and also a relation between thermal energy (GWh) and road density (- 0,771, 0,550 if correlated by kWh/m^2). When increasing height usually a building also increases floor area, and this leads to the increase in total thermal energy needs, however, when seen by m^2 the energy demand decreases, this can be related with the fact that by m^2 the tallest buildings have more exposed façade than buildings with a small height, therefore reducing energy demand by m^2. No significant relations were found between heating and cooling energy needs and the heterogeneity metric (PSCOV).

9.3.4 Relation between urban daylight and thermal energy

An important but not significant relation (-0,878) was found between Passive Volume Ratio and thermal energy (GWh) which indicates that as the passive volume ratio increases the thermal energy needs decrease. This is plausible since a higher exposure to solar radiation, consequence of a higher passive volume, will decrease the heating energy needs that is the largest share of the thermal energy needs (Figure 204).

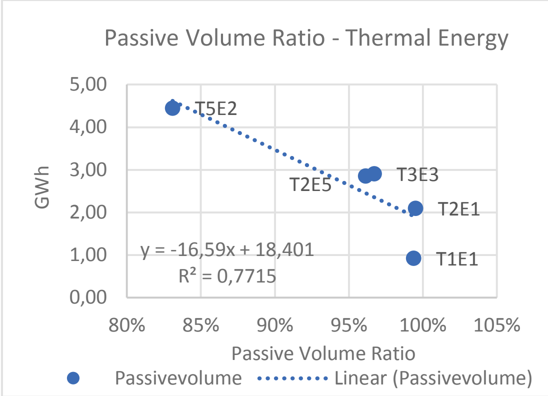


Figure 204: Relation between thermal energy (kWh/m²/year) and passive volume ratio

An inverse tendency was registered when comparing envelope radiation with energy needs in kWh/m². In this case if the passive volume ratio is increased the energy needs (kWh/m²) also increase. This is because total floor area, envelope area and volume, and consequently the surface to volume ratio (SVRatio) are critical in calculating the energy needs by kWh/m², influencing positively the energy needs by kWh/m², which indicates that the higher the passive volume ratio, the higher the SVRatio (correlation of 0,880) and the higher the energy needs by kWh/m². It also means, that other metrics are more important to explain energy needs by kWh/m² than passive volume ratio for the simulation tool that was used, that is the case of the envelope radiation (and indirectly shading availability), as it will be seen further ahead, and also urban form complexity, as it was seen before. Buildings with small areas and/or complex forms, and/or elongated forms will tend to have high passive volume ratios but consequently also higher energy needs by kWh/m², because they tend to have less facades exposed to solar radiation, and usually exist in higher shading contexts. The decrease in the heating energy needs with the decrease of passive volume ratio and vice versa, may also be related by the fact that in the UMI simulations method, buildings with a larger area (and consequently a higher passive volume ratio) tend to present lower energy needs values (kWh/m²) than buildings with smaller areas, which can be related with gains of efficiency – as it was seen before in chapter 9.3.1.

Analyzing the relation between thermal energy (both in m² and total) and CDA and DA, no important correlations were found. On the other hand, an important correlation of - 0,949 was found between thermal energy (kWh/m²) and ER (total) which indicate that has the solar radiation increases so the thermal energy decreases, and this is true since most of the thermal energy is heating energy (Figure 205). These results seem to indicate is that to understand the thermal energy needs it could be more important to look out to the total solar radiation received than the solar radiation autonomy that the buildings have above the minimum requirement for adequate lighting.

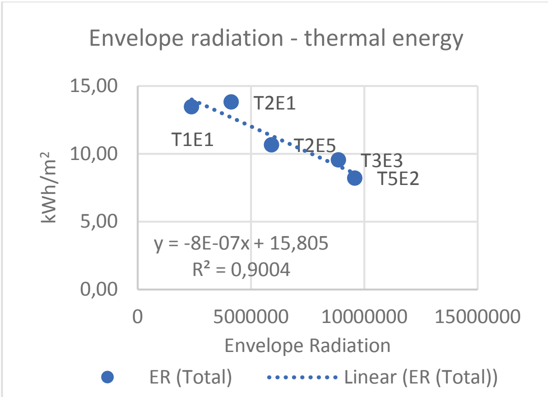


Figure 205: Relation between thermal energy (kWh/m^2/year) and envelope radiation

SECTION E - Discussion and conclusions

10. Main findings on the relation between urban form and energy

10.1 Urban form analysis

Regarding the identification of urban typologies, five construction periods were identified (pre-1919, 1920-1945, 1946-1970, 1971-1990, 1991-present) and their forms clearly show that Lisbon´s urban form evolution went from a high compaction (pre-1919 and 1920-1945), to an expansion along axes of transportation (1946-1970, 1971-1990), to a progressive occupation of interstitial spaces between those axes (1991-present), leading nowadays to a fragmented form, but with a tendency for increased compaction.

In what regards the comparative analysis of the urban typologies, and specifically the complexity dimension, the MPFD for Lisbon was similar to other European cities values that were indicated by Encarnação (2011). MPFD and ED metrics showed that there is a high fractality of the urban form in more traditional typologies than in contemporary ones. In the SV Ratio metric there was a positive evolution of this metric until the 1970´s, which indicates a predominance of small to medium size buildings with low to medium height. From 1970´s onwards there was an increase in the buildings size and height that contributed to the decrease in this metric. Concerning heterogeneity, the PSCoV metric suggests that the heterogeneity of the urban form is increasing until 1970´s-1990´s, and then decreasing in more recent typologies. Regarding compaction, the PD metric suggests that the density of buildings decreased until the 1970´s-1990´s but then stabilized in the 1990-present typologies. The ANN metric points out to a progressive tendency of clusterization (fragmentation) of the urban form in small centers. The coverage ratio metric for the city of Lisbon showed a tendency of dispersion of its urban form mainly until the 1990´s. More recent typologies from the last 20 years are inverting that tendency, presenting more compact urban areas. Density also decreased until the 1970´s. This tendency can be observed through the evolution of the FAR metric, and also through the average height metric coverage. Analyzing both metrics and comparing with the evolution of the coverage ratio metric, it can be concluded that the increase in density from the 1970´s onwards was achieved mainly through the increase in height in the 1971-1990 period, and with an increase in compactness and height (but with less importance) in the period from 1991 to present. The road density metric registered a negative evolution in the 1946-1970´s period, mainly due to the typologies that have a strong presence of detached housing.

Important relations were found between metrics through the correlation analysis:

a) Divergence between compact urban forms (complex with smaller and irregular buildings and a high patch density), and disperse forms (low complexity, regular and large form and low density);

b) As the buildings forms became more complex – small and irregular – so the SVRatio increases, and as they became less complex – large and linear –so the SVRatio decreases. This is a similar tendency than the one registered by Salat (2011) that when analyzing three different archetypes – traditional courtyard, small pavilions, and large pavilions, the traditional courtyards had the greatest surface-to-volume ratio (0.58), followed by the small pavilions (0.4) and large pavilions (0.27). SVRatio according to LSE (2014) also has a negative relation with FAR, which indicates that has the typologies became more dense, so the SVRatio decreases;

c) Smaller and lower buildings tend to contribute to more complex forms than large and tall buildings;

d) High densities tend to have more complex forms since there is less space available, and low densities tend to have less complex forms since there is more space available;

e) High-rise building typologies tend to be less compact - this tendency was also registered by Salat (2009) in what regards the FAR that was much higher in traditional courtyard blocks than in modernist textures and detached housing according to LSE (2014);

f) Typologies with very different building sizes tend to be more fragmented;

g) As the density of buildings increase their distribution in space becomes more space filling, and thus the corresponding road network;

h) Denser urban areas are also more compact areas;

g) Low height buildings tend to have higher SV Ratios and vice-versa.

The cluster ranking analysis allowed the identification of 5 typologies based on the metrics results:

- *Complex Urban Areas*: comprehends traditional typologies that maintain (almost) intact their original form. Usually are forms with a high complexity, compaction and density;
- *Heterogeneous Urban Areas*: urban forms that usually comprehend a mix of housing typologies, they tend to fragmentation and relatively low levels of density;
- *Elongated Urban Areas*: typologies that present overall a homogeneous urban form, with relatively low levels of heterogeneity, complexity, compaction and density. They develop along axis of adjoined and elongated building configurations;
- *Compact Urban Areas*: it has as a main characteristic the urban block configuration, with a predominant orthogonal configuration, constant building sizes and volumes and high density and compaction;
- *Modern Urban Areas*: more approximate to the modern urban planning with very low complexity in its buildings, medium heterogeneity in buildings sizes, low compaction and density.

10.2 Urban energy needs analysis

In what regards the urban energy analysis, when displaying the complete set of correlations between urban daylight metrics and thermal energy needs and urban form metrics, and among urban daylight metrics and thermal energy, it is possible to understand some tendencies:

a) Urban daylight metrics correlate mainly with themselves, also with operational energy in some cases. In particular, envelope radiation correlates positively with energy (GWh), and to some degree passive volume that correlates negatively;
b) Urban complexity is negatively correlated with thermal energy needs, but also envelope radiation and to some degree, passive volume. In particular surface to volume ratio, contribute strongly to energy needs than previous research done by Ratti et al. (2005) and LSE (2014);
c) Heterogeneity is positively correlated with envelope radiation, and to some degree daylight autonomy;
d) Urban compaction is negatively correlated with urban daylight metrics, particularly daylight autonomy, envelope radiation, and also negatively correlated with the thermal energy needs. Salat (2009) also pointed out to this influence, indicating that a greater solar admittance was registered in the modernist typologies, which are usually less compact;

e) Urban density is negatively correlated with daylight autonomy, envelope radiation and passive volume, and to some degree negatively correlated with thermal energy needs (kWh/m^2) in what regards AVHeight and positively correlated in what regards road density. This result is in line with the LSE (2014) study that pointed out to a negative relation between Av. Height and energy needs. The complete set of correlations is presented in Figure 206.

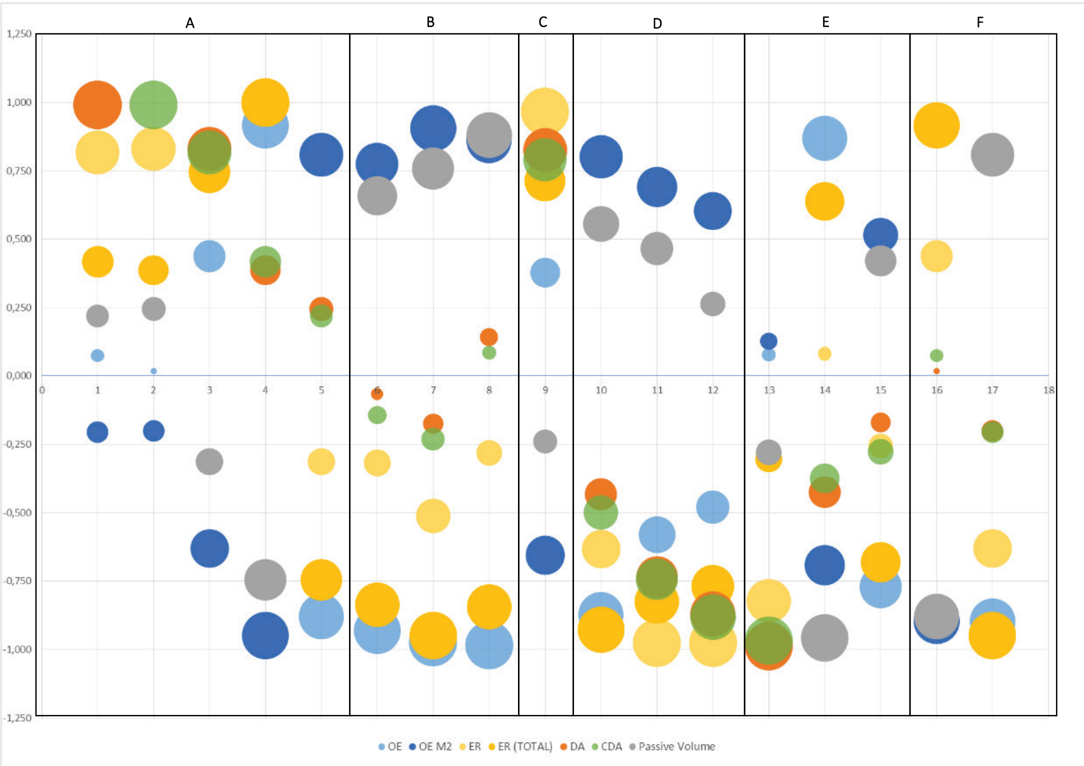


Figure 206: Complete set of correlations between thermal energy, urban daylight metrics and urban form metrics. Bubble size is equivalent to the correlation strength. X-Axis correspondence: A) 1- CDA, 2- DA, 3- ER (m2), 4- ER (total), 5- Passive Volume Ratio; B) 6- MPFD, 7- ED, 8- SVRatio; C) 9- PSCOV; D) 10- PD, 11- ANN, 12- CR; E) 13- FAR, 14- AVHeight, 15- RD; F) 16- OE, 17- OE (m2)

Some general conclusions can be drawn while analyzing the 5 urban typologies that were selected in the city of Lisbon:

1) Urban daylight access is important to understand thermal energy needs (directly in what regards envelope radiation and passive volume, and indirectly in what regards daylight autonomy);

2) Typologies with a high passive volume ratio have lower energy needs (GWh), but higher energy needs if seen by kWh/m^2, because other factors such as the area of the building, surface to volume ratio and envelope radiation strongly contribute to this increase. This is an inverse tendency of the one registered by Ratti et al. (2005), however it is important to note that the

study of Ratti et al. (2005) only analyzed 3 cases and all from the same climatic regions. Also, the highest passive volume ratio obtained by Ratti et al.(2005) was in the range of 80% which is equivalent to the lowest passive volumes ratios registered in the typologies that were analyzed. This indicates that urban form of more historical cities (that present a still important traditional urban form presence that is usually constituted by small and more complex buildings) with a variety of morphological periods, and with other climatic regions, may influence this parameter, as it was also indicated by Ratti et al. (2005:775);

3) Typologies with very complex and elongated urban forms tend to have higher energy needs, this can also be related with urban daylight access;

4) Typologies that have a more heterogeneous urban form, allow more solar exposure and therefore a higher envelope radiation and daylight autonomy;

5) On the other hand, compact and dense typologies have lower levels of daylight access and consequently daylight autonomy;

6) There is a more than 70% difference on the heating and cooling energy needs (kWh/m^2) of the typology with the lowest energy needs (Modern urban areas) to the one with the highest energy needs (Complex urban areas), only taking into account urban form variables;

Since heating energy needs have the most important share in what regards the total thermal energy needs distribution, and since the predominant period of occupation that mas chosen was during night and morning/afternoon (which corresponds to a general residential buildings occupation pattern), urban typologies with higher levels of urban daylight characterized by medium to high heterogeneity and density and medium to low compaction and complexity, tend to perform better. This way, the modern urban areas, with a very low complexity and low compaction, and high heterogeneity and density of their urban form were the ones that performed better. This is because they allow more solar exposure since buildings are farther from each other, explained by the high heterogeneity and low compaction, and also because buildings have more exposed façade to solar radiation, explained by the high density associated with increased height of buildings and also complexity through the SVRatio.

Both the heterogeneous and compact urban areas present average performances. The heterogeneous urban areas presented an overall better than expected performance. This does not mean that in the typology there is an important groups of buildings that perform very poorly, which is true and significant, since this is the most heterogeneous typology in what regards buildings types. Therefore, the result of the typology is in part (and more importantly than in other typologies) due to the average of the energy demand across buildings. This indicates that most probably, to achieve an overall energy efficiency throughout the typology, energy efficiency measures might have to be applied to an important share of the buildings. On the other hand, it also proves that an urban design with mixed buildings typologies might be more efficient than expected. The compact urban areas performed similarly than the heterogeneous urban areas. Despite being commonly associated with sustainability, the fact that very compact urban areas present a high shading availability, a result of the short distance between buildings (low heterogeneity and high compaction), and also by the fact that all buildings present a very similar height therefore reducing façade exposure, leads up to a higher heating energy demand.

Finally, both complex urban areas, and specially elongated urban areas, presented the highest energy demand. Here, the homogeneity of buildings is even higher, therefore the exposed building façade due to difference in height is specially reduced. To note that the complex urban areas, specifically Alfama, performed better than the elongated urban areas mainly due to the orography of the area, that by being very dramatic allowed more solar exposition and therefore lower heating needs and higher cooling needs than the elongated urban form of Penha de França. Other factor that also explains the higher energy demand of these two typologies is the very high complexity of their urban form. Buildings in these typologies are characterized by small and intricate forms which allow for more shading conditions and increase the heating energy demand.

10.3 Understanding the impact of urban form on energy needs

Residential energy consumption data for Portugal is not abundant. There is an important survey that characterizes in detail energy consumption in households in Portugal (Portuguese survey to residential energy consumption in 2010, INE & DGEG 2010), which according to Pereira (2016:9) "[…] *is still the best multipurpose reference regarding the residential energy use in Portugal*". According to this survey the average household final energy consumption for Portugal is 5582 kWh with 22% attributed to house heating and only 0,5% to cooling. If we consider an average of household size in Portugal of 106 m^2 (INE, 2011), this indicates a value of 55,82 kWh/m^2 for total energy consumption. Other important reports to understand energy consumption, but in this case in Lisbon, are the Lisbon Energy Matrix of

2004 and 2014. As it was indicated before, if we consider the DGEG and Pina (2016) information on final energy consumption for the city of Lisbon from 2008-2014, and the 2011 census number of households in Lisbon (INE, 2011), and an average of 96m^2 of an household average in Lisbon (INE, 2011), the resulting value will be of 40,94 kWh/m^2/year per household or 3.930 kWh/year.

Other authors characterized in more detail the residential energy consumption, in particular in what regards thermal energy. Climaco (2011:292) presented results of 13 households in Lisbon (apartments) from the 1960´and 1970´s, and with areas that ranged 80 – 135m^2. The households were both modeled and monitored (to understand the differences that may exist between estimated and real energy consumption). The heating energy consumption ranged from 5,1 to 17,4 kWh/m^2 (monitored) and 6,0 to 19,9 kWh/m^2 (estimated), and the cooling energy consumption ranged from 0,1 to 3,4 kWh/m^2 (monitored) and 0,1 to 3,6 kWh/m^2 (estimated). Pereira (2016:60) also used monitored data from 60 households from Lisbon and periphery. The households were mainly from 1981 onwards, and comprised both apartments (69,5%) and houses (30,5%). The author also divided the energy consumption according to the heating and cooling equipment´s, being that energy consumption values for heating ranged from 2,6 kWh/m^2/year (dwellings without AC and Central Heating [CH]) to 16,9 kWh/m^2/year (dwellings with AC and CH); and for cooling ranged from 0 kWh/m^2 (dwellings without AC and Central Heating) to 1,8 kWh/m^2 (dwellings with AC and CH).

These results are in line with the ones presented for the typologies, in what regards their magnitude, which indicate that the thermal energy needs that were calculated offer robustness in what regards the specific Portuguese context, however being calculated for specific households, not complete sets of buildings. In Portugal the calculation of heating and cooling energy needs at the typology scale is scarce. Sousa Monteiro (2015 and 2016) has developed a method for the generation of multi-detail building archetype definitions and applied it to the city of Lisbon, to characterize typologies of buildings based on their specific materials stock, equipment's and occupation, however final results are not yet available. Also the SUSCITY MIT Portugal research project is aiming at the development of an urban energy model also using the UMI program in order to "*test various energy supply side options, as a tool to design sustainable options in the urban space.*" And also to use the results in other work packages namely in what regards mobility.

Other important data source to access heating and cooling energy needs are the Portuguese Energy Performance Certificates (EPC) (ADENE, 2013). Energy audits are mandatory in Portugal for new buildings or buildings with important retrofit measures since 2013 according to Decree Law n. 118/2013. Therefore information on energy certificates for the areas of the typologies was used (first series from 2013 since they had more complete information), in order to compare the energy performance of households that were audited, and the energy needs modeled for the typologies. Information on each household included geospatial information (used to select only the energy certificates that were inside the area of the typologies to better compare the values), buildings typology, materials, types of equipment, and the respective domestic hot water, cooling and heating energy needs, mechanical ventilation energy consumption, renewables impact on the total energy needs, and finally total energy needs. Detailed information on the calculations made is presented in Appendix xv. The representativeness of the energy certificates in what regards the total number of households for the city of Lisbon is still not very high, being that the number of analyzed households are a fraction of the total number of households for the typology (2-5% of the total), also because only certificates with complete information on energy needs, and correct geospatial data were used. In any case, the distribution of the energy certificates throughout the typologies areas is uniform therefore providing a comparable measure in what regards the impact of different buildings configurations (Figure 207).

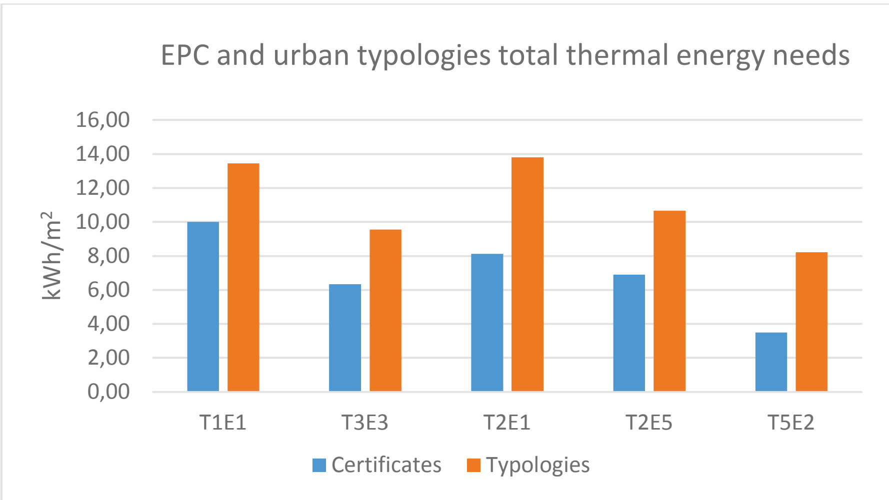


Figure 207: Energy performance certificates and urban typologies total thermal energy needs

Despite differences in the total energy needs values that exist when comparing the EPC data and the modeled typologies data, it is important to note that the difference between typologies – the impact of urban form on energy needs – is almost the same, with the exception of the T2E1 typology. Differences in the total energy needs values may reside in the low availability of energy certificates for the typologies areas, and also by the fact that energy needs are calculated with different methods - one for households and the other for buildings - but also the impact of the context of that building and solar radiation throughout the year which significantly raises the energy needs through shading. Despite these limitations and when comparing typologies, again both the T5E2 and the T1E1 present the more extreme values, being the first the one with a lower energy needs, and the last the one with higher energy needs. T2E1 typology is now the second typology with higher energy needs values followed by T2E5 and T3E3. The certificates results therefore also point out to the importance of urban form for understanding energy demand. The tendency of more complex urban forms, to present higher energy needs than less complex urban forms is still maintained through the analysis of energy certificates data.

Looking at the disaggregation of the total energy needs through heating and cooling (Figure 208), it can be seen that the biggest differences proportionally, are in the heating energy needs, and that can be explained by the already mentioned importance of the shading that is considered in a more detailed way through the UMI simulations, being that shading strongly influences the heating energy needs.

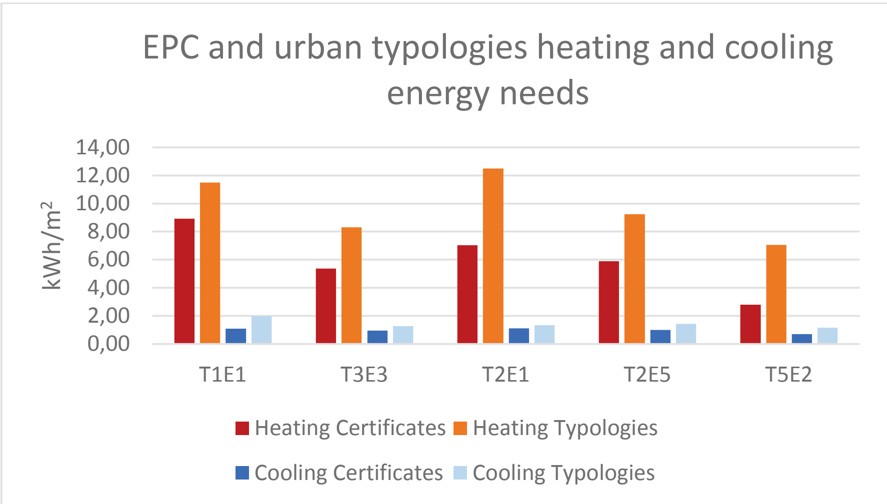


Figure 208: Energy performance certificates and urban typologies heating and cooling energy needs

However, it is also important to compare the selected typologies with other typologies, and therefore it is presented a comparison of the calculated thermal energy values with other relevant literature. The tendency for complex urban areas – higher energy needs – and modern urban areas – lower energy needs, is also evident across research on urban areas and energy. Also important to mention that from the typology that had the highest energy needs to the one with the lowest, it was registered a 1.70x difference (1.77x for heating), similar to the ones indicated by Baker and Steemers (2000) that was of 2.5x, 2x indicated by Ratti et al. (2005) and 1.8x for heating indicated by Salat (2009).

Salat (2009) which compared 3 different typologies – traditional dense urban block (from before 1919), free standing high rise blocks (from 1945-1967) and large urban blocks adjoining buildings of six to eight floors, also included in the analysis different construction technologies (with consequently different U values), and also different energy mixes for the 3 different forms. This analysis in some way deludes the urban form effect, because other variables are included in the analysis, however, traditional dense urban forms of Paris (which are in any case less complex than the ones presented in Lisbon) presented the second highest final heating energy needs with 133 kWh/m^2/year, only after the free standing high rise blocks (with 176 kWh/m^2/year) and very distant with the large urban blocks wit 39 kWh/m^2. These results are in line with the results obtained with the 5 selected typologies, perhaps with the exception with the T3E3 results. However, despite being of the same period, the T3E3 typology and the free standing typology of high rise blocks of Salat present many differences, mainly because the T3E3 typology is composed of a high heterogeneity of buildings types, from free standing high rise blocks, but also to continuous apartments blocks with lower height, large buildings with 2 floors, and also detached housing. In his other research Salat (2011) also compared traditional urban areas, with modernist urban areas, compact urban areas and modern urban areas, also with their original U value, and results also point out that modernist urban forms are the ones with higher heating energy needs (181 kWh/m^2/year), followed by traditional urban areas (158 kWh/m^2), compact urban areas (129 kWh/m^2), and also modern urban areas (31 kWh/m^2). Once again the same tendency registered in the 5 selected typologies, with the exception of the T3E3 typology. To note also that the range of Salat´s values end up being higher since he takes into consideration different U-values. This clearly increase the heating energy needs of the Modernist typologies, since it is a typology with usually higher glazing ratio and thermal bridges, when compared with the modern typology which usually has a higher quality construction with double glazing and better isolated building structures.

The LSE study (2014) presented different performances across the same typologies which is a result of the fact that the definition of the typologies was not made based solely on their urban form properties but on other factors. This fact proves that the methodology that was used in this thesis may be useful in other similar analysis of the impact of urban form on energy needs, since it groups typologies based solely on their urban form characteristics, which reduces the energy performance range among the same typology. In any case, common tendencies can be addressed, and those indicated that detached housing was the typology that presented the highest heating energy needs. Despite none of the 5 selected typologies is a solely detached housing urban area that can be assessed if we look into the detached housing area of the T3E3 typology that presented one of the highest energy needs on pair with the complex urban areas. The LSE study also indicated that compact urban areas are the ones that performed better, and if looked closely to the high rise typologies of Paris (similar to the T5E2 typology), or the slab housing of Paris (similar to the T3E3 typology) those also present similar values to most compact urban areas, in some cases even lower values, which is in line with the results of this research. As for the complex urban areas (T1E1 typology), there isn´t a specific typology in this study, however the compact urban blocks of Istanbul resemble the patterns and metrics of Alfama, and in these specific cases Istanbul presented one of the higher energy needs registered in the LSE study only after detached housing and one specific typology of very high density apartment towers in Berlin.

10.4 Possible applications, research limitations and future work

- **Possible applications**

While the more "traditional" urban morphology perspective is still fundamental to understand the urban phenomena and characterize urban typologies, the contribution of spatial metrics is a valid and complementary approach to characterize the differences between urban typologies in what concerns their design and geometric characteristics, and also to estimate the impact of urban form on heating and cooling energy needs. The research that was presented can constitute a valuable input for urban-related thematic models, like an urban-energy model. On one hand it provides key metrics that can be used as an input in the urban morphology component of a model, while it also allows the precise identification (made through a qualitative analysis on the urban morphology perspective and a quantitative analysis on the metrics calculation and cluster) of case studies that will be used to implement the urban thematic model. The energy model that was used was flexible enough to calculate both heating and cooling energy and daylight metrics in very different urban contexts, and with considerable complexity and detail. The model does not require special computation requirements, and the majority of the software and plugins are available freely in the internet, which allow a great number of researchers to replicate it and compare their results with this research. The results of this research can constitute a valuable input to urban decision-makers, namely government bodies that are responsible for urban planning, municipalities, companies, academic community and also to the general public. This model allows agents that intervene in urban areas, to understand the impact of current and future urban configurations, and in conjunction with other socio-economic, environmental, mobility and other types of data, contribute to better decision making on the future of current and to be planned urban areas. A strategy of densification/dispersion or compaction/fragmentation can be better informed if information like the one produced in this thesis, and many other in the same field, is taken into account. This is because the physical reflex of choices made in urban areas is ultimately the urban form, and research that enables the diagnosis of the urban form current status is most needed not only in urban areas that are expanding very fast, but also in urban areas that aren´t expanding but consolidating or even diminishing. This because, contrary to our daily perceptions, urban form is an "organism" that is constantly evolving. And this way, urban research on urban form, is crucial and should be addressed by the urban agents periodically and constantly monitored in order to prevent future impacts in urban environment, mobility, economy and social context that disruptions on urban form can have, ultimately contributing negatively to the quality of life or the urban citizens.

- Research limitations

The research that was presented has also its limitations. One of the limitations is the fact that in what regards buildings construction properties, systems, and behavioral aspects the same values were defined for all buildings. This is an important limitation of this research since this way, it is not possible to accurately extrapolate present energy needs for the selected typologies. However, it was the method that allowed the detailed and accurate characterization of solely the impact of urban form on energy needs, and this was the main objective of the study. Also, despite sacrificing some detail, the comparison of the energy needs results with relevant literature allowed to understand that the results both in terms of their magnitude, and mainly in terms of their proportion and differences across typologies offer robustness.

Other limitation of this research was the fact that only typologies of one climate zone were analyzed. Only typologies from the city of Lisbon were selected, and the reason for this was the fact that if typologies from another climate were introduced it would introduce another layer of complexity to the research, while not contributing at this stage to a correct understanding of the urban form impact on energy needs since they could produce conflicting results. As it is known, different climates would produce opposite results (e.g. a climate of North of Europe will have comparatively much higher heating energy needs and lower cooling needs than a climate from South of Europe), and the objective of the research was first and foremost to isolate other variables that have influence on energy needs, to capture the contribution of urban form to energy needs. Other limitation was the number of energy simulations made, that were 5 from the 25 case studies. This limitation was due to the methodology itself, since one of the objectives of the research was to implement a clustering method based on urban form metrics to develop a methodology for urban typologies "typification". On the other hand there were also time limitations, since each typology had hundreds of buildings that had to be configured according to their function (contextual geometry, blockage geometry, or building to be simulated), and also the time each simulation step would take, and corresponding analysis.

Finally, other limitation was the Portuguese energy performance certificates data handling, since the database with thousands of energy certificates, and incorrect or missing information that led to difficulties in the geolocation of the certificates and consequently to a relatively low number of certificates for the comparison with the estimated energy needs.

- Future work

Possible developments of current research could be the expansion of the analysis at a first stage to other socio-cultural contexts in the same climate zone and then expand the analysis to other climatic zones, to have a higher set of typologies and contextual elements. Other development would be the comparison of this research with real data from energy meters to validate the simulated energy results. Also important could be the comparison of this data with urban economic activities, therefore bridging research made on urban diversity and urban form with research on urban form and energy, since the type and number of economic activities also correlate with urban form (Quigley 1998, Sevtsuk 2010, Spencer 2015). Other possible research development could be the use of climate change scenarios based on IPCC data, to simulate how the selected typologies would perform in the future, in terms of daylight and thermal energy, with the impact of increased temperatures and other extreme events.

Finally, one important output of this research could be an online platform were similar research on other urban forms and typologies all around the world could be aggregated. This way it could contribute to the productivity of the academic community working on the theme, but also to a better understanding from any person interested in the theme, on how urban form affects energy, and ultimately why cities play a crucial role for sustainability and climate change that constitute today major challenges for our societies.

SECTION F – Bibliography and Appendixes

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Appendixes

Appendix i: Geospatial information used in the thesis

Format	Type	Name	Detail	Scale/ Administrative limits	Years	Source
ArcGIS	Administrative Limits and CENSUS	BGRI Lisboa	Administrative limits of the city of Lisbon Number of classic buildings Number of exclusively residential buildings Number of mainly residential buildings Number of mainly not residential buildings Number of floors Period of construction Type of construction Number dwellings Number of family dwellings Number of residents total, per gender, others Number residents per education Number residents per activity	Municipality – statistical subsection	1991, 2001, 2011	INE
ArcGIS	Administrative Limits	Lisbon Parishes	Lisbon Parishes according to CAOP 2013	Parish	2013	dgTerritório
ArcGIS	Administrative Limits	Lisbon Parishes	Lisbon Parishes according to CAOP 2012	Parish	2012	dgTerritório
ArcGIS	Aerial photography	Aerial photography for the city of Lisbon	Aerial photography for the city of Lisbon	Metropolitan	2005	IGP
ArcGIS	Land use	CLC - Corine Land Cover	CLC90_PT, CLC00_PT, CLC06_PT, CHA06_PT - CORINE Land Cover Changes 2000-2006, High-resolution built-up areas layer	1: 100.000/Municipality	1990, 2000, 2006	European Environmental Agency
ArcGIS	Land use	COS - Land use map	Portuguese land use map for the city of Lisbon at the levels 1 and 2	1:25.000/ Municipality	1990, 2007	IGP
ArcGIS	Land use	Urban Atlas	Urban atlas series for the city of Lisbon	1:10.000/Metropolitan	2006	Urban Atlas
ArcGIS	Land use	Atlas AML - CARTUS	Land use for the city of Lisbon		1990	AML
ArcGIS	Natural elements	Hydrographic network	Hydrographic network for the city of Lisbon	-	2012	CML

ArcGIS	Network	Road network	Lisbon city road network	Municipality	2012	CML
ArcGIS	Network	Road network	Road network according to the Lisbon Municipality Plan	Municipality	2011	Lisbon PDM 2011
ArcGIS	Land Use	Qualification of urban space	Types of land uses and their spatial distribution that are allowed in the Lisbon PDM 2011	Municipality	2011	Lisbon PDM 2011
ArcGIS	Land Use	Urban Blocks	Urban blocks of the Lisbon city	Municipality	2012	CML Open Data
ArcGIS	Land Use	Buildings 2012	BGRI Code, designation, address, parish, area, perimeter	Municipality	2012	CML Open Data
ArcGIS	Land Use	Buildings typological classification	Typological classification of buildings for the Lisbon City	Municipality	2012	CML Open Data
ArcGIS	Land Use	Buildings 2006	Existing building stock of the city of Lisbon. Area, volume, height, length, number floors	Municipality	2006	CML

Appendix ii: Metrics that were calculated for the analysis of Lisbon´s urban form

Source: Adapted from McGarigal and Marks (1995); Rempel, R.S., D. Kaukinen., and A.P. Carr. (2012); LSE (2014)

Group	Name	Description	Units	Range	City	Typo.	Build.
Group I	Built-up area (m2)	Total built area for the typology/city	Sqm.	-			
	Land area (m2)	Total area for the typology/city	Sqm.	-			
	Coverage ratio	Ratio of the sum of the building footprint areas to that of the sample area	-	0-1			
	Floor area (m2)	Total floor area for the typology/city	Sqm.	-			
	Floor area ratio (FAR)	The ratio of the sum of the areas of all building floors to that of the sample area	-	-			
	Surface-to-volume ratio (SV Ratio)	or shape factor, it´s the ratio of the envelope of a building (external facades and roof) to the entire volume of that building	Sqm./cbm.	-			
	% Built-up area	Ratio of the sum of the building footprint areas to that of the sample area in %	%	0-100			
	% Unbuilt area	Area that is not comprehended by buildings	%	0-100			
	Road Density	Total road length dividing by the total land area of the typology/city	m. per sqm.	-			
	Average volume	Average of all the buildings volumes of the typology/city	Sqm.	-			
	Average height (AV Height)	Average of all the buildings heights of the typology/city	Meters	-			
	Average number of floors	Average of all the buildings number of floors of the typology/city	-	-			
Group II	Class Area (CA)	Sum of areas of all patches belonging to a given class	Hect.	-			
	Total Landscape Area (TLA)	Sum of areas of all patches in the landscape	Hect.	-			
	No. of patches (NumP)	Sum of areas of all patches in the landscape	-	-			
	Mean Patch Size (MPS)	Average patch size	Hect.	-			
	Median Patch Size (MedPS)	The middle patch size, or 50th percentile	Hect.	-			
	Patch Size Coefficient of Variance (PSCoV)	Coefficient of variation of patches.	-	0-100			
	Patch Size Standard Deviation (PSSD)	Standard Deviation of patch areas.	Hect.	-			
	Patch Density (PD)	Number of patches regarding total area of typology/city	Build./Hect.	-			
	Euclidean Nearest Neighbor Distance (ENN)	The ratio of the Observed Mean Distance to the Expected Mean Distance	-	ANN < 1 / ANN > 1			
	Total Edge (TE)	Perimeter of patches.	Meters	-			
	Edge Density (ED)	Amount of edge relative to the landscape area.	m./hect.	-			
	Mean Patch Edge (MPE)	Average amount of edge per patch.	m./building	-			
	Shape Index (SI)	Shape Complexity	-	= 1 SI ≥ 1			
	Mean Shape Index (MSI)	Shape Complexity	-	= 1 MSI ≥ 1			
	Area Weighted Mean Shape Index (AWMSI)	It differs from the MSI in that it's weighted by patch area so larger patches will weigh more than smaller ones.	-	= 1 AWMSI ≥ 1			
	Perimeter Area Ratio (PARA)	Shape Complexity	m./Hect.	PARA > 0			
	Mean Perimeter-Area Ratio (MPARA)	Shape Complexity	m./Hect.	PARA > 0			
	Fractal Dimension (FD)	Shape Complexity	-	1 ≤ FD ≤ 2			

	Mean Patch Fractal Dimension (MPFD)	It´s another measure of shape complexity. Approaches 1 for shapes with simple perimeters and approaches 2 when shapes are more complex.	-	1 ≤ MPFD ≤ 2			
	Area Weighted Mean Patch Fractal Dimension (AWMPFD)	It is the same as mean patch fractal dimension with the addition of individual patch area weighting applied to each patch	-	1 ≤ AWMPFD ≤ 2			
	Mean Patch Fractal Dimension Variation (MPFDV)	MPFD variance of each patch according to the MPFD value of the city of Lisbon	-	1 ≤ MPFDV ≤ 2			

Appendix iii: Predominance of the reference period in for each case

Run	Example	Place	Predominance
1	Typology1	Alfama	89%
1	Typology2	Penha França	73%
1	Typology3	Campo Grande/Alvalade	93%
1	Typology4	Marvila	77%
1	Typology5	Parques das Nações - sul	99%
2	Typology1	Mouraria	73%
2	Typology2	Arroios	48%
2	Typology3	Alvalade	94%
2	Typology4	Av. Brasil	76%
2	Typology5	Telheiras	92%
3	Typology1	Bairro Alto	78%
3	Typology2	Avenidas Novas	52%
3	Typology3	Olivais	78%
3	Typology4	Chelas	77%
3	Typology5	Lumiar	52%
4	Typology1	Estrela	74%
4	Typology2	Bairro Azul	88%
4	Typology3	Benfica	66%
4	Typology4	Carnide	75%
4	Typology5	S Domingos Benfica	67%
5	Typology1	Baixa	52%
5	Typology2	Igreja Anjos	60%
5	Typology3	Estrada Benfica	78%
5	Typology4	Benfica	69%
5	Typology5	Lumiar 2	80%

Appendix iv: Average Hourly Relative Humidity % for Lisbon

Average Hourly Relative Humidity % for Lisbon (LNEG-DGEG, 2011)													
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Av. Hour
0:01- 1:00	91	89	86	83	82	82	81	82	85	88	90	92	17,7
1:01- 2:00	93	91	88	85	84	84	84	85	88	90	91	93	21,6
2:01- 3:00	94	92	90	87	86	86	86	87	90	92	93	95	25,5
3:01- 4:00	94	93	92	88	87	88	88	89	92	94	94	95	29,6
4:01- 5:00	95	94	93	89	88	89	90	90	93	95	95	96	33,6
5:01- 6:00	95	94	93	90	89	90	91	91	93	95	95	96	37,7
6:01- 7:00	95	94	93	90	89	90	91	91	93	95	95	96	41,6
7:01- 8:00	95	94	92	89	88	89	89	90	92	94	94	96	45,4
8:01- 9:00	93	91	88	85	84	85	84	85	88	91	92	93	49,2
9:01-10:00	87	86	82	79	78	78	77	78	81	84	86	89	52,7
10:01-11:00	81	80	75	73	72	70	69	70	73	77	80	83	55,9
11:01-12:00	75	74	69	67	66	64	62	63	66	71	74	78	58,8
12:01-13:00	71	70	64	62	61	59	57	58	61	67	71	75	61,3
13:01-14:00	70	69	63	61	60	57	55	56	59	65	69	73	63,7
14:01-15:00	70	69	63	61	60	58	55	56	59	65	69	73	66,0
15:01-16:00	71	70	64	62	61	58	56	57	60	66	70	74	68,3
16:01-17:00	72	71	65	63	62	60	58	58	62	67	71	75	70,7
17:01-18:00	74	73	67	65	64	62	60	60	64	69	73	76	73,2
18:01-19:00	76	74	69	67	66	64	62	63	66	71	75	78	75,9
19:01-20:00	78	77	71	69	68	67	65	66	69	74	77	80	78,7
20:01-21:00	80	79	74	72	71	70	68	69	72	76	79	82	78,4
21:01-22:00	83	82	77	75	74	73	71	72	75	79	82	84	78,2
22:01-23:00	86	84	80	78	76	76	75	76	79	82	84	87	78,1
23:01-24:00	88	86	82	80	79	79	78	79	82	85	86	89	78,2
Av. Month	83,6	82,3	78,3	75,8	74,8	74,1	73,0	73,8	76,8	80,5	82,7	85,3	**78,4**

Appendix v: Average Hourly Statistics for Direct Normal Solar Radiation Wh/m² for Lisbon

Average Hourly Statistics for Direct Normal Solar Radiation Wh/m² for Lisbon (LNEG-DGEG, 2011)													
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Av. Hour
0:01- 1:00	0	0	0	0	0	0	0	0	0	0	0	0	75,7
1:01- 2:00	0	0	0	0	0	0	0	0	0	0	0	0	71,0
2:01- 3:00	0	0	0	0	0	0	0	0	0	0	0	0	66,4
3:01- 4:00	0	0	0	0	0	0	0	0	0	0	0	0	61,8
4:01- 5:00	0	0	0	0	0	60	21	0	0	0	0	0	57,4
5:01- 6:00	0	0	0	114	267	398	435	198	22	0	0	0	53,6
6:01- 7:00	0	14	190	373	383	465	532	444	338	67	0	0	55,8
7:01- 8:00	147	256	331	442	446	529	603	522	465	282	214	82	64,1
8:01- 9:00	314	348	403	506	505	587	667	592	543	364	353	239	78,8
9:01-10:00	382	416	463	560	553	634	720	649	607	432	421	298	98,3
10:01-11:00	432	465	506	598	587	668	757	690	652	480	471	343	120,7
11:01-12:00	459	490	529	618	605	685	776	711	676	505	498	367	145,2
12:01-13:00	459	490	529	618	605	685	776	711	676	505	498	367	170,7
13:01-14:00	432	465	506	598	587	668	757	690	652	480	471	343	196,2
14:01-15:00	382	416	463	560	553	634	720	649	607	432	421	298	220,5
15:01-16:00	314	348	403	506	505	587	667	592	543	364	353	239	242,4
16:01-17:00	147	256	331	442	446	529	603	522	465	282	214	82	261,3
17:01-18:00	0	14	190	373	383	465	532	444	338	67	0	0	275,4
18:01-19:00	0	0	0	114	267	398	435	198	22	0	0	0	283,1
19:01-20:00	0	0	0	0	0	60	21	0	0	0	0	0	285,0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0	281,4
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0	268,0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0	255,8
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0	244,7
Av. Month	144,5	165,8	201,8	267,6	278,8	335,5	375,9	317,2	275,3	177,5	163,1	110,8	**234,5**

Appendix vi: Average Hourly Statistics for Total Sky Cover % for Lisbon

Average Hourly Statistics for Total Sky Cover % for Lisbon (LNEG-DGEG, 2011)													
Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Av. Hour
0:01- 1:00	98	92	66	34	17	8	6	17	41	85	96	100	292,8
1:01- 2:00	99	92	66	33	17	8	6	17	43	85	96	100	289,5
2:01- 3:00	98	93	66	33	17	8	6	15	44	85	95	100	280,6
3:01- 4:00	98	93	66	33	17	8	6	15	44	85	95	100	265,3
4:01- 5:00	98	93	66	33	17	8	6	15	44	85	95	100	245,5
5:01- 6:00	98	93	66	33	17	8	6	15	44	85	95	100	222,7
6:01- 7:00	40	46	42	18	5	0	0	5	41	43	41	40	197,7
7:01- 8:00	100	100	82	39	15	6	5	17	60	98	100	100	170,3
8:01- 9:00	100	96	74	39	19	10	6	19	52	91	99	100	144,4
9:01-10:00	97	91	65	35	21	11	7	18	44	84	95	100	119,7
10:01-11:00	94	84	60	33	20	11	7	16	38	77	89	97	96,9
11:01-12:00	91	82	56	32	20	11	7	16	36	73	86	96	76,9
12:01-13:00	91	82	56	32	20	11	7	16	36	73	86	96	61,4
13:01-14:00	94	84	60	33	20	11	7	16	38	77	89	97	52,3
14:01-15:00	97	91	65	35	21	11	7	18	44	84	95	100	48,9
15:01-16:00	100	96	74	39	19	10	6	19	52	91	99	100	51,3
16:01-17:00	100	100	82	39	15	6	5	17	60	98	100	100	54,3
17:01-18:00	45	41	47	7	3	0	1	2	36	41	44	41	57,3
18:01-19:00	98	93	66	33	17	8	6	15	44	85	95	100	58,6
19:01-20:00	98	93	66	33	17	8	6	15	44	85	95	100	61,3
20:01-21:00	98	93	66	33	17	8	6	15	44	85	95	100	52,4
21:01-22:00	98	93	66	33	17	8	6	15	44	85	95	100	52,5
22:01-23:00	98	93	66	33	17	8	6	15	44	85	95	100	52,6
23:01-24:00	98	93	66	33	17	8	6	15	44	85	95	100	52,7
Av. Month	92,8	87,8	64,8	32,4	16,8	8,1	5,7	15,1	44,2	81,3	90,2	94,5	**52,8**

Appendix vii: Urban form metrics for the 25 urban typologies. The values are the average for each typology.

Metric	Before 1919 (T1)	1920-1945 (T2)	1946-1970 (T3)	1971-1990 (T4)	1991-present (T5)	LISBON
Coverage ratio	0,50	0,45	0,23	0,24	0,28	0,20
Floor Area Ratio	2,42	2,17	1,03	1,12	1,57	0,80
Surface-to-volume ratio	0,341	0,302	0,338	0,267	0,223	0,256
Average height	13,09	13,36	12,36	16,11	16,81	11,30
Road density	4,46	3,84	2,73	4,20	3,23	2,05
MPFD	1,65	1,61	1,6	1,56	1,56	1,62
ED	3587,97	3099,77	3103,28	2278,22	2145,44	2401,76
PSCOV	116,57	119,07	120,77	142,69	134,76	374,33
PD	38,71	24,47	12,63	6,01	6,92	7,23
ANN	1,09	1,08	1,02	0,93	0,91	0,75

Appendix viii :Urban form metrics with absolute values

Typology	MPFD	ED	PSCOV	PD	ANN	Coverage ratio	Floor Area Ratio	Surface-to-volume ratio	Average height	Road density
Tipologia1_Exemplo1	1.72	4910	70.00	69.69	1.14	0.506	1.911	0.434	10	6.880
Tipologia1_Exemplo2	1.68	4046	94.13	30.34	0.89	0.318	1.304	0.385	12	3.262
Tipologia1_Exemplo3	1.66	3522	145.52	45.46	1.13	0.625	2.895	0.325	13	4.728
Tipologia1_Exemplo4	1.63	2919	154.02	21.93	0.96	0.415	1.691	0.316	11	2.812
Tipologia1_Exemplo5	1.57	2542	119.16	26.14	1.31	0.648	4.292	0.246	20	4.619
Tipologia 2_Exemplo1	1.62	3776	39.30	31.94	1.11	0.426	1.839	0.362	12	3.029
Tipologia 2_Exemplo2	1.57	2851	124.76	26.55	1.18	0.549	2.595	0.293	14	3.284
Tipologia 2_Exemplo3	1.58	2383	124.55	12.23	1.02	0.406	2.640	0.226	16	3.634
Tipologia 2_Exemplo4	1.69	3527	244.80	26.98	0.93	0.351	1.351	0.342	9	5.921
Tipologia 2_Exemplo5	1.58	2961	61.96	24.64	1.17	0.495	2.410	0.289	14	3.346
Tipologia 3_Exemplo1	1.56	2825	82.31	14.84	1.41	0.347	1.713	0.295	14	2.565
Tipologia 3_Exemplo2	1.67	3890	121.55	18.60	0.98	0.222	0.545	0.457	7	2.171
Tipologia 3_Exemplo3	1.60	2757	193.67	5.33	0.86	0.132	0.527	0.329	11	3.438
Tipologia 3_Exemplo4	1.57	3023	86.21	12.20	0.94	0.228	1.277	0.297	17	3.533
Tipologia 3_Exemplo5	1.58	3021	120.09	12.17	0.91	0.245	1.072	0.314	13	1.927
Tipologia 4_Exemplo1	1.57	2465	128.87	3.95	1.00	0.178	0.973	0.297	18	3.367
Tipologia 4_Exemplo2	1.63	1986	299.04	6.09	0.80	0.234	0.541	0.301	7	3.032
Tipologia 4_Exemplo3	1.55	2523	82.28	6.18	0.98	0.208	1.092	0.274	16	2.919
Tipologia 4_Exemplo4	1.51	2016	66.85	5.81	1.03	0.343	1.509	0.235	19	5.038
Tipologia 4_Exemplo5	1.54	2400	136.41	8.00	0.83	0.221	1.502	0.227	21	6.618
Tipologia 5_Exemplo1	1.59	2075	114.10	9.17	0.96	0.421	1.866	0.210	11	3.965
Tipologia 5_Exemplo2	1.55	2073	109.05	8.42	0.95	0.326	2.199	0.205	21	2.944
Tipologia 5_Exemplo3	1.57	2158	199.65	6.03	0.79	0.259	1.239	0.236	17	2.355
Tipologia 5_Exemplo4	1.58	2361	131.51	5.78	0.78	0.193	1.127	0.228	18	3.333
Tipologia 5_Exemplo5	1.53	2061	119.48	5.19	1.07	0.225	1.430	0.235	18	3.559

Appendix ix: Urban form metrics with standardized values

Typology	ZMPFD	ZED	ZPSCOV	ZPD	ZANN	ZCOVERAGE	ZFAR	ZSVRATIO	ZAvHEIGHT	ZROADDENS
Tipologia1_Exemplo1	2,350	2,770	-0,980	3,377	0,877	1,163	0,295	2,103	-,98269	2,48165
Tipologia1_Exemplo2	1,625	1,613	-0,563	0,819	-0,743	-0,157	-0,423	1,370	-,67511	-,33368
Tipologia1_Exemplo3	1,134	0,910	0,324	1,802	0,776	1,995	1,459	0,457	-,38362	,80685
Tipologia1_Exemplo4	0,696	0,102	0,470	0,272	-0,299	0,523	0,035	0,326	-,83919	-,68451
Tipologia1_Exemplo5	-0,546	-0,403	-0,131	0,546	1,966	2,158	3,113	-0,724	1,31444	,72186
Tipologia 2_Exemplo1	0,462	1,250	-1,509	0,923	0,650	0,601	0,211	1,025	-,48713	-,51530
Tipologia 2_Exemplo2	-0,394	0,010	-0,035	0,573	1,086	1,465	1,105	-0,024	,03617	-,31708
Tipologia 2_Exemplo3	-0,357	-0,616	-0,038	-0,359	0,111	0,459	1,158	-1,031	,52002	-,04487
Tipologia 2_Exemplo4	1,768	0,917	2,037	0,600	-0,488	0,070	-0,367	0,718	-1,22166	1,73567
Tipologia 2_Exemplo5	-0,353	0,159	-1,118	0,448	1,061	1,085	0,886	-0,082	-,07840	-,26869
Tipologia 3_Exemplo1	-0,601	-0,025	-0,767	-0,189	2,553	0,041	0,061	0,016	-,07902	-,87628
Tipologia 3_Exemplo2	1,352	1,403	-0,090	0,056	-0,150	-0,836	-1,321	2,447	-1,92751	-1,18305
Tipologia 3_Exemplo3	0,012	-0,115	1,154	-0,808	-0,898	-1,470	-1,343	0,516	-,78490	-,19718
Tipologia 3_Exemplo4	-0,410	0,242	-0,700	-0,360	-0,402	-0,793	-0,455	0,034	,54646	-,12289
Tipologia 3_Exemplo5	-0,294	0,239	-0,115	-0,363	-0,617	-0,676	-0,698	0,294	-,23838	-1,37307
Tipologia 4_Exemplo1	-0,474	-0,506	0,036	-0,897	-0,002	-1,144	-0,815	0,035	1,02206	-,25231
Tipologia 4_Exemplo2	0,566	-1,148	2,973	-0,758	-1,307	-0,750	-1,327	0,099	-1,92097	-,51269
Tipologia 4_Exemplo3	-0,755	-0,428	-0,768	-0,752	-0,181	-0,932	-0,674	-0,310	,43890	-,60086
Tipologia 4_Exemplo4	-1,565	-1,108	-1,034	-0,776	0,132	0,015	-0,180	-0,891	1,11264	1,04786
Tipologia 4_Exemplo5	-1,095	-0,593	0,166	-0,634	-1,109	-0,844	-0,189	-1,006	1,54760	2,27827
Tipologia 5_Exemplo1	-0,180	-1,029	-0,219	-0,558	-0,292	0,565	0,242	-1,267	-,74936	,21324
Tipologia 5_Exemplo2	-0,842	-1,032	-0,306	-0,607	-0,365	-0,104	0,636	-1,351	1,54650	-,58135
Tipologia 5_Exemplo3	-0,545	-0,918	1,258	-0,762	-1,348	-0,579	-0,501	-0,871	,58484	-1,04028
Tipologia 5_Exemplo4	-0,245	-0,646	0,082	-0,778	-1,433	-1,040	-0,633	-0,992	,87097	-,27868
Tipologia 5_Exemplo5	-1,309	-1,048	-0,126	-0,816	0,422	-0,814	-0,275	-0,893	,82733	-,10262

Appendix x: Pearson Correlation for each urban form metric

		Zscore(MPFD)	Zscore(ED)	Zscore(PSCOV)	Zscore (PD)	Zscore(ANN)	Zscore(COVERAGE)	Zscore(FAR)	Zscore(SVRATIO)	Zscore(AvHEIGHT)	OADDENS)
Zscore(MPFD)	Correlaçã	1	,831**	,208	,734**	-,044	,246	-,097	,820**	-,773**	,215
	Sig. (2		,000	,319	,000	,834	,236	,643	,000	,000	,303
	N	25	25	25	25	25	25	25	25	25	25
Zscore(ED)	Correlaçã	,831**	1	-,268	,845**	,236	,302	,016	,894**	-,534**	,240
	Sig. (2	,000		,196	,000	,256	,143	,939	,000	,006	,249
	N	25	25	25	25	25	25	25	25	25	25
Zscore(PSCOV)	Correlaçã	,208	-,268	1	-,247	-,507**	-,251	-,308	-,049	-,357	,002
	Sig. (2	,319	,196		,234	,010	,226	,135	,817	,080	,991
	N	25	25	25	25	25	25	25	25	25	25
Zscore(PD)	Correlaçã	,734**	,845**	-,247	1	,443*	,692**	,420*	,633**	-,374	,458*
	Sig. (2	,000	,000	,234		,027	,000	,037	,001	,065	,021
	N	25	25	25	25	25	25	25	25	25	25
Zscore(ANN)	Correlaçã	-,044	,236	-,507**	,443*	1	,671**	,658**	,115	,084	,091
	Sig. (2	,834	,256	,010	,027		,000	,000	,583	,690	,667
	N	25	25	25	25	25	25	25	25	25	25
Zscore(COVERAGE)	Correlaçã	,246	,302	-,251	,692**	,671**	1	,881**	,062	-,042	,314
	Sig. (2	,236	,143	,226	,000	,000		,000	,768	,841	,126
	N	25	25	25	25	25	25	25	25	25	25
Zscore(FAR)	Correlaçã	-,097	,016	-,308	,420*	,658**	,881**	1	-,270	,358	,281
	Sig. (2	,643	,939	,135	,037	,000	,000		,192	,079	,173
	N	25	25	25	25	25	25	25	25	25	25
Zscore(SVRATIO)	Correlaçã	,820**	,894**	-,049	,633**	,115	,062	-,270	1	-,732**	,019
	Sig. (2	,000	,000	,817	,001	,583	,768	,192		,000	,929
	N	25	25	25	25	25	25	25	25	25	25
Zscore(AvHEIGHT)	Correlaçã	-,773**	-,534**	-,357	-,374	,084	-,042	,358	-,732**	1	,127
	Sig. (2	,000	,006	,080	,065	,690	,841	,079	,000		,546
	N	25	25	25	25	25	25	25	25	25	25
Zscore(ROADDENS)	Correlaçã	,215	,240	,002	,458*	,091	,314	,281	,019	,127	1
	Sig. (2	,303	,249	,991	,021	,667	,126	,173	,929	,546	
	N	25	25	25	25	25	25	25	25	25	25

**Correlation significant at the 0.01 level (2-tailed)/*Correlation significant at the 0.05 level (2-tailed)

Appendix xi: Agglomeration schedule for the hierarchical cluster analysis

Agglomeration Schedule

Stage	Cluster Combined		Coefficients	Stage Cluster First Appears		Next Stage
	Cluster 1	Cluster 2		Cluster 1	Cluster 2	
1	14	18	,600	0	0	3
2	7	10	1,313	0	0	11
3	14	16	2,273	1	0	7
4	23	24	3,503	0	0	14
5	8	22	4,904	0	0	9
6	19	25	6,445	0	0	13
7	14	15	8,568	3	0	14
8	2	6	11,316	0	0	12
9	8	21	14,178	5	0	13
10	13	17	17,645	0	0	18
11	7	11	21,326	2	0	19
12	2	4	25,049	8	0	15
13	8	19	29,269	9	6	16
14	14	23	34,315	7	4	20
15	2	12	40,520	12	0	21
16	8	20	47,378	13	0	20
17	3	5	54,777	0	0	19
18	9	13	63,950	0	10	21
19	3	7	73,372	17	11	22
20	8	14	85,121	16	14	24
21	2	9	105,316	15	18	23
22	1	3	134,269	0	19	23
23	1	2	178,812	22	21	24
24	1	8	240,000	23	20	0

Appendix xii: Proximity Matrix

Proximity Matrix

	Squared Euclidean Distance																								
Case	1:T1E1	2:T1E2	3:T1E3	4:T1E4	5:T1E5	6:T2E1	7:T2E2	8:T2E3	9:T2E4	10:T2E5	11:T3E1	12:T3E2	13:T3E3	14:T3E4	15:T3E5	16:T4E1	17:T4E2	18:T4E3	19:T4E4	20:T4E5	21:T5E1	22:T5E2	23:T5E3	24:T5E4	25:T5E5
1:T1E1	0,000	22,024	17,046	36,660	53,678	22,942	38,089	53,929	26,612	36,267	49,850	36,796	58,356	47,486	53,414	61,116	76,170	60,765	65,132	64,897	55,176	71,943	76,444	68,480	69,654
2:T1E2	22,024	0,000	15,189	6,624	43,709	5,495	17,747	21,450	12,438	15,452	22,313	5,993	14,536	11,275	9,955	18,550	28,415	17,458	31,420	32,979	20,677	28,850	24,589	20,839	27,800
3:T1E3	17,046	15,189	0,000	11,004	14,799	10,298	6,958	16,000	15,055	9,466	21,088	30,415	33,639	23,286	25,893	30,868	41,994	30,359	30,987	35,550	19,474	29,182	34,696	34,356	32,000
4:T1E4	36,660	6,624	11,004	0,000	27,233	7,293	6,513	7,813	10,938	7,462	12,515	12,123	8,655	7,315	4,656	10,621	14,645	9,649	18,719	23,429	6,604	14,300	10,460	11,702	13,888
5:T1E5	53,678	43,709	14,799	27,233	0,000	26,212	8,698	12,372	43,845	11,605	20,279	64,411	51,893	30,510	38,373	33,952	64,684	33,335	23,082	33,753	22,448	20,681	39,103	39,038	26,500
6:T2E1	22,942	5,495	10,298	7,293	26,212	0,000	7,717	14,633	22,109	4,546	9,816	13,176	21,703	9,777	10,583	17,517	39,606	14,129	22,224	32,465	16,206	22,192	27,120	23,234	21,227
7:T2E2	38,089	17,747	6,958	6,513	8,698	7,717	0,000	4,549	22,728	1,425	6,757	28,676	23,019	11,415	12,970	15,097	33,506	13,459	13,880	24,161	8,334	11,653	18,557	19,568	12,862
8:T2E3	53,929	21,450	16,000	7,813	12,372	14,633	4,549	0,000	24,195	5,094	10,456	34,447	17,125	6,752	10,102	8,230	27,464	7,097	6,421	12,119	3,021	2,802	8,949	8,224	5,199
9:T2E4	26,612	12,438	15,055	10,938	43,845	22,109	22,728	24,195	0,000	26,017	33,037	19,079	14,367	21,420	21,762	24,662	16,618	28,337	35,469	27,687	21,144	35,920	25,853	25,772	31,805
10:T2E5	36,267	15,452	9,466	7,462	11,605	4,546	1,425	5,094	26,017	0,000	5,000	26,342	23,139	8,727	11,483	13,816	38,097	10,546	11,531	23,505	7,863	11,288	20,456	18,373	11,822
11:T3E1	49,850	22,313	21,088	12,515	20,279	9,816	6,757	10,456	33,037	5,000	0,000	25,774	21,827	10,793	12,108	11,698	37,916	9,918	14,385	29,533	13,303	14,926	22,402	21,394	9,984
12:T3E2	36,796	5,993	30,415	12,123	64,411	13,176	28,676	34,447	19,079	26,342	25,774	0,000	13,360	18,878	12,393	23,662	24,471	22,873	43,863	48,694	30,206	42,494	30,985	30,108	35,182
13:T3E3	58,356	14,536	33,639	8,655	51,893	21,703	23,019	17,125	14,367	23,139	21,827	13,360	0,000	7,445	4,884	6,334	6,934	7,975	20,008	18,112	13,185	18,874	7,185	7,496	12,159
14:T3E4	47,486	11,275	23,286	7,315	30,510	9,777	11,415	6,752	21,420	8,727	10,793	18,878	7,445	0,000	2,721	2,050	24,354	1,201	7,001	10,415	7,764	6,820	7,962	3,940	4,661
15:T3E5	53,414	9,955	25,893	4,656	38,373	10,583	12,970	10,102	21,762	11,483	12,108	12,393	4,884	2,721	0,000	4,421	16,840	2,912	14,844	20,230	9,412	10,702	6,176	5,883	8,332
16:T4E1	61,116	18,550	30,868	10,621	33,952	17,517	15,097	8,230	24,662	13,816	11,698	23,662	6,334	2,050	4,421	0,000	20,988	1,430	7,031	9,949	9,708	6,235	5,546	3,256	2,524
17:T4E2	76,170	28,415	41,994	14,645	64,684	39,606	33,506	27,464	16,618	38,097	37,916	24,471	6,934	24,354	16,840	20,988	0,000	23,724	37,184	33,342	19,779	32,055	12,441	18,887	25,936
18:T4E3	60,765	17,458	30,359	9,649	33,335	14,129	13,459	7,097	28,337	10,546	9,918	22,873	7,975	1,201	2,912	1,430	23,724	0,000	5,939	12,136	7,114	5,354	6,432	3,366	2,384
19:T4E4	65,132	31,420	30,987	18,719	23,082	22,224	13,880	6,421	35,469	11,531	14,385	43,863	20,008	7,001	14,844	7,031	37,184	5,939	0,000	5,941	7,602	5,069	13,613	8,796	3,081
20:T4E5	64,897	32,979	35,550	23,429	33,753	32,465	24,161	12,119	27,687	23,505	29,533	48,694	18,112	10,415	20,230	9,949	33,342	12,136	5,941	0,000	13,628	10,558	13,798	8,090	8,925
21:T5E1	55,176	20,677	19,474	6,604	22,448	16,206	8,334	3,021	21,144	7,863	13,303	30,206	13,185	7,764	9,412	9,708	19,779	7,114	7,602	13,628	0,000	6,966	8,849	7,876	6,755
22:T5E2	71,943	28,850	29,182	14,300	20,681	22,192	11,653	2,802	35,920	11,288	14,926	42,494	18,874	6,820	10,702	6,235	32,055	5,354	5,069	10,558	6,966	0,000	6,419	4,988	3,205
23:T5E3	76,444	24,589	34,696	10,460	39,103	27,120	18,557	8,949	25,853	20,456	22,402	30,985	7,185	7,962	6,176	5,546	12,441	6,432	13,613	13,798	8,849	6,419	0,000	2,461	6,697
24:T5E4	68,480	20,839	34,356	11,702	39,038	23,234	19,568	8,224	25,772	18,373	21,394	30,108	7,496	3,940	5,883	3,256	18,887	3,366	8,796	8,090	7,876	4,988	2,461	0,000	5,003
25:T5E5	69,654	27,800	32,000	13,888	26,500	21,227	12,862	5,199	31,805	11,822	9,984	35,182	12,159	4,661	8,332	2,524	25,936	2,384	3,081	8,925	6,755	3,205	6,697	5,003	0,000

This is a dissimilarity matrix

Appendix xiii: Passive and non-passive volume ratio for the 25 selected cases

Clusters	Typology	Total passive volume	Total non passive volume	Passive volume ratio	Passive volume %	Average
Complex Urban Areas	T1E1	244187	1542	0.994	99.37%	99.37%
Heterogeneous Urban Areas	T2E4	432171	35615	0.924	92.39%	88.11%
	T3E3	937349	31916	0.967	96.71%	
	T4E2	609349	200589	0.752	75.23%	
Enlongated Urban Areas	T1E2	311309	1800	0.994	99.43%	97.20%
	T1E4	969328	77304	0.926	92.61%	
	T2E1	497397	2485	0.995	99.50%	
	T3E2	463073	13068	0.973	97.26%	
Urban block	T1E3	962135	41161	0.959	95.90%	94.43%
	T1E5	2017307	210253	0.906	90.56%	
	T2E2	831896	45891	0.948	94.77%	
	T2E3	1243646	127088	0.907	90.73%	
	T2E5	874343	35199	0,961	96,13%	
	T3E1	863197	47420	0.948	94.79%	
Modern Urban Areas	T3E4	1454523	40191	0.973	97.31%	90.60%
	T3E5	1417512	41318	0.972	97.17%	
	T4E1	1012882	45997	0.957	95.66%	
	T4E3	657522	59704	0.917	91.68%	
	T4E4	413400	61804	0.870	86.99%	
	T4E5	2405099	89463	0.964	96.41%	
	T5E1	927108	133870	0.874	87.38%	
	T5E2	1490474	303494	0.831	83.08%	
	T5E3	2044565	358897	0.851	85.07%	
	T5E4	2095463	280086	0.882	88.21%	
	T5E5	1281057	180489	0.877	87.65%	

Appendix xiv: Pearson Correlation analysis for each urban form, urban daylight and energy metric

		CDA	DA	ER_M2	ER	PASSVOL	MPFD	ED	SVRATIO	PSCOV	PD	ANN	CR	FAR	AVHEIGHT	RD	OE_GWH	OE_M2
CDA	Pearson Correlation	1	,992**	,818	,419	,220	-,143	-,230	,086	,792	-,498	-,743	-,881*	-,967**	-,374	-,277	,075	-,205
	Sig. (2-tailed)		,001	,091	,483	,722	,819	,709	,891	,111	,393	,150	,048	,007	,535	,651	,905	,741
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
DA	Pearson Correlation	,992**	1	,830	,387	,245	-,065	-,174	,142	,826	-,432	-,735	-,869	-,988**	-,425	-,170	,018	-,201
	Sig. (2-tailed)	,001		,082	,520	,691	,918	,780	,819	,085	,468	,157	,056	,002	,476	,784	,977	,746
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
ER_M2	Pearson Correlation	,818	,830	1	,746	-,313	-,317	-,511	-,281	,967**	-,633	-,976**	-,975**	-,822	,082	-,256	,438	-,630
	Sig. (2-tailed)	,091	,082		,148	,608	,603	,379	,648	,007	,252	,004	,005	,088	,896	,678	,460	,254
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
ER	Pearson Correlation	,419	,387	,746	1	-,745	-,837	-,948*	-,844	,714	-,927*	-,824	-,769	-,303	,638	-,681	,917*	-,949*
	Sig. (2-tailed)	,483	,520	,148		,149	,077	,014	,072	,176	,023	,086	,129	,620	,247	,206	,028	,014
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
PASSVOL	Pearson Correlation	,220	,245	-,313	-,745	1	,659	,759	,880*	-,240	,556	,467	,263	-,279	-,957*	,421	-,878	,809
	Sig. (2-tailed)	,722	,691	,608	,149		,226	,137	,049	,698	,330	,428	,669	,650	,011	,480	,050	,097
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
MPFD	Pearson Correlation	-,143	-,065	-,317	-,837	,659	1	,965**	,930*	-,279	,924*	,442	,427	-,070	-,716	,924*	-,931*	,775
	Sig. (2-tailed)	,819	,918	,603	,077	,226		,008	,022	,650	,025	,456	,473	,912	,173	,025	,022	,124
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
ED	Pearson Correlation	-,230	-,174	-,511	-,948*	,759	,965**	1	,947*	-,478	,948*	,621	,575	,060	-,741	,828	-,975**	,906*
	Sig. (2-tailed)	,709	,780	,379	,014	,137	,008		,015	,415	,014	,263	,310	,924	,152	,083	,005	,034
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
SVRATIO	Pearson Correlation	,086	,142	-,281	-,844	,880*	,930*	,947*	1	-,239	,806	,427	,321	-,244	-,906*	,750	-,983**	,861
	Sig. (2-tailed)	,891	,819	,648	,072	,049	,022	,015		,698	,100	,473	,599	,692	,034	,144	,003	,061
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
PSCOV	Pearson Correlation	,792	,826	,967**	,714	-,240	-,279	-,478	-,239	1	-,585	-,901*	-,925*	-,813	-,006	-,165	,378	-,655
	Sig. (2-tailed)	,111	,085	,007	,176	,698	,650	,415	,698		,301	,037	,024	,095	,992	,791	,530	,231
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
PD	Pearson Correlation	-,498	-,432	-,633	-,927*	,556	,924*	,948*	,806	-,585	1	,717	,735	,313	-,528	,885*	-,872	,802
	Sig. (2-tailed)	,393	,468	,252	,023	,330	,025	,014	,100	,301		,173	,157	,608	,361	,046	,054	,103
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
ANN	Pearson Correlation	-,743	-,735	-,976**	-,824	,467	,442	,621	,427	-,901*	,717	1	,965**	,717	-,265	,386	-,580	,691
	Sig. (2-tailed)	,150	,157	,004	,086	,428	,456	,263	,473	,037	,173		,008	,173	,667	,521	,306	,197
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
CR	Pearson Correlation	-,881*	-,869	-,975**	-,769	,263	,427	,575	,321	-,925*	,735	,965**	1	,835	-,075	,426	-,479	,603
	Sig. (2-tailed)	,048	,056	,005	,129	,669	,473	,310	,599	,024	,157	,008		,078	,905	,474	,414	,281
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
FAR	Pearson Correlation	-,967**	-,988**	-,822	-,303	-,279	-,070	,060	-,244	-,813	,313	,717	,835	1	,478	,034	,079	,127
	Sig. (2-tailed)	,007	,002	,088	,620	,650	,912	,924	,692	,095	,608	,173	,078		,415	,956	,900	,838
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
AVHEIGHT	Pearson Correlation	-,374	-,425	,082	,638	-,957*	-,716	-,741	-,906*	-,006	-,528	-,265	-,075	,478	1	-,528	,869	-,691
	Sig. (2-tailed)	,535	,476	,896	,247	,011	,173	,152	,034	,992	,361	,667	,905	,415		,360	,056	,196
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
RD	Pearson Correlation	-,277	-,170	-,256	-,681	,421	,924*	,828	,750	-,165	,885*	,386	,426	,034	-,528	1	-,771	,516
	Sig. (2-tailed)	,651	,784	,678	,206	,480	,025	,083	,144	,791	,046	,521	,474	,956	,360		,127	,374
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
OE_GWH	Pearson Correlation	,075	,018	,438	,917*	-,878	-,931*	-,975**	-,983**	,378	-,872	-,580	-,479	,079	,869	-,771	1	-,896*
	Sig. (2-tailed)	,905	,977	,460	,028	,050	,022	,005	,003	,530	,054	,306	,414	,900	,056	,127		,040
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
OE_M2	Pearson Correlation	-,205	-,201	-,630	-,949*	,809	,775	,906*	,861	-,655	,802	,691	,603	,127	-,691	,516	-,896*	1
	Sig. (2-tailed)	,741	,746	,254	,014	,097	,124	,034	,061	,231	,103	,197	,281	,838	,196	,374	,040	
	N	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

**Correlation significant at the 0.01 level (2-tailed)/*Correlation significant at the 0.05 level (2-tailed)

Appendix xv: Results for the Portuguese EPC for the selected typologies, and results for the 5 typologies that were modeled. Eren.p/Ap: renewable energy contribution (none of the analyzed buildings presented installed renewable energy production); W_{vm}/Ap: mechanical ventilation; N_{ac}: useful energy for hot water; N_{ic}: useful energy for heating; N_{vc}: useful energy for cooling; N_{tc}:: total primary energy; N_{tcf}: total final energy

Typologies	Portuguese Energy Certificates for the selected typologies										Typologies		
	kWh/m²/year (Useful Energy)					kWh_{ep}/m²/year (Primary Energy)	kWh/m²/year (Final Energy)						
	Eren.p/Ap(1)	W_{vm}/Ap(1)	N_{ac}(2)	N_{ic}(2)	N_{vc}(2)	N_{tc}(2)	N_{tcf}(3)	Heating (4)	Cooling (4)	Total	Heating	Cooling	Heating and Cooling
T1E1	0	0,08	117,2	155,5	18,8	17,13	16,73	8,92	1,08	10,00	11,49	1,97	13,46
T3E3	0	0,03	87,7	106,5	18,9	11,02	10,76	5,37	0,96	6,33	8,30	1,26	9,56
T2E1	0	0,04	96,5	148,6	23,2	13,00	12,69	7,03	1,10	8,13	12,49	1,32	13,81
T2E5	0	0,04	78,7	126,2	21,4	10,83	10,58	5,90	1,00	6,90	9,23	1,42	10,66
T5E2	0	0,02	45,9	62,7	15,8	5,66	5,53	2,79	0,70	3,49	7,06	1,15	8,21

1 – Calculated through Despacho (extrato) n.º 15793-I/2013/ 2 – According to ADENE (2013)/ 3- Primary energy share according to E-Nova (2009); Conversion Factors applied through Despacho n.º 17313/2008, and also SGCIE conversion tool[19]/ 4 – Based on the useful energy share of each typology for Domestic Hot water, Heating, Cooling, Mechanical Ventilation and Renewables contribution.

[19] http://sgcie.publico.adene.pt/_layouts/SGCIE_ExternalEntities/ConversorSGCIE.aspx