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A MULTI-SCALE DECISION-SUPPORT MODEL TO INTEGRATE ENERGY IN URBAN PLANNING

MAFALDA LEITE DE FARIA COELHO DA SILVA
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Abstract

Cities and urban areas are inevitably linked to the sustainability agendas worldwide. Because they concentrate a great number of environmental issues, cities are where the ability to take action resides. In particular, the implications from the physical form of urban areas on energy have long been acknowledged in the international debate, whether considering travel patterns or thermal comfort in buildings. However, the complexity of the object at stake, together with a culture of sectorial analysis, has contributed to a limited understanding of this relationship.

This research aims at contributing to provide insights on the nature of the urban form-energy link, with important implications for energy conservation in urban areas. This is done in a comprehensive way, considering the two most important urban sectors (buildings and transport), and a diversity of urban attributes.

In a first instance, it collects and reviews energy-relevant urban form attributes and metrics to be used in the characterization of urban settings, so that urban form may be incorporated in an urban energy analysis in a structured and comprehensive way.

In a second stage, the metrics of urban form selected are used to build a spatially-explicit model (both exploratory and predictive) for the analysis of the influence of urban form on energy demand, comprising three relevant end uses (heating and cooling in buildings and mobility). This is done for two case study cities in Portugal (Porto and Lisbon). Modelling buildings and transport together led to more fitting results than doing it separately. Among the modelling techniques explored, neural networks performed best. The models built enabled to estimate the combined effect of urban form on energy demand, as well as the relative contributions of the different attributes considered. For the cities analysed, the most relevant attributes are density, granularity, centrality and accessibility.

In this sequence, the ANN models are applied in the analysis of several development alternatives for both case studies, regarding their energy performance. The alternatives vary in terms of their physical configuration and development location. The analysis was then extended to accommodate not only energy implications, but also additional criteria influencing urban performance and the cohesion of the urban environment, allowing to identify the best performing alternatives.

Finally, the research acquires a strategic dimension, with a view to linking the insights from the physical analysis to the means of implementing the desired changes in the urban environment. As such, a set of spatial planning policy mechanisms are collected, compared, and selected in order to provide a straightforward framework for informing decision-making in urban and energy planning.

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Resumo

As cidades e as áreas urbanas estão inevitavelmente ligadas à agenda da sustentabilidade em todo o mundo. Por serem foco de um grande número de problemas ambientais, as cidades são também onde se encontra a capacidade de agir. Em particular, as implicações da forma física das áreas urbanas na energia têm estado presentes há várias décadas no debate internacional, seja considerando os padrões de mobilidade, ou o conforto térmico nos edifícios. No entanto, a complexidade do objeto em causa, juntamente com uma cultura de análise setorial, contribuiu para uma compreensão limitada desta relação.

Esta investigação tem como objetivo contribuir para aprofundar a natureza da relação entre forma urbana e energia, com importantes implicações para a conservação de energia nas áreas urbanas. Isto é feito de forma abrangente, considerando os dois setores urbanos mais importantes (edifícios e transportes), e também uma diversidade de atributos urbanos.

Primeiro, os atributos e métricas de forma urbana relevantes para a energia são compilados e analisados, de forma a serem utilizados na caracterização dos ambientes urbanos, e de modo a que a forma urbana possa ser incorporada na análise energética das cidades, de forma estruturada e abrangente.

Numa segunda fase, as métricas de forma urbana selecionadas são usadas para construir um modelo espacialmente explícito (exploratório e preditivo) para a análise da influência da forma urbana na procura de energia, compreendendo três usos finais relevantes (aquecimento e arrefecimento nos edifícios, e mobilidade). Isto é levado a cabo para duas cidades que representam dois casos de estudo em Portugal (Porto e Lisboa). Modelar edifícios e transportes de forma combinada levou a melhores resultados do que fazê-lo separadamente. Entre as técnicas exploradas, as redes neuronais apresentaram os resultados mais satisfatórios. Os modelos construídos permitiram estimar o efeito combinado da forma urbana na procura de energia, bem como as contribuições ou pesos relativos dos diferentes atributos considerados. Nas cidades analisadas, os atributos mais relevantes são a densidade, a granularidade, a centralidade e a acessibilidade.

Nesta sequência, os modelos ANN são aplicados na análise de várias alternativas de desenvolvimento em ambos os casos de estudo, tendo em conta o seu desempenho energético. As alternativas variam em termos de configuração física e da localização do novo desenvolvimento. A análise foi então alargada de forma a acomodar, além das implicações energéticas, critérios adicionais que influenciam o desempenho e a coesão do ambiente urbano, permitindo identificar as alternativas com melhor desempenho.

Finalmente, a investigação adquire uma dimensão estratégica, com o objetivo de fazer a ponte entre os resultados da análise física e os meios de implementação das mudanças desejadas no ambiente urbano. Como tal, foram reunidos, comparados, e selecionados um conjunto de mecanismos políticos de ordenamento do território, com vista a fornecer um enquadramento sistemático e objectivo para o apoio da tomada de decisão no planeamento urbano e energético.

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Contents

ACRONYMS

AADT	Annual Average Daily Traffic
ADENE	*Agência de Energia* (National Energy Agency)
AiSi	Spatial Distribution of Green Areas
ANN	Artificial Neural Network
BC	Base Case
BFGS	Broyden – Fletcher – Goldfarb – Shanno
BRT	Bus Rapid Transit
CAD	Computer Assisted Design
CBD	Central Business District
CCS	Congestion Charging Scheme
CD	Consolidated Development
CEC	Commission of the European Communities
CFI	Comparative Fit Index
CML	*Câmara Municipal de Lisboa* (Lisbon Municipality)
CMP	*Câmara Municipal do Porto* (Porto Municipality)
Connect	Connectivity
DivAct_Ped	Pedestrian Diversity of Activities
DivAct_PT	Public Transport Diversity of Activities
EC	European Commission
E_c	Final energy demand for cooling
E_h	Final energy demand for heating
EPBD	Energy Performance of Buildings Directive
ET	Final energy demand for transport
EU	European Union
F	Number of Floors
FSI	Floor Space Index
GDP	Gross Domestic Product
GFA	Gross Floor Area
GHG	Greenhouse Gas
GI	Green Infrastructure
GIS	Geographic Information System
GJ	Giga Joule
GSI	Ground Space Index
HDD	Heating Degree Day
HOT	High Occupancy Toll
HOV	High Occupation Vehicle
ICLEI	Local Governments for Sustainability
IEA	International Energy Agency
IN	Infill development
INE	*Instituto Nacional de Estatística* (National Statistics Office)
IPCC	Intergovernmental Panel on Climate Change
KDD	Knowledge Discovery in Databases
LEM	Location-efficient mortgages
LM	Levenberg-Marquardt
LT	Lighting and Thermal
LUT	Land Use and Transport
MAPE	Mean Absolute Percentage Error
MCDA	Multi-criteria Decision Analysis
MD	Modern Development
MFH	Multi-family Housing
MLR	Multiple Linear Regression
MSE	Mean Squared Error
MXI	Mixed-use Index
NDVI	Normalized Difference Vegetation Index
Nic	Nominal energy for heating
NID	Neural Interpretation Diagram
Nvc	Nominal energy demand for cooling
OD	Origin Destination
OECD	Organization for Economic Co-operation and Development
OSV	Obstruction Sky View
PDM	*Plano Diretor Municipal* (Municipal Masterplan)
PES	Primary Energy Savings
PMV	Private Motorized Vehicle
PP	Purchase Power
PT	Public Transport
PT_RD	Public Transport Route Density
R^2	Coefficient of Determination
RCP	Representative Carbon Pathway
RMSEA	Root Mean Squared Error of Approximation
RMSPE	Root Mean Squared Percentage Error
SAL	Structural Accessibility Layer
SCG	Scaled Conjugate Gradient
SE	Standard Error
SEM	Structural Equation Model
SID	Special Improvement Districts
SS_Area	Subsection Area
STV	Surface-to-Volume
SubDiv	Sub-division Indicator
SVF	Sky View Factor
SVR	Support Vector Regression
SW	Sidewalks
TDR	Transfer of Development Rights
TIF	Tax increment financing
TOD	Transit-oriented Development
UGB	Urban Growth Boundaries
UHA	Urban Horizon Angle
UHI	Urban Heat Island
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USB	Urban Service Boundaries
VMT	Vehicle Miles Travelled
WCED	World Commission on Environment and Development
WO	Weighting Option

CHAPTER 1. CITIES AND ENERGY

1.1. Why do cities matter?

In the past decades, a significant amount of attention has been drawn to the influence of urban areas on global sustainability (with climate change concerns at the top), by considering their potential for improving the *status quo* concerning issues like energy conservation and efficiency. There are a number of reasons why cities and towns matter. At present, more than half of the world's population is living in towns and cities, with the urbanization rate estimated to increase until 2050 (United Nations, 2015a). In the past 50 years, the percentage of urban population worldwide more than doubled, currently being of 53.8% (Figure 1). In the developed world, urbanization acquires another dimension. The countries from the Organisation for Economic Co-operation and Development (OECD) have one of the largest shares of urban population (over 80% in 2015) and Europe is closely following with nearly 75% (World Bank, 2016; EEA, 2016). In this matter, Portugal is currently halfway between the world and the European Union's (EU) urbanization levels.

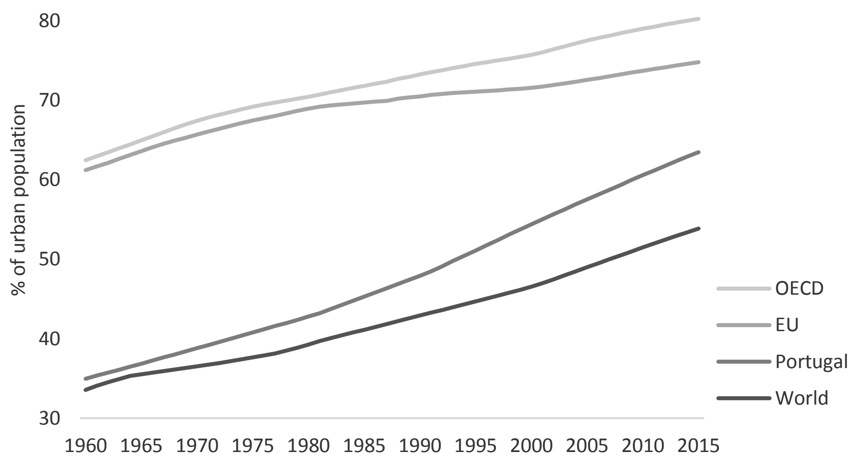

Figure 1.Evolution of urban population in different geographical contexts.
Source: The World Bank

Most of the future urban growth is expected to happen in small- to medium-sized cities, with the greatest challenges in the developing world where governance and institutional capacities are typically more reduced. The contribution of 'megacities' (over 10 million inhabitants) is expected to be relatively small (Grubler et al., 2012).

Not only cities are the place where people live and work, but they are also the centre of political power, the venue of cultural activities, the cradle of innovation, and important drivers of economic development and investment. Nevertheless, urban development has often come at the expense of environmental integrity and quality, including effects such as resource depletion, waste and wastewater production, poor air quality and greenhouse gas (GHG) emissions, soil sealing, traffic, noise, and poor built environment. The importance of addressing urban issues lies, at a great extent, on the improvement of the quality of life of a large number of citizens. Environmental problems in cities are particularly complex, as their causes are frequently inter-related (CEC, 2006). Tackling one problem is often acknowledged to bring co-benefits (Somanathan et al., 2014). For instance, reducing motorized traffic may not only cut energy demand and GHG emissions, but it also contributes to decreasing noise and congestion.

There have been several perspectives on how to improve urban areas. In the beginning of the twentieth century, Ebenezer Howard proposes the concept of garden city as an answer to the urban problems faced at the time (Howard, 1902), which has been later adapted to regional planning (Geddes, 1915). In the middle of the twentieth century, the development of the modern city has been subject to criticism (e.g. Jacobs (1961)), whereas more explicit concerns with the quality of urban form have been raised by Lynch (1960, 1981). Nevertheless, these early works have a strong social emphasis. Concerns about urban form and sustainability (and energy) emerged more recently, with Jenks et al. (1996) and Williams et al. (2000) being notable examples.

The incorporation of sustainability concerns in international policies was accelerated after the release of the Brundtland report also known as “Our Common Future Report” (WCED, 1987), while in 1992, the Rio Summit and its main output (the Agenda 21) emphasized the importance of local action to meet sustainability objectives. More recently, sustainable cities integrate the 2030 UN agenda for sustainable development, under the goal #11 (UN, 2015). In the EU, the Aalborg Charter launched the European Campaign for Sustainable Cities in 1994, and more recently, the Leipzig Charter on Sustainable European Cities (2007) was adopted by Member States, who agreed on a set of principles and strategies for the urban development policy. Table 1 presents the key elements of EU’s approach to the urban environment (EC, 2010).

Table 1. Key elements of EUS’s approach to the urban environment

First published	*Revised*	*Document*
2000	*2005*	*Lisbon Strategy*
2001	*2009*	*Sustainable Development Strategy for the EU*
2006	-	*Thematic Strategy on the Urban Environment*
2007	-	*Leipzig Charter on Sustainable European Cities*
2010	-	*Europe 2020 Strategy*
2013	-	*The 7th Environmental Action Programme to 2020*

Adapted from EC (2010).

In addition to the sustainability concerns at large, cities play an important role in climate change mitigation and adaptation (IPCC, 2007). On the one hand, they are important producers of GHG emissions, which assigns urban areas a key role on climate change mitigation. One the other hand, since more than half of worldwide citizens already live in cities, it is virtually unmanageable to relocate such a great amount of people. Cities should adapt to climate change as well. Under the scope of the 21st Conference of the Parties of the *United Nations Framework Convention on Climate Change*

(UNFCCC), and for the first time, all parties agreed (Paris Agreement[1]) to put forward their best efforts in tackling climate change (United Nations, 2015b). Here, cities are unequivocally called to join this effort. Aligned with this, a large number of transnational initiatives, focused on urban areas, have emerged in view to developing responses to tackling climate change (Betsill and Bulkeley, 2007; Bansard et al., 2016). A few renowned examples include:

- Climate Alliance (1990)
- Energy Cities (1990)
- Cities for Climate Protection (ICLEI, 1993)
- C40 Cities Climate Leadership Group (2005)
- Covenant of Mayors (2008)

The current debate on cities is placed, on a large extent, on how the cities of the future should be. Although there is a general agreement on the general goals for urban areas, the specific features that should be promoted to achieve such goals are often unclear. In other words, it is consensual that cities should be sustainable. Nevertheless, *what* may help a city moving towards sustainability may be overlooked when a new urban project is being discussed. This is aggravated by the fact that the built environment has a long permanency in time. It is urgent to improve the assessment of the impact of urban decisions, because the cities of the future already exist or are being built now.

Acknowledging that sustainability is a wider and complex concept, this research particularly focuses on opportunities for energy conservation in cities, thus contributing to addressing the challenge of climate change mitigation (Figure 2).

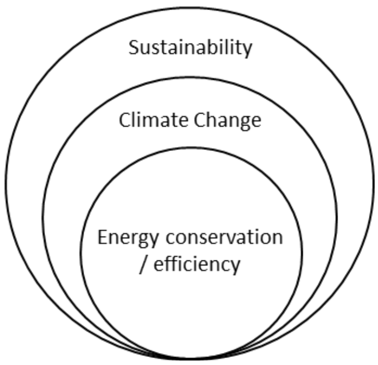

Figure 2. Hierarchy of the different concepts addressed by the research

Section 1.2 describes the patterns of energy use in urban areas and Section 1.3 introduces urban form as a driver of energy demand. The research problem and goals are presented in Section 1.4, while Section 1.5 depicts the research design. Section 1.6 concludes with the thesis roadmap by providing the reader with an overview of the topics addressed in the following chapters.

[1] The United States have recently (June 2017) announced withdrawal from the Paris Agreement.

1.2. Urban energy use: issues and patterns

The use of energy worldwide is the source of approximately two-thirds of all anthropogenic GHG emissions (IEA, 2015). Energy is a fundamental driver of life, particularly life in cities. Cities represent approximately two-thirds of the world's energy use and account for 71% of the global GHG emissions (IEA, 2008a). By 2030, these values are expected to increase to about 73% and 76%, respectively, and urban population is estimated to be 60% of total global population — the equivalent to the total global population in 1986 (IEA, 2008a). This evidences the potential for cities to curb current trends. It is in cities that action should have the greatest impacts.

The link between climate change and increasing GHG emissions is now clear (IPCC, 2013). The climate change is a result of a set of complex phenomena such as the warming of the atmosphere and the ocean, changes in the global water cycle, the rise of global mean sea level, and extreme weather events (IPCC, 2013). The consequences include the loss of biodiversity, the vulnerability of agricultural crops (and thus, food supply), and the safety of coastal populations (IPCC, 2007).

In its 5th Assessment Report, the Intergovernmental Panel on Climate Change defined a set of scenarios called *Representative Carbon Pathways* (RCP) to predict the effect of GHG concentrations in global average temperatures. GHG emissions are projected to increase in all scenarios until the end of this century, whereas the only scenario that is able to limit warming to 'safe' limits (below 2.0 °C) is the RCP2.6 depicted in dark blue (Figure 3). Policy-makers are urged to adopt strict measures to curb climate change.

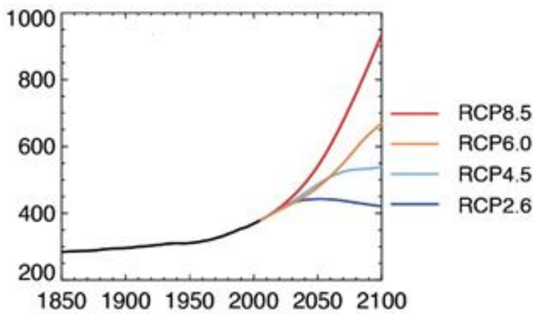

Figure 3. RCP CO_2 pathways (ppm)
Source: IPCC (2013)
The increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be within the following ranges for each RCP: 0.3°C - 1.7°C (RCP2.6), 1.1°C - 2.6°C (RCP4.5), 1.4°C - 3.1°C (RCP6.0), 2.6°C - 4.8°C (RCP8.5).

In Europe, GHG emissions per capita are lower in urban areas compared with non-urban areas (IEA, 2008b; European Commission, 2011). For instance, in 2006 the ratio between per capita primary energy demand in cities and the regional average in the EU was 0.94 (IEA, 2008b). This may be attributed to more energy-efficient forms of housing, transport and service provision arising from urban agglomeration. In addition, it is argued that the adoption of measures to address climate change may be more cost-effective in large and compact cities than in less densely populated areas.

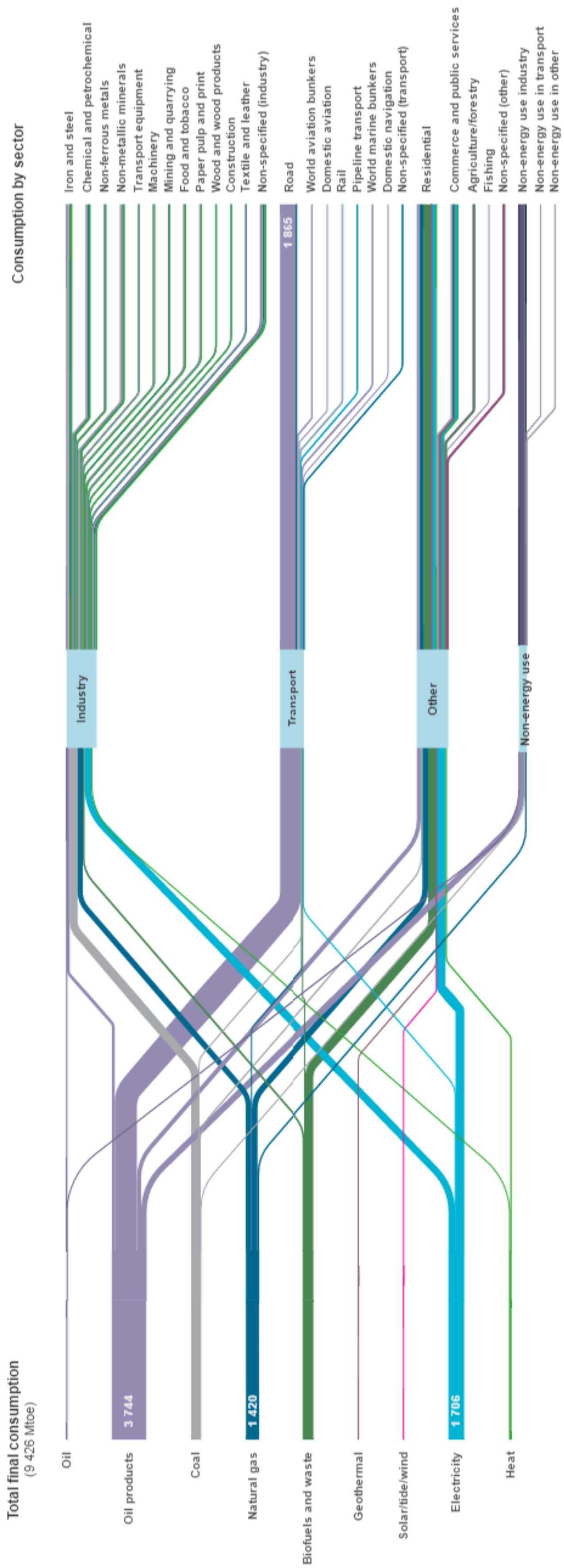

Figure 4. World final energy flows by energy source and sector (2014)
Source: IEA

Both worldwide and in the EU, fossil energy sources hold a dominant share of the total primary energy use (IEA, 2015; Eurostat, 2016). Furthermore, the greatest share of final energy use (97% both worldwide and in the EU) takes place within three key sectors – buildings, transports and industry (IEA, 2008a). The former two are intrinsically linked to urban areas. Figure 4 depicts a Sankey diagram of the final energy flows worldwide, where the thickness of the lines is proportional to the size of the flow. In 2014, buildings (residential and non-residential), transports and industry roughly amounted to 30% of final energy, each. Particularly in the transportation sector, it is evident the weight of road transport, in relation to the remaining modes (Figure 4). This trend remains in the European context (Eurostat, 2016).

In Europe, the weight of the building sector is relatively larger, which may be due to, on one hand, the delocalization of some industries to developing countries and, on the other hand, a larger share of public transport use than in other world geographies. By 2014 buildings accounted for 38.1% of total final energy use – 24.1% for households and 13.3% for services (Eurostat, 2016) – and 36% of total CO_{2eq} emissions (EC, 2010a). The transport sector used 33.2% of overall final energy and Industry 25.9%, in the EU-28 by 2014 (Eurostat, 2016).

With regard to residential buildings, space heating typically holds the largest share of energy use (Figure 5). However, a decrease in heating needs has been felt in the past decade, which may be a result of the enforcement of regulation on the energy performance of buildings (Directive 2002/91/EC, 2002; Directive 2010/31/EU, 2010). Cooling and lighting needs are still residual comparing to the overall demand, although cooling has been evidencing significant increases. There are fluctuations on the patterns of energy use between the different European countries. One of the reasons is the relationship between thermal energy demand and the local climate (Lapillonne et al., 2015).

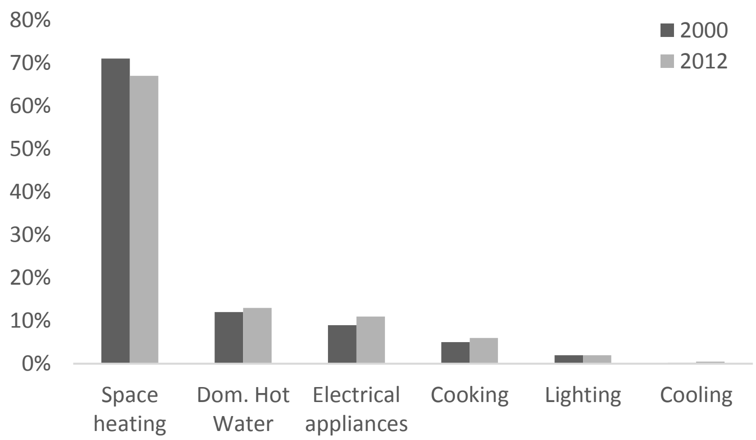

Figure 5. Household energy consumption by end-use in the EU (2000-2012).
Source: Lapillonne et al. (2012)

Considering mobility patterns, passenger transport is typically associated to the urban environment, and to a larger share of energy use, comparing with freight. The use of private vehicles is still dominating the transportation landscape both in the EU and in Portugal (Figure 6). For the period between 2000 and 2012, and in the case of the EU, private motorized vehicles have slightly increased its share (by 1 percent point), while in the case of Portugal the increase is much more significant (8.1 percent points). In both cases, the increase in the use of private vehicles has come at the expense of a decrease in the use of coaches and buses.

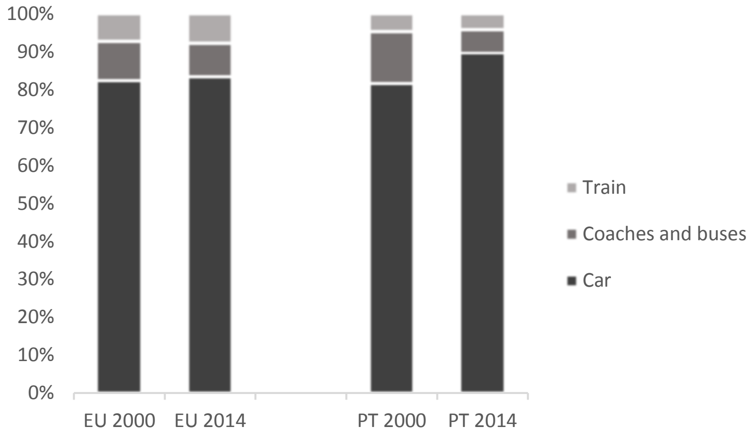

Figure 6. Modal Split of passenger transport in Portugal and in the EU (2000-2014)
Source: Eurostat

Figure 7 complements Figure 6 in the sense that it makes evident the carbon intensity of different transport modes. Public transport systems such as passenger trains and trams or buses are the transport modes with lower carbon intensity (surpassed by soft modes only), whereas some patterns of private vehicle occupancy can be as intensive as air travel, considering per passenger emission levels.

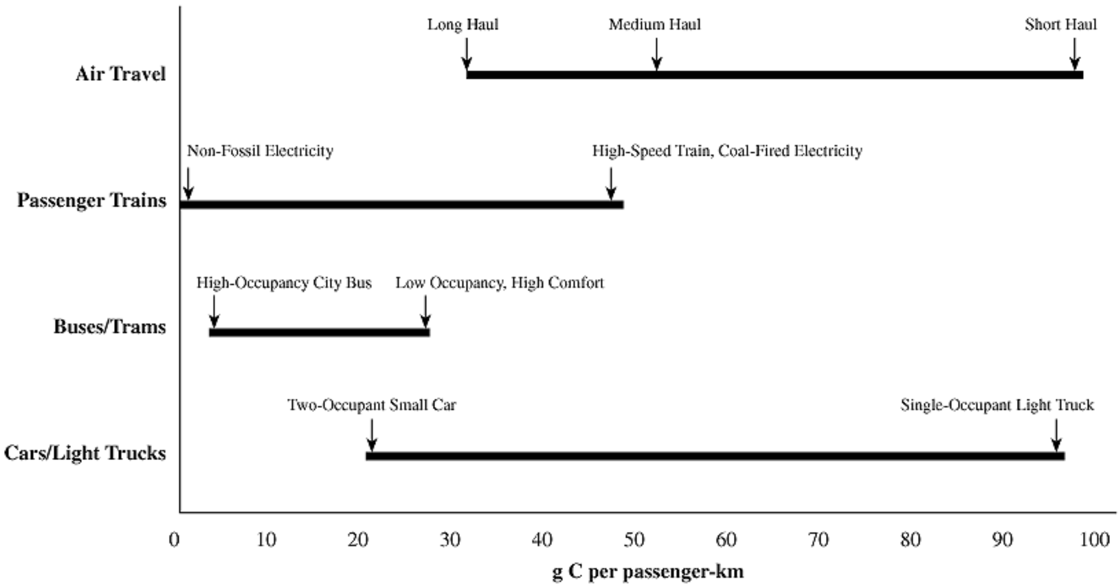

Figure 7. GHG intensity of passenger transport
Source: IPCC (1999)

Given the existing trends and projections, tackling climate change will be an enduring challenge for the next decades. While technological innovation may deliver efficiency gains in urban systems, efficiency improvements are at the end of a sustainable hierarchy policy (Bosseboeuf, 2013). At the very base of the hierarchy is the avoidance of emissions by reducing the needs of energy use – i.e. energy conservation. It is of high importance to build cities to work with as little energy as possible, from scratch, and still supplying people's needs without diminishing the inhabitant's quality of life and the access to urban services. While Bosseboeuf (2013) refers to the transport sector (avoiding motorized trips and shifting transport modes before seeking efficiency gains); in the case of buildings this has also been called energy sufficiency (IEA, 2013), and is based on a set of non-technological solutions related to the design of the building to reduce the energy required for its daily operation.

Urban energy systems have some specificities in relation to other energy systems. Energy use and associated emissions are a result of a high concentration of population and activities, there is a high level of system openness, and a high concentration of capital and other resources that may be applied in the transition towards more sustainable urban pathways (Grubler et al., 2012).

Another important aspect of urban energy systems is their lifetime span (Figure 8). While the capital stock of final consumption equipment typically has a short lifetime span, making it easily replaced by more efficient ones, the elements of the built environment, conversely, have a medium-to-large durability (IEA, 2011). Actions performed upon this dimension are expected to impact the energy performance of cities for decades or even centuries.

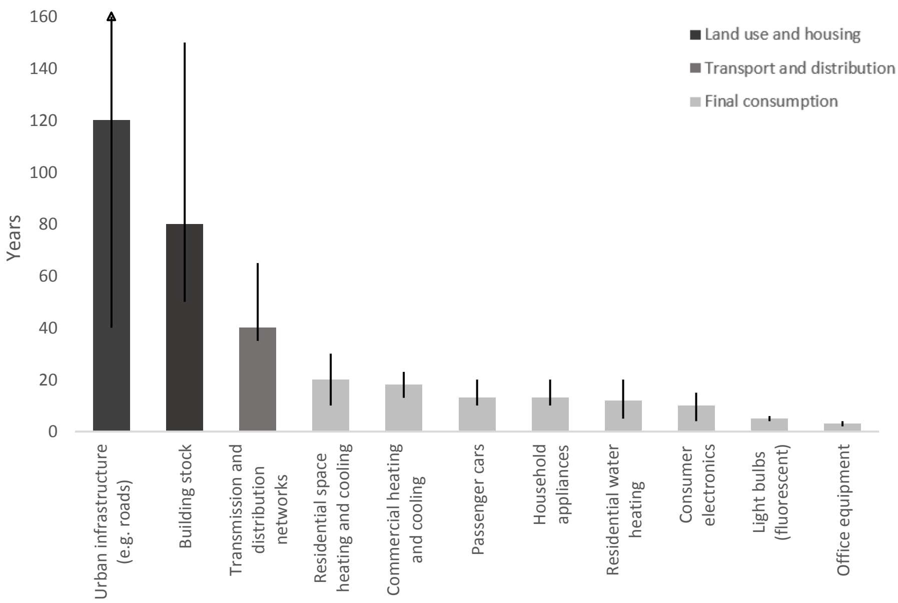

Figure 8. Typical lifetime of energy-related capital stock
Note: Solid bars represent average lifetimes while the range lines show typical variations. Adapted from IEA (2011).

There are many drivers of energy demand. Section 1.3 will present an overview of the different drivers of energy demand, highlighting the role of urban form amongst the remaining.

1.3. Urban form as a driver of energy demand

Energy demand is a result of a set of intricate factors and drivers. Creutzig et al. (2015) found, from their macro analysis of 274 cities that economic activity, transportation costs, geographic factors (such as climatic variables), and urban form explain 37% of direct urban energy use and 88% of urban transport energy use. Particularly, the variables with higher significance affecting transportation are gasoline price and population density, whereas overall final energy use is mostly explained by variables relating to economic activity and climate. GHG emissions, in their turn, seem to be consistently influenced by economic activity, population density and gasoline price. Additional significant variables explaining GHG emissions are population size, household size, urbanization level and an index of economic centrality. Figure 9 evidences a positive non-linear relationship between energy use and Gross Domestic Product (GDP) per capita. The colours of the markers indicate fuel prices and its shape indicates its geography. It is visible a red cluster on the right referring to American cities with high GDP values, lower fuel prices and high levels of energy use, while purple medium-to-large sized cities with high fuel prices use smaller amounts of energy. Also, a blue cluster is visible on the left side of the graph. It shows that for the same fuel price category, and for cities with a relatively low GDP level, energy use varies significantly. This suggests that there may be additional factors explaining the data observed.

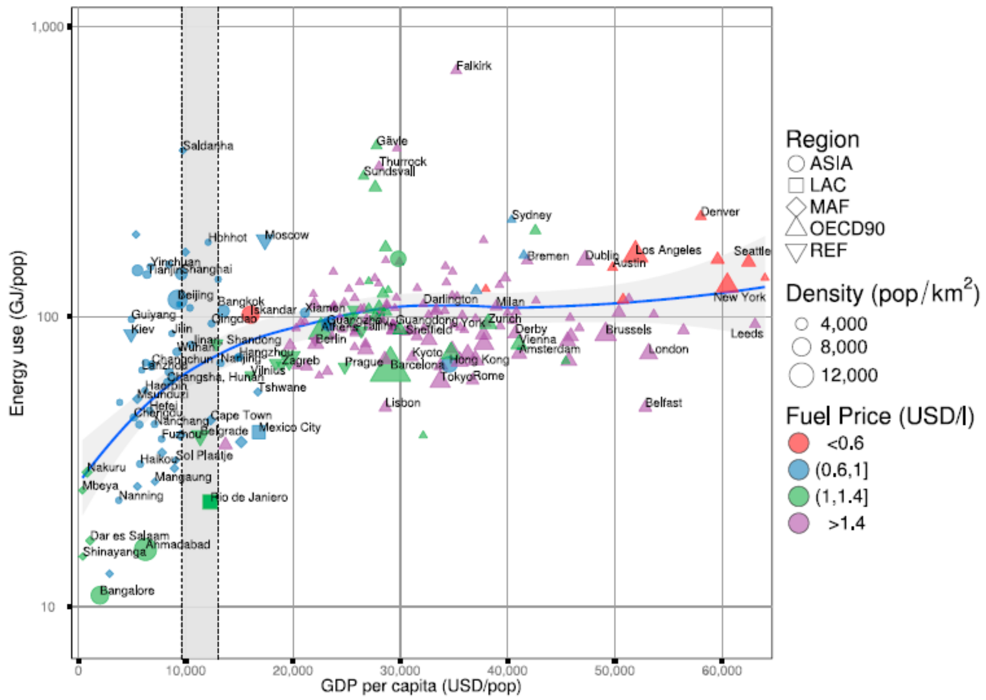

Figure 9. The relation between energy use (GJ/ per capita) and GDP (USD/per capita).
Source: Creutzig et al. (2015)

Climate is another important driver of energy use, particularly in buildings. Kennedy et al. (2009) found a linear relationship between energy use for heating and industrial fuels (excludes electricity for heating purposes) and heating degree days (HDD) from a sample of 9 cities in different geographies (Figure 10).

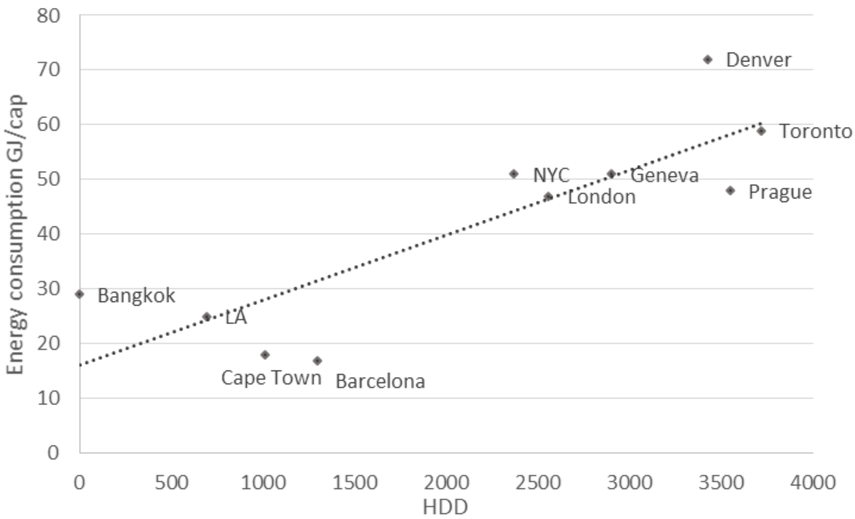

Figure 10. Energy use from heating and industrial fuels with HDD.
Source: Kennedy et al. (2009)

Grubler et al. (2012) consider five groups of factors determining urban energy use: 1. natural environment (geographic location, climate, and endogenous resources), 2. socioeconomic characteristics of a city (economic structure and dynamics, demography…), 3. national/ international context (i.e. the role of a city in relation to the country – division of labour, share of production and consumption), 4. urban energy systems characteristics including governance and access, and 5. urban form (including the built urban environment, transportation infrastructure, and density and functional arrangement of urban activities).

More recently, the working group III to the 5th Assessment Report of the IPCC (Seto et al., 2014) consider four clusters of drivers of greenhouse gas (GHG) emissions:

- Economic geography and income
- Socio-demographic factors
- Technology
- Infrastructure and urban form

The later, urban form, is ranked in the report as being a driver of high importance in mature cities. Such importance is attributed to its influence on the existing transport patterns and on other energy uses, such as heating and cooling in buildings. Nevertheless, the IPCC report is criticized by providing no guidance with regard to the importance of urban form in relation to the remaining factors (Creutzig et al., 2015).

Still, the factors affecting the energy requirements of the two main urban sectors (buildings and transport) may differ (Creutzig et al., 2015). Household energy requirements are affected by aspects like income and expenditure, household composition and size, population density, and climate (Wiedenhofer et al., 2013). Moreover, Ratti et al. (2005) identify five physical factors (socioeconomic aspects are not considered) influencing the energy performance of buildings. Figure 11 shows the size of the variation related to each factor. Note that the urban context is the only factor whose influence is not quantified.

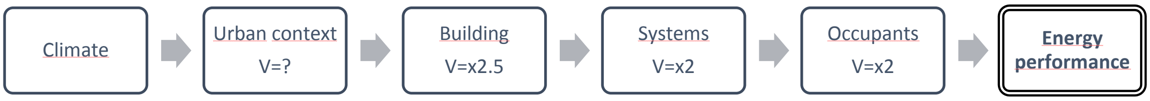

Figure 11. Factors that affect energy consumption in buildings
Source: Ratti et al. (2005)

In regard to transports, and in addition to the urban form, the drivers that are typically identified include: purchase power or GDP, fuel cost, and car ownership. Also attitudinal/behavioural factors are advocated to play a relevant role in auto trip generation (Kitamura et al., 1997). It may not be straightforward to disentangle structural drivers from behavioural ones. Behavioural choices may be locked-in the structural patterns of urban form and transport infrastructure (Köhler, 2005; Dawson et al., 2014).

In spite of the diversity of drivers affecting energy demand, the effect of urban form, referring to the spatial composition and configuration of urban elements, has been advocated to be an important aspect to control for, as part of more efficient future urban plans and policies. It is "*highly promising to use urban form analysis as a heuristic tool with which to draw the basic outlines of a resource efficient city and shed light on phenomenon's of form and relations of factors*" (Behnisch et al., 2012). Urban structure and design, has been pointed out as a determinant factor of energy demand (Kanaroglou and South, 2001; Stead and Marshall, 2001; Newman and Kenworthy, 2006). As Lynch reminds us in *Good City Form*, "some sense of goodness" is needed when it comes to city form, whereas efficiency is pointed as a key dimension of urban performance (Lynch, 1981).

Whether referring to urban form, urban structure or urban design, the physical features of cities are advocated to be of major importance not only in determining energy flows, but more broadly, metabolic flows. Nevertheless, it is acknowledged that their role is not investigated or quantified enough (Weisz and Schandl, 2008). Spatially-explicit studies are suggested to be the key to uncover the specificities on urban energy use (Grubler et al., 2012).

The importance of acting upon the urban structure is concerned with an energy demand side management paradigm or with the sustainable hierarchy policy referred to above. In other words, instead of relying on external factors whose development and deployment is not easily controllable (e.g. technological solutions), planning efficient urban areas from scratch may be the answer to tackle energy issues through an "acting upon the source" philosophy. In line with this, Grubler and his colleagues claim that "(…) *it is entirely unrealistic to expect "grand" new urban "ecodesigns" (…) into the physical, economic, and social fabric of cities*". The authors point that urban development models such as *Masdar* (Abu Dhabi), that are heavily reliant on technology, are not feasible to host an increasing urban population and should be seen as "learning labs" only. Relying on such models would convey extreme (around 20 years of current world GDP) investment levels (Grubler et al., 2012). In its turn, urban form is at a large extent determined by urban planning, which may be considered a cost-effective way of achieving more efficient patterns of energy use in cities (e.g. *versus* technological add-ons).

From the above, it is acknowledged that energy demand in cities is determined by several factors (Annex I). Still, this research will focus specifically on the role of urban form for two fundamental reasons:

i. Urban form is the basis upon which urban life takes place. Building a weak structure would hardly retrieve an efficient city, or would at least, undermine any improvement undertaken for other drivers of energy demand.
ii. The combined influence of urban form on energy is not yet fully understood or quantified. Further research is needed on this topic.

1.4. Problem statement and research objectives

There is scientific evidence that urban form has an impact on energy demand. However, the quantification of the effect of urban form, *per se*, on the energy use of cities is not a straightforward task. This is due to several reasons (Silva et al., 2016):

- It is difficult to isolate urban form from other drivers of energy demand;
- There are many variables of urban form to be considered;
- The degree of interaction amongst each of the variables is not fully defined;
- Two key sectors often addressed in isolation (buildings and transport) should be considered together.

While there is a wide array of studies reinforcing the relationship between urban form and energy use, not all factors influencing this relationship are simultaneously addressed, neither fully quantified. The motivation for this research grounds on three fundamental bottlenecks identified in the state of the art:

The first is that existing studies tend to be sectorial, either focusing on buildings and on transport separately, or capturing only one or few attributes of urban form at a time. While contributing to the existing knowledge so far, these studies somehow fail at integrating the relationship between the urban environment as a whole and energy demand. As a result, they also fail at addressing the inherent urban complexity. An urban analysis should integrate both urban sectors and the different structural elements (buildings, plots, urban blocks, streets…). Different arrangements of these elements create different urban patterns and environments, which most likely present different energy performances.

The second issue is that when the city scale is addressed, energy analysis is often accounted through input-output models, neglecting the drivers and processes taking place "inside" the city, and lacking a spatially explicit approach. It is considered important to capture with enough detail some fine-grained elements within the city, while simultaneously extending the analysis to the urban area as a whole.

Finally, research on urban form and energy seldom feeds policy-making. There is a gap on linking the physical analysis of urban areas to producing strategic and operational knowledge for the design of effective and energy-oriented urban planning policies.

The hypothesis to be tested in the present research is: **Given the relationship between the physical form of a city and its energy performance, it is possible to build a model oriented towards evaluating the energy performance of an urban area, integrating the physical features of the built environment and transport networks, in order to inform the design of more efficient development policies, and contribute to achieving more sustainable urban areas.**

The premise under which this work is built upon is that the way that cities are planned, structured and built largely influences energy demand, notably in two key urban sectors: buildings and transport. Although this assumption may also be valid for embodied energy, this work will specifically focus on operational energy, i.e. the energy needed to make cities work. In buildings, the physical structure of the cities has been acknowledged to particularly affect space heating and cooling, although effects on lighting needs have also been pointed out in the literature at a lower extent (e.g. Batty, 2008). Effects on mobility have been equally recognised for a long time (e.g. Cervero and Kockelman, 1997). Urban morphology is able to reconcile these two sectors and to consider a diversity of variables.

The conceptual model of this research is depicted in Figure 12. Urban form is considered to be a product of two main urban features: the built environment and transport networks. Their possible configurations influence specific energy uses (e.g. space heating and cooling in buildings, and mobility patterns), affecting the overall urban energy demand. Finally, both urban form and energy demand in cities are influenced and controlled by policy-making, taking place at a strategic level, while simultaneously serving as a reference point for formulating future policies.

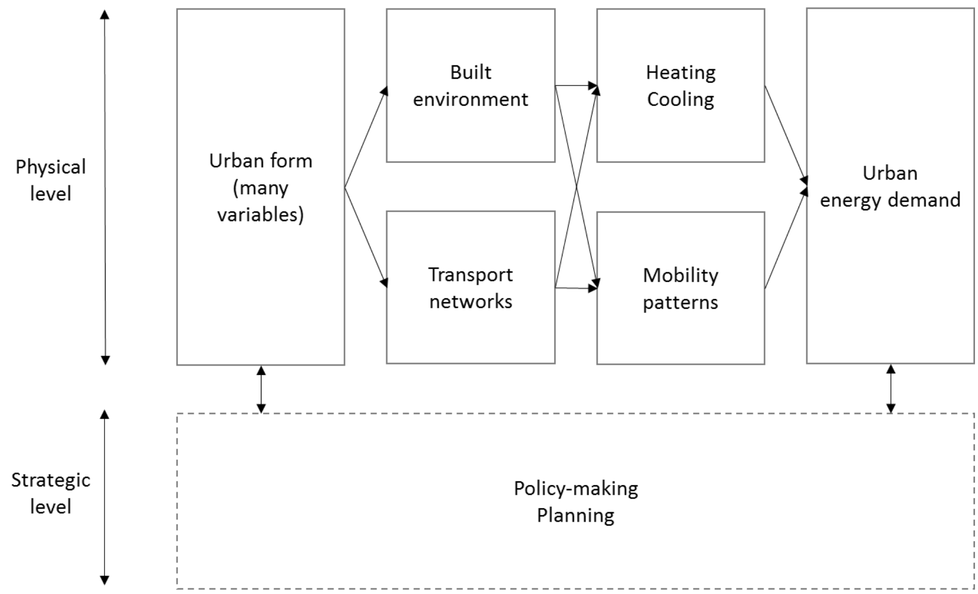

Figure 12. Conceptual Model of the Research

In a first instance, the research will explore the links between the physical structure of cities and the energy required to make them work, in a spatially explicit way. This will lead to a second stage where the physical analysis will be linked to the planning and policy implications for creating more efficient urban settings. This research aims at developing a model to evaluate in an integrated way the energy demand resulting from the physical structure of the city. It also aims at providing a deeper understanding on the effect of different attributes of urban form on energy demand and, as a result, to help identifying more efficient urban (re)development pathways. Suitable implementation mechanisms will also be identified.

The relevance of this study is two-fold. First, it is expected to help characterizing the combined effect of urban form on energy demand, contributing to decades of research on the topic. Second, it lies on the ability to evaluate the energy behaviour of urban (re)development projects at an early stage. It is expected to deliver a decision-support tool that integrates energy as a criterion for urban planning. The model developed will be case-specific, working as an appraisal tool of urban projects/plans in their development phase, and allowing for periodical updates. Also the methodological framework proposed is designed in order to be extended to different cities and contexts, while keeping its overall framework.

1.4.1. Research Questions

The main purpose of the research is to develop a decision-support tool that enables to evaluate, in an integrated way, the energy demand resulting from the physical structure of a city. In order to do so, it is essential to identify the attributes of urban form with a significant impact on energy demand, to describe such impact, and finally, to select the aspects to act upon to improve the urban energy performance. As a result, the research questions are formulated as follows:

- Which are the relevant attributes of urban form affecting the energy performance of cities?
- How do different approaches perform when modelling the effect of a comprehensive set of urban form attributes on energy demand, altogether?
- What is the weight of each urban form attribute, and what is the combined influence of urban form on energy demand?
- Considering specific urban contexts, what changes in urban form lead to an improved energy performance while simultaneously meeting additional urban goals/ interests?
- What are the suitable policy mechanisms to implement such changes?

The research design presented in the following section depicts the research stages and tasks for addressing the research problem, and for answering the research questions.

1.5. Research design

This section provides the description of how the research work is structured. It entails five main stages (Figure 13). The first stage corresponds to the definition of the conceptual framework. This includes the definition of the research scope, a preliminary literature review to structure the work according to the state of the art, and finally, the problem statement, with the definition of the research goals and research questions.

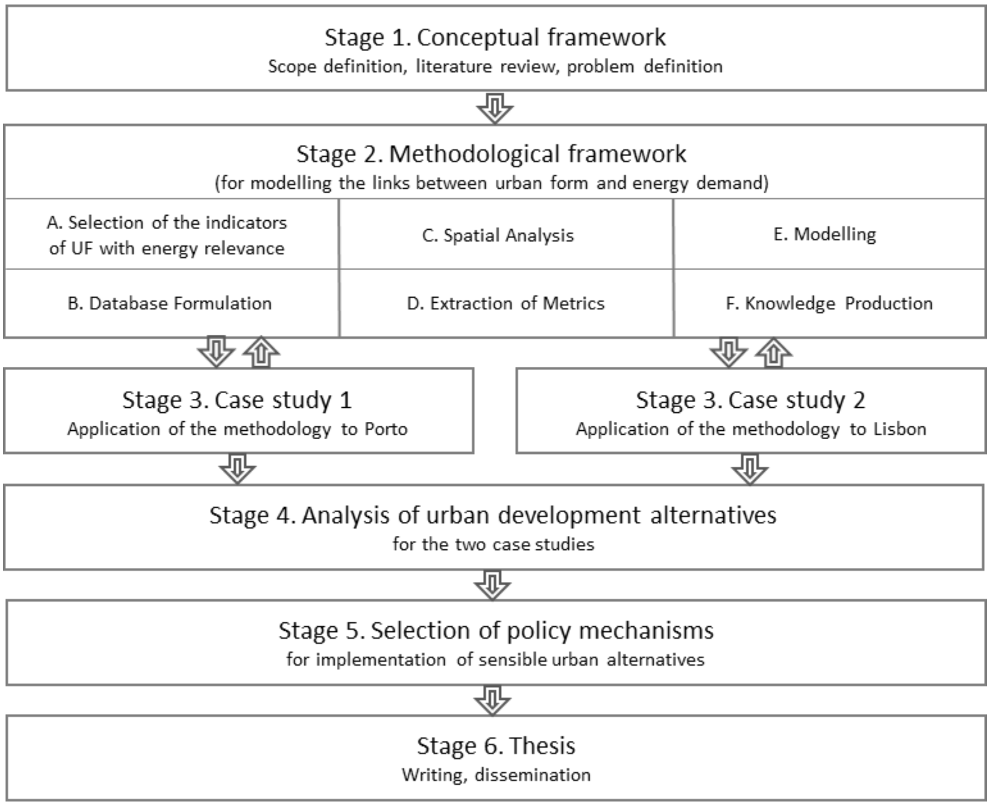

Figure 13. Research Design

The second stage consists of the methodological development, including six steps (A-F). Step A has a conceptual nature and consists of the definition of the indicators and respective metrics of urban form with energy relevance. It grounds on a literature review, which is sifted in Chapter 2, for the identification of the most significant urban attributes influencing energy demand. While these attributes have been pointed out in the literature, the characterization of the existing links is lacking substance. This research aims at deepening and systematizing the existing knowledge in order to produce quantifiable and operational means for evaluating the energy-relevant attributes of urban form. This is the basis of the following methodological steps.

The steps B to F have an operational nature, and are presented in Chapter 3. Step B corresponds to the database formulation. It consists of gathering the information required in the adequate formats in order to perform the subsequent analysis. Recall that this research aims at keeping a spatial character (it deals with the physical attributes of the city, which are a result of the spatial arrangement of its elements). As a consequence, the data required includes vector data on the urban elements considered (buildings, streets, green and public areas), high resolution statistical data (particularly, on urban functions, building heights, street width…), as well as data on building energy demand and transport energy demand for each of the spatial units under analysis. This data will be managed and analysed in a Geographical Information System (GIS) environment.

Step C, the spatial analysis, consists of the necessary preliminary operations in order to obtain the desired metrics (e.g. clipping, joining, merging…), together with the spatial analysis *per se*, which consists of measuring the indicators defined in step A, for each of the spatial units considered in the GIS. The spatial units to be considered should be of an intermediate scale, between the city as a whole and a single building or street. In this sense, the urban block or the neighbourhood arise as interesting options. Although the literature on urban form and energy, with few exceptions, has been focusing on two specific scales: the building and the city as a whole (Oliveira and Silva, 2013a), intermediate scales of analysis have been advocated. According to Ewing and Cervero (2001), neighbourhoods are the spatial scale at which urban activities take place. *"Land use patterns are characterized by residential densities within neighborhoods; employment densities within activity centers; various measures of land use mix within neighborhoods and activity centers; and measures of microaccessibility, which reflect the numbers of specific attractions within a given distance of residences"*. In line with this, all the methodological stages and steps need to be coherent in terms of the scale of analysis selected (including those described above regarding the definition of the urban indicators and metrics).

After the spatial analysis, the indicators computed should be exported in a format that is compatible with the modelling process, for instance a single spreadsheet. At this point it is of utmost importance to ensure that the information of a unit of analysis is matched with the corresponding ones for all the indicators (step D).

Afterwards, step E of the methodology corresponds to the modelling process in itself. A set of urban attributes of the built environment and of transport networks will be modelled together. These will represent input variables of the model. Methods for modelling energy demand at urban scale (within similar contexts) will also be reviewed. This will enable to get an overview of different modelling options, and will help selecting the most suitable method(s) to be tested.

The model is expected to be multi-scale, i.e. it should be able to estimate the energy demand of a single spatial unit (e.g. an urban block), while also capturing interactions and patterns between the different units forming the city (such as urban neighbourhoods, urban districts and the whole city). Additionally, as suggested by the literature (e.g. O'Brien et al., 2010), it is expected that modelling buildings and transport networks together leads to more accurate results (by capturing existing trade-offs) than the current practice, that considers them separately.

Finally, step F of the methodology is to convert the results of the model into knowledge directly useful for policy-making. The findings will enable to understand the impact of the different variables of urban form, and will be interpreted in the light of urban planning and development policies.

After the methodological development, the third stage of the research corresponds to the application of the methodology to two case studies (presented in Chapters 4 and 5). This is an iterative process. Alternative modelling variables will be considered in order to find those that will more accurately describe the urban environment and have more energy relevance. This iterative process will also help fine-tune operational aspects of the methodology. At this point, different algorithms, model parameters, and software are explored. The two case studies are expected to enable validating the methodology developed with two different real world urban contexts.

Stage 4 will draw on the methodological application to both case studies, and will use the model developed to assess the energy performance of a set of urban development alternatives, enabling to conclude on the most efficient development pathways for the case studies analysed. The urban development alternatives will be compared not only considering the energy savings, but also additional urban criteria, notably linked to the social and economic performance of the cities at stake. Stage 5 will explore possible means of implementation of the most interesting urban alternatives, under a strategic way. It will review, select and recommend spatial planning policy mechanisms for climate change mitigation that suit the best development alternatives for the case study urban areas. The last stage, Stage 6, is the process of writing the thesis, as well as working on dissemination, through scientific papers or conference presentations.

1.6. Thesis structure

This section briefly introduces the contents of the thesis chapters.

Chapter 1 introduces the topic of energy in cities. It explores why cities are important in addressing sustainability and energy-related challenges. It describes energy use in urban areas, and presents urban form as a driver of energy demand. Finally, it presents the research problem and questions, and concludes with the research design.

Chapter 2 presents an overview of the study of the urban form-energy link, followed by an in-depth review of the properties or attributes of urban form that affect energy demand in cities, for the building and the transport sectors. It describes how such attributes are expected to exert their influence, evidencing existing trade-offs, and collects indicators for characterizing such attributes. In the end, a set of indicators and metrics for the urban attributes considered is proposed.

Chapter 3 presents the operational steps of the methodological framework. It starts by reviewing methods for modelling energy demand in cities, with an emphasis on those that, both within the building and transport sectors, have considered urban form. Afterwards, it describes a novel methodological framework, and presents a few modelling techniques to be tested, compatible with the research problem and data.

Chapter 4 presents the application of the methodology to the city of Porto and Chapter 5 follows a similar approach for Lisbon. They demonstrate the applicability of the research methodology to two real-world case studies. Both chapters begin with an introduction to the case study at stake, and are followed by the illustration of the methodological process, the data used and the different techniques applied. They conclude with the results obtained for each case study.

Chapter 6 defines different urban development alternatives for improved urban energy performance. It begins with the rationale for the definition of the different urban pathways. Then, it describes the different scenarios and the urban development alternatives considered in a quantitative way. Finally, it presents the results obtained from the application of the models developed for each case study to the different scenarios and urban development alternatives.

Chapter 7 draws on the set of sensible urban development alternatives, identified in the previous chapter, and explores spatial planning policy mechanisms to support their implementation. It starts with a review of existing land use mechanisms for climate change mitigation, and selects those that meet the goals of the development alternatives considered. It concludes with a discussion on the strengths and limitations of the applicable policy mechanisms, targeted at informing decision-makers on their choices.

Finally, Chapter 8 presents the conclusions of the research work performed, along with future research pathways.

CHAPTER 2. THE IMPLICATIONS OF URBAN FORM ON ENERGY: REVIEW AND INDICATORS

Given the patterns of energy use in cities (Chapter 1), and the acknowledgement that the way that cities are organized and structured (i.e. their physical form) significantly impacts the overall urban energy performance, it becomes key to explore how this influence takes place. This thesis adopts a similar definition of urban form to Anderson et al. (1996). Here, urban form is seen as the spatial configuration of specific elements within an urban region, including the spatial pattern of land uses and their densities, as well as the design of transportation and communication infrastructure.

The relationship between urban form and energy has long been present in the international debate. It is not the only driver of energy demand, and arguably not the most important. While there is scientific evidence that urban form, or some of its attributes, have an impact on the demand for this resource, the characterization of the effect of urban form, *per se* remains a major challenge. As mentioned above, this can be attributed to several reasons (Silva et al., 2016): i) it is difficult to isolate urban form from other drivers of energy demand; ii) there are many variables of urban form to be considered; iii) the degree of interaction amongst each of the variables is not fully defined; and iv) two key sectors often addressed in isolation (buildings and transport) should be simultaneously considered.

Despite the fact that there is a wide array of studies emphasizing the relationship between urban form and energy, not all factors influencing this relationship are simultaneously addressed, nor are they fully quantified. It has been argued that the effect of each variable of urban form has a relatively small effect on the overall urban energy demand. Their combined effect, however, is expected to be more significant and worth controlling for (Ewing and Cervero, 2010). There is a broad set of urban form attributes with relevance for energy conservation. However, the existing research has been sectorial and focusing only in one or few variables at a time (Naess, 2003; Rickwood et al., 2008). The energy trade-offs between the different urban form attributes have not been duly investigated.

In order to allow for a comprehensive analysis of the effect of urban form on energy demand, Chapter 2 reviews the literature considering effects both in buildings and in transport. It will focus on the attributes of the physical form of cities and on their energy implications at different scales. The metrics used for characterizing these urban attributes are reviewed as well. Whereas the effect of specific parameters of urban form has been widely studied, the suitability of the metrics employed has been subject to limited discussion. The relevance of the physical attributes to urban planning lies on the ability to thoroughly characterize and quantify them, so that increasingly more objective and tailored policies can be adopted towards energy conservation in cities. Although the connections between land use and energy supply have recently been brought to the fore (e.g. Kaza and Curtis, 2014), the scope of the review is placed on the demand side. In line with Grubler et al. (2012), urban energy and climate policy should recognize that the largest potential for the efficiency in energy use is placed on the demand side of the energy system, rather than on the supply side.

Section 2.1 presents an overview of how the body of research on urban form and energy has developed over the years. Section 2.2 reviews the attributes of urban form with energy relevance, discussing how a given attribute affects energy demand and presents metrics that may be applied in an energy analysis. Finally, Section 2.3 systematizes the findings from the review performed in Section 2.2 and proposes a set of urban indicators and metrics to be considered for an analysis of the energy implications of urban form.

2.1. Urban form and energy demand: an overview

The fields of urban form and energy have merged over two decades ago. Despite the identification of some previous work (e.g. Pushkarev and Zupan, 1977), a seminal study in the United States in the late eighties explores how the density of built environment affects energy demand (Newman and Kenworthy, 1989), probably driven by the acknowledgement that the American dispersed development model (urban sprawl) leads to higher fuel costs and congestion. The authors analyse the consumption of gasoline in 10 U.S. cities, concluding that a significant share of the variation could be attributed to land use and transport planning choices (instead of price or income). Despite some criticism invoking the validity of global comparisons or the interaction between transport, labour, housing, and land (Gordon and Richardson, 1989), this study is undeniably a landmark in the analysis of the energy demand derived from the physical structure of the city. Since then, it has been generally accepted that higher urban densities lead to energy savings for travel purposes (Banister et al., 1997; Newman and Kenworthy, 2006; Glaeser and Kahn, 2010). In the same year, Cervero (1989) point out the jobs-housing balance as a factor with an impact on mobility patterns, and a few years later, Frank and Pivo (1994) explore several features of the urban environment simultaneously, reinforcing the correlation between density and mix of land uses and mobility patterns (and indirectly energy, as mobility patterns affect transport-related energy demand). Mixed land uses have increasingly been advocated to reduce motorized travel (Ewing et al., 1994; Cervero, 1996; Dieleman et al., 2002; Lee and Moudon, 2006a). Nevertheless, the analysis of the urban environment could still benefit from a more comprehensive description. The effects of other urban form attributes on travel, such as accessibility, connectivity and design, have also been explored, although not as extensively as density and diversity (Handy, 1993; Ryan and McNally, 1995; Naess, 2003). Few studies consider a broad set of attributes simultaneously to describe the urban environment, although there are exceptions (Ewing and Cervero, 2001, 2010).

At present, urban form and travel is a vast field of research. While there is still disagreement on the role of urban form, especially in relation to behavioural or economic factors (Crane, 2000), the importance of scale when addressing travel patterns is widely acknowledged (Crane, 2000; Stead and Marshall, 2001; Ewing and Cervero, 2001; Anderson et al., 2015), since the attributes at stake and their effects depend on the level of detail considered. Stead and Marshall (2001) argue that the literature has been focusing on macro features, such as settlement size, mix of land uses and density, while lower scale features, such as the proximity to transport networks, network features and neighbourhood type, may also be relevant but have been overlooked. The effect of micro-urban attributes on travel has not been widely investigated (Soltani and Allan, 2006).

This debate has moved from the transport field to effects within the building sector. Buildings (households and services) are the largest energy consumers and GHG emitters in the EU (EEA, 2015). Some urban form attributes influencing travel patterns (e.g. density and the existence of green spaces), have also been linked to the urban heat island (UHI) effect (Oke, 1982, 1988), as well as to building thermal comfort, and thus energy conservation in buildings. The effect of urban form on the UHI is, in fact, a vast field of research *per se*. Nevertheless, the implications on energy are not always explored.

While the patterns of energy use in non-residential buildings are more complex, urban form is expected to be particularly relevant in dwellings. Ewing and Rong (2008) argue that after controlling for economic factors, the physical aspects of housing significantly influence energy use. Anisimova (2011) claims that the type of construction largely determines energy demand, with compact structures and the passive use of solar energy as the basis of low-energy design. Ko (2013) reviews the body of research on the effects of urban form on residential energy demand, considering house size and type, density, community layout, planting, and surface coverage. The estimation of the overall magnitude of the effect of urban form on building's energy demand is still underexplored (Lee and Lee, 2014) when compared to that on the transportation field. Nevertheless, for both sectors the combined influence of urban form is still unclear. Comprehensive studies are still lacking.

The implications of urban form in buildings are mostly concerned with building geometry and surroundings, and the UHI, although electric transmission and distribution losses have also been pointed out as a causal pathway for this link (Ewing and Rong, 2008). Macro features of the urban environment, such as density or compactness (usually evidenced through clustered building patterns and increased heights) are often associated with lower heating needs in winter (Høyer and Holden, 2003; Rode et al. 2014). However, Kaza (2010) points that the focus of densification should be on transportation and argues that only dramatic changes in the housing type mix could lead to sizeable effects in energy conservation. Lower-scale characteristics of urban texture, notably building shading and passive gains have also been investigated (Baker and Steemers, 2000; Ratti et al., 2005). Baker and Steemers (2000) estimate the weight of different factors in the energy performance of buildings. Unlike building design (leading to a variation of 2.5x), systems' design (2x) and occupant's behaviour (2x), the contribution of the urban context is still unquantified.

Two additional studies attempt at estimating the effect of urban form on heating. From an analysis of three urban tissues in Paris, Salat (2009) concludes that urban form has an effect of a factor 1.8. The main features considered are density and a shape factor (defined by an index relating the external surface of the building and its volume). Rode et al. (2014) consider different indicators of building density and compactness in four cities, and find that the parameters analysed can lead to a variation of 6-fold. Still, both approaches disregard relevant features of the urban environment, notably those related to mobility.

Despite significant progress in characterizing the relationship between the physical environment and energy demand, it is widely agreed that further analysis and more robust conclusions are needed. Table 2 summarizes the urban attributes addressed in existing review papers and their unique contributions. It evidences that sectorial research still dominates. While most studies point to the existence of relationships, they haven't dedicated much effort on exploring *how* attributes affect energy demand, the existing intra and inter-sectors trade-offs and especially, on discussing a systematic way of measuring each attribute to enable more solid conclusions.

For the sake of clarity, the remainder of this thesis will refer to *attribute* as an urban property or quality (e.g. density). The term *metric* will refer to the means of measuring such property (e.g. the ground space index is a metric for density).

The review performed in the present chapter attempts to summarize what is known on the attributes of urban form with energy relevance, belonging to the built environment and to the urban networks (Figure 14). It explores how they are expected to influence energy demand, accounting for potential trade-offs, and suggests metrics to promote the development of a coherent analysis framework in the planning practice. Two key questions will be addressed: i) *how* do urban attributes influence energy demand, and ii) *how* to describe and measure each attribute of urban form with energy relevance. It is argued that a straightforward assessment of the impact of urban form on energy could contribute to defining more informed planning strategies, as well as to prioritizing the physical aspects that can be intervened for more efficient and sustainable urban planning.

Section 2.2 reviews the attributes of urban form with energy relevance, discussing how these attributes may determine energy needs in buildings and in transport, and collects a set of metrics for describing the urban environment to be used in future analytical studies.

Table 2. Summary of key reviews published on urban form and energy demand

Author (year)	Sector	Urban attributes addressed	Contribution /Key findings
(Anderson et al., 1996)	T (mostly)	Mostly macro attributes (density, diversity, distance to CBD, accessibility)	- Urban form influences energy demand. - Further research is needed to improve knowledge of existing relationships. - Suggestions for future models.
(Anderson et al., 2015)	B/ T	Orientation, shape, compactness, shading, passive condition (within a category named *architectural design*) / Density (single category), mix of uses (*urban form* category).	- Urban form influences energy demand. - Review focuses on two scales (the building and the urban scale, each with several subcategories). - Considering only one is insufficient to capture existing interactions.
(Crane, 2000)	T	Density (different measures), land use mixing, traffic calming, street and circulation pattern, pedestrian features.	- Urban form and travel represents a complicated interaction of several factors, including economic and attitudinal ones, which should be included in the analysis. - Acknowledges the importance of scale.
(Ewing and Cervero, 2001)	T	Density; land use mix; accessibility (within *land use patterns*), connectivity, directedness of routing, block sizes, sidewalk continuity (within *urban networks*), building orientation, pedestrian amenities, and parking (as *urban design* features)	- Urban form influences energy demand. - Derived composite land use-travel elasticities for VMT and trip frequency. - Trip frequencies are more influenced by socio-economic factors, while VMT are more dependent of built environment. - Land use-travel elasticities are advocated to be descriptors or the link between travel and the built environment, able to be transferred between different regions.
(Ewing and Cervero, 2010)	T	"Six Ds": density, diversity, and design + destination accessibility and distance to transit + demand management (parking).	- Urban form influences energy demand. - Performed a meta-analysis arriving at weighted averages of elasticities. - Walking and transit use are new trip outcomes considered. - Population and job densities are weakly associated with travel behaviour once other variables are controlled for.
(Ewing and Hamidi, 2015)	T	Sprawl (density, diversity, connectivity, centrality, clustering, shape, size)	- Urban form influences energy demand. - Sprawl is a multidimensional issue. - Discusses costs and benefits of sprawl (incl. energy). - Conclude that disaggregating the different elements of urban form to study the effects of sprawl may lead to more precise conclusions.
(Ko, 2013)	B	House size, housing type, density, community layout, planting, and surface coverage.	- Urban form influences energy demand. - Bridges design-based and planning-based; - Research on urban form and residential energy is much fewer than that on travel. - Existing research is insufficient to understand the full impact of urban form on energy efficiency. - It is unlikely the existence of an ideal urban form due to trade-offs across urban forms and climates.
(Rickwood et al., 2008)	B/ T	Dwelling type (construction, design, size, and orientation) Density	- Urban form influences energy demand. - Consider the effect of urban structure on embodied and operational energy. - Literature lacks studies combining travel and in-house energy use, resulting on inaccurate estimates of the overall effect.
(Stead and Marshall, 2001)	T	Distance to CBD; settlement size; mix of land uses; provision of local facilities; density; proximity to	- Urban form influences energy demand. - Reviews research across local to regional scales.

		transport networks; parking; road network type; neighbourhood type	- Interactions between socio-economic factors, urban form and travel patterns complicate the analysis of existing relationships. - Different ways of expressing the same variable makes interpretations more difficult.
(Steiner, 1994)	T	Density (incl. mixed uses and proximity to public transport).	- Addresses the need to include socio-economic factors along urban form studies. - Review categorizes research into empirical and policy formulation studies.

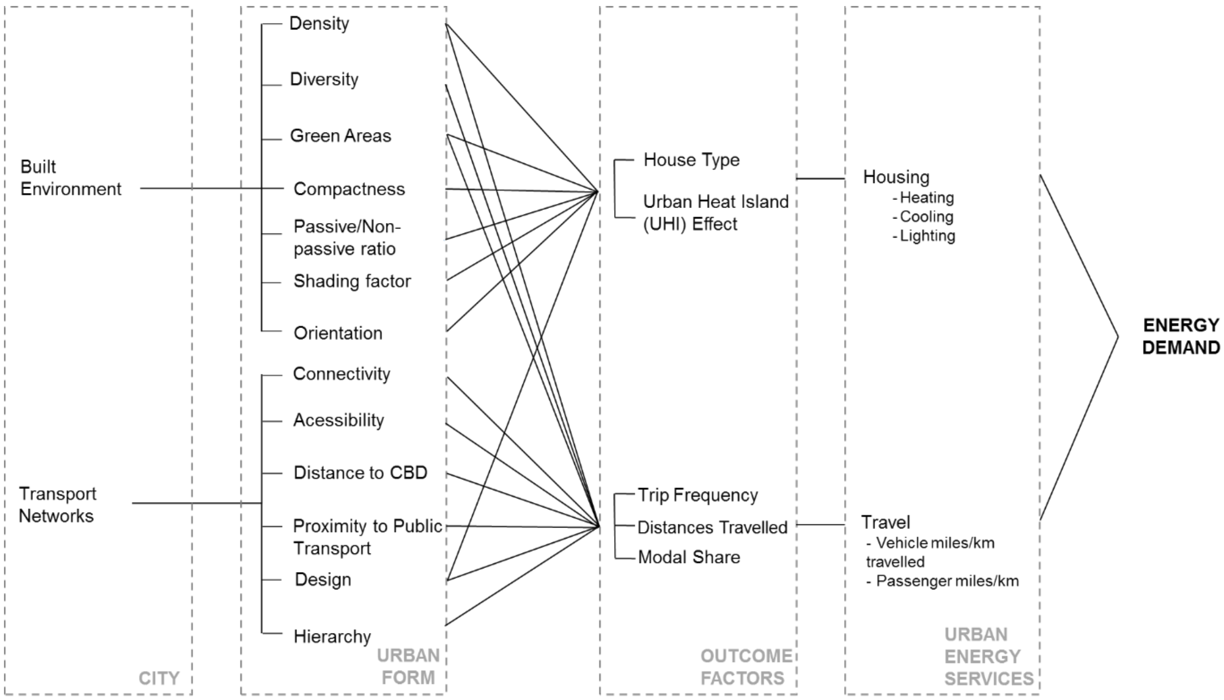

Figure 14. Urban form attributes, their outcome factors, and expected effects on overall urban energy demand

2.2. A review of the attributes of urban form with energy relevance

The physical attributes of the urban environment affecting energy demand have been pinpointed and discussed in the literature in the last decades. The degree to which these attributes are explored in existing research varies greatly, and comprehensive studies are still a few. This raises the need to broaden the scope of the physical dimension in urban energy analysis throughout different scales. Although micro-scale attributes may play an important role in reducing energy demand at the local scale, they have been underexplored (Soltani and Allan, 2006). Additionally, the two most important form-related sectors consuming energy in cities (buildings and transportation) are repeatedly treated separately, although it is acknowledged that they are interconnected, entailing energy trade-offs (Grubler et al., 2012; Lee and Lee, 2014), and that they should be analysed together whenever possible (O'Brien et al., 2010).

The review performed in Section 2.2 identifies a set of energy-relevant urban attributes within two major focus areas (built environment and urban networks), and presents a number of measures to quantify them. It is acknowledged that the classification proposed and the metrics identified are not definitive. Different perspectives are presented and their suitability for an effective urban energy analysis is discussed. While the review is not scale-specific, particular attention is given to indicators that can be measured at an intermediate scale of analysis (such as the urban block or the neighbourhood), as discussed in Chapter I.

Section 2.3 grounds on the review performed in Section 2 and proposes a selection of suitable indicators and metrics to capture the influence of the urban environment on energy demand. Because the attributes of urban form may have an ambiguous definition, the selection of the indicators should be non-overlapping. The purpose of the review is not to decide on a single metric for each urban attribute. Whenever needed, the urban environment should be described in a comprehensive way, to better capture the existing variations. The metrics proposed should be applicable at the scale of the urban block or the neighbourhood (according to the research design in Chapter 1). Urban features at a higher level of detail than the single building (like construction materials or fenestration aspects) are disregarded, as they are not seen as belonging to the urban form debate. The studies examined explore urban attributes considering their impact on energy demand. Research unrelated with energy, or focused on energy supply is not considered in this review.

2.2.1. Built environment

The built environment refers to the urban settings which are effectively built-up (i.e. the building stock), together with those areas which are not built-up, but that are shaped by the former, such as public or green spaces. These are man-made environments with specific urban functions. Urban areas allocated to transport infrastructure will be dealt with in a separate category.

Density

Density is likely the most prominent and frequently cited urban attribute acknowledged to influence energy demand in cities, feeding a large debate on its benefits and dangers (Jenks et al., 1996; Williams et al., 2000). Density can be defined in many ways. Two types of definitions can be considered: density of the built environment and density of people living or working in a given area (Porter et al., 2013). In all, it is a variable of interest per unit of area. However, density described as population per area unit may refer to different urban environments (Pont and Haupt, 2005; Salat, 2009). The distribution of a fixed amount of residents or households within an urban area may vary greatly, depending on the configuration of the built structures, specifically building footprints and number of floors (Marins and Roméro, 2013). As a result, population or housing density alone will hardly capture these different configurations and the corresponding energy behaviour.

Density of urban activities was pointed back in 1989, in the seminal study by Newman and Kenworthy, as one of the most important factors influencing gasoline consumption in cities. In this case, density was measured as persons or jobs per unit of area, which was also called an "urban intensity" indicator (Newman and Kenworthy, 2006). Cervero and Kockelman (1997), considered density as one of the "3Ds" affecting travel demand (along with diversity and design, and more recently extended to six Ds, including destination accessibility, distance to transit and (parking) demand management (Ewing and Cervero, 2010)). It was expressed under three metrics: i) population density, ii) employment density, and iii) accessibility to jobs.

Density (or compactness[2]) is expected to influence travel patterns because it potentially brings urban activities closer and shortens distances to be travelled, thus reducing motorized travel needs (Kanaroglou and South, 2001; Cervero and Murakami, 2010). Denser urban areas also promote more reliable public transport means (Dieleman et al., 2002). Frank and Pivo (1994) analyse the effect of population and jobs density (and mix of land uses) on mode choice both for work and shopping purposes. The strongest correlation between mode choice and density was verified for average gross population density at trip origins and destinations for shopping trips. However, the net benefits of density are far from being consensual. It has been questioned whether density is the driver of lower energy intensities or if it works as a proxy for other variables often found in dense urban areas, such as proximity to public transport or accessibility to activities (Handy, 1997; Ewing et al., 2008; Ewing and Cervero, 2010). Critics of density point it as a cause of traffic congestion, thus increasing energy needs, air pollution and noise (Gordon and Richardson, 1997; Nijkamp and Rienstra, 1996), as well as crowding and lower housing availability (Echenique et al., 2012). In addition, while density may decrease everyday travel needs, it has been linked to higher

[2] Despite there are conceptual differences between density and compactness, these terms are many times employed as synonyms. Urban compactness may be seen as a type of density, referring to how clustered buildings are. Compact development is often treated as in opposition to urban sprawl (for a recent review on the topic see Ewing and Hamidi, 2015). For this reason, studies referring to this type of compactness will be treated in the density category. Compactness will be explored later in a different sense.

levels of out-of-city leisure travel by plane (Holden and Norland, 2005) as a compensation for lower access to local green spaces.

In addition to effects on travel, density has also been treated as a driver of energy demand for the built environment. Density (or compactness) is accredited to influence the Urban Heat Island (UHI) effect, as extensive impervious urban surfaces may increase local air temperatures, and thus cooling loads (Taha, 1997). Compact and dense urban forms (Giridharan et al., 2004; Chun and Guldmann, 2014) and development patterns like the infill development (Tran et al. 2017) have been associated with higher urban temperatures. Conversely, Stone and Rodgers (2001) affirm that sprawled patterns emit more radiant heat energy per parcel than high-density urban patterns. Density has also been associated with lower thermal losses to the outside environment in the cold season, due to more clustered urban fabrics with fewer exposed surfaces, promoted by multi-family housing (Ewing and Rong, 2008). However, whilst minimizing heat losses, denser urban fabrics usually have limited solar gains (Steemers, 2003). Kanters and Wall (2014) argue that density is the most influential urban attribute on the solar potential of building blocks, whereas Hachem et al. (2012) claim that higher densities, achieved by attached housing units, reduces both heating and cooling loads by up to 30% and 50%, respectively, when compared to detached configurations.

Due to the wide array of perspectives on the effects of density, the variables used to describe it become of major relevance. Pont and Haupt (2005) argue that if density is expressed through one metric only it may be referring to very different urban environments. In order to better understand the urban types associated to a certain density, the authors resort to four different variables: Floor Space Index (intensity), Ground Space Index (often considered under different designations, like the building ground footprint area (Chun and Guldmann, 2014)), number of floors (height), and open space ratio (pressure on the unbuilt space). The authors develop a diagram to illustrate different aspects of urban density – the Spacemate, claiming that this tool may help identifying efficient urban forms. Figure 15 illustrates different urban configurations with similar floor area, evidencing different facets of density. The degree of dispersion of buildings (Zhao, 2011) also correlates to average building energy consumption in passive zones. The dispersion degree is measured as follows: $T = L/4\sqrt{S}$, where L is the perimeter of the façades, and S is the gross floor area.

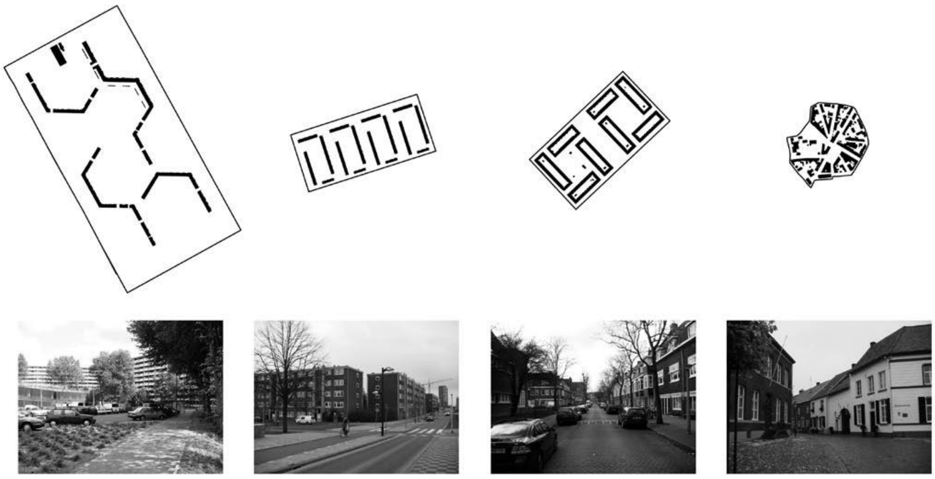

Figure 15. Different urban configurations with different heights and with the same FSI (app. 0,7).
Source: Pont and Haupt (2005)

Behnisch et al. (2012) use three different density metrics: the so-called building load (persons/ha), building density (structural urban density) and street network density. Finally, Bourdic et al. (2012) propose a simple metric that accounts for the number of parcels per unit of area. While this may not be a conventional indicator for measuring density, this subdivision index provides a sense of the granularity of the urban environment, which is expected to affect energy behaviour through the spatial configuration of urban elements.

It has been shown that the effects of density are complicated and are not fully understood. While higher densities are mostly associated to higher energy efficiencies in mobility, their net effect in buildings is not evident. A denser pattern may be associated to lower thermal losses through the building envelope, but also to lower solar gains due to shading from surrounding buildings. Trade-offs should be considered, and solutions may depend on the geographies at stake. In order to capture the different facets of density, the use of a diversified set of metrics is advocated. With a view to better understanding the effect of urban form on energy, metrics should consider elements of the built environment in addition to population ratios.

Diversity

After density, diversity (referring to the mix of the different land uses or urban functions) may be the second most cited urban attribute affecting energy demand, especially for travel. It is worth noting that some dissonance may be found between diversity and mix of land uses. Jabareen (2006) claims that diversity is a wider concept that promotes more desirable urban features, concerning not only a variety of land uses but also different building types, household sizes and cultural urban environments. Here, diversity specifically refers to land uses.

Diversity is claimed to decrease motorized needs – vehicle miles travelled (VMT) – by bringing housing and urban activities closer, thus shortening travel distances (Cervero and Kockelman, 1997; Jabareen, 2006; Lee and Moudon, 2006b; Baran et al., 2008). In addition, it creates more vibrant and interesting urban environments, and it is positively associated to the adoption of soft modes, notably walking (Kenworthy, 2006; Baran et al., 2008; Ewing and Cervero, 2010). Diversity may be defined as a measure of the spatial distribution of urban uses, or of how heterogeneous the unit of analysis is. It is often called a measure of entropy.

Diversity is the second D affecting travel demand (Cervero and Kockelman, 1997), characterized by different metrics that vary in complexity. The dissimilarity index, entropy, vertical mixture, intensities of land uses, activity centre mixture, and commercial intensities may be considered as more elaborate measures, whereas proximities to commercial-retail uses are simpler metrics. Frank and Pivo (1994) conclude that having retail activities within neighbourhoods is closely associated to mode choice for work trips, probably because people may use the “way to/from work” to do shopping and other daily activities.

Behnisch et al. (2012) use a contagion index to express heterogeneity of land uses following O’Neill et al. (1988) and Li and Reynolds (1993). This is somehow similar to the entropy index proposed by Cervero and Kockelman (1997). Entropy is also used by O’Kelly and Niedzielski (2009) to describe the relative location of jobs and housing with respect to excess commuting. Another frequently used metric for diversity is the Gini coefficient, which measures the inequality of distribution of a characteristic in defined spatial units. Here, it refers to the distribution of urban functions (population as proxy for residential areas, and jobs as proxy for commerce and services).

Straightforward metrics of diversity are the percentage of the plot area occupied by major land uses (Baran et al., 2008) and the job-housing ratio (Cervero, 1989). Cervero points out that the job-housing ratio only indicate a potential of community balance. It may happen that jobs in a certain area are not held by local residents. Similarly, the mixed-use index (MXI) is an easy-to-measure tool for assessing the diversity of a given urban location, weighting residential floor area against gross floor area (van den Hoek, 2008). The author argues that a desirable mix of residential and non-residential areas is 50/50. This index was further applied and extended to three types of functions by Mashhoodi and Pont (2011). Bourdic et al. (2012) refer to the Simpson index for analysing the diversity of urban projects, although admitting that it may not be appropriate for measuring cases where an even distribution of urban elements is not the objective. They propose an alternative for such cases, called structural diversity. It analyses the distance from a given share of current land uses to a target. Moreover, it is claimed that diversity indicators focus on the proportion of different land uses, but not on their spatial distribution. In order to overcome this, they propose another index for analysing the spatial distribution of urban elements.

There is a wide array of metrics to define diversity. The choice may depend on the level of complexity desired, but also on the scale of analysis. Some metrics are more appropriate for the city scale, such as entropy or the Gini coefficient, while others may better capture lower scale aspects, like the MXI. Accordingly, diversity indicators that consider the number of different activities in a given area make more sense at city or district scales, where representation gains importance (for instance, it is not expected that every urban block has a pharmacy, however at the district scale the number of pharmacies matters); while at lower scales indicators should be targeted at measuring the balance between the main land uses. Whatever the scale considered, diversity is a desirable feature of the urban environment. Regarding the proportion between residential and non-residential uses it is widely agreed that a certain degree of mixing has benefits mostly in reducing motorized travel (VMT).

Green areas

Green areas or green infrastructure may influence energy demand in different ways. Green infrastructure such as urban parks and trees, is advocated to help saving energy through maintaining the amenity of the urban climate (Giridharan et al., 2004; Taha, 1997). It is acknowledged to help preventing the UHI effect (Ko and Radke, 2014; Tran et al. 2017) and is associated to lower cooling needs (Vaz Monteiro et al., 2016). The UHI is characterized by increased temperatures in urban areas in relation to their rural hinterlands. This is due to differences in land cover, i.e. to the lack of green areas (Stone and Rodgers, 2001). Relevant physical characteristics of green areas include their size, width and geometry. Small- to medium-sized green areas provide a cooling service that extends beyond their boundaries, and regular geometries seem to deliver higher cooling intensities (Vaz Monteiro et al., 2016). Nevertheless, although the size of parks is a relevant feature for urban cooling, large green areas may also imply longer distances to other urban amenities. It is important to consider the trade-off between the effect of density and the presence of vegetation (Grubler et al., 2012). Other aspects like the type of vegetation cover (captured, for instance, by Kim and Guldmann (2014) through the NDVI – normalized difference vegetation index) also affect the UHI. These, however, are not explored here as they are not considered urban form attributes – the same NDVI may refer to different land uses, as it reflects spectral imaging bands.

In addition to parks, Cervero and Kockelman (1997) consider that the presence of trees in streets provides a sense of a sheltered corridor for walking – trees provide shade in summer and some shelter from rain and wind (Forsyth et al., 2008). Trees are considered an element of urban design, promoting walking-friendly environments and more pleasant urban places (Forsyth et al., 2008; Kim et al., 2014). At lower densities, they are also claimed to define space both at a horizontal and a vertical level, providing a sense of enclosure that is pleasant and encourages walking (Ewing and Handy, 2009). With regard to buildings, if properly located, deciduous trees contribute to reduce excessive solar gains by providing shading in summer and enabling solar gains in winter. In the Northern hemisphere trees should be located South in relation to the building (Ko, 2013). They may also block unwanted winter winds (UN-Habitat, 1990). Nevertheless the preferred location is geography-dependent.

The existence of green areas is not a common feature of urban form to be analysed, especially in a quantitative way. It may be measured in absolute terms - e.g. number of parks or total green area, or in terms of green density - green area per total urban area, or green area per inhabitant (e.g. Urban Audit). Distance to parks and other open spaces has been used as an accessibility indicator when analysing travel implications (Kitamura et al., 1997; Lund, 2003), and park geometry has been captured by the perimeter/area ratio (Vaz Monteiro et al., 2016). Bourdic et al. (2012) suggest the use of the spatial distribution index, referred to above, to understand if green areas are more or less evenly distributed. Their spatial distribution is claimed to affect the equity of the urban environment, and also the influence of these areas on the whole city. It is expected that the existence of small- to medium sized parks located within relatively small distances from each other brings larger benefits than a single large park (Vaz Monteiro et al., 2016). This applies to the UHI effect, and is expected to work similarly regarding the effects on travel.

Cervero and Kockelman (1997) use the proportion of blocks with trees, as an element of the third D – design, to analyse the effect of tree presence on travel. Forsyth et al. (2008) measure the number of trees (within a distance buffer) per length of road. Under a different scope, Bremer et al. (2016) measure the vegetation volume in order to build a detailed 3D model of solar irradiation. Both green areas and the effect of trees deserve further attention in the urban form-energy research. In this case, simple indexes may be useful, such as the proportion of land covered by green areas, or the proportion of street length with trees.

Compactness

Referring to the urban tissue, compactness measures how clustered the built structures are (Ewing and Rong, 2008). Although this was partly addressed in the *density* section, this concept also refers to building geometry, with significant energy relevance. The energy demand of a building depends on its exposed surfaces, which directly affect heat flows between the inside and the outside environment, as well as on its access to natural light. This indicator is strongly dependent on building types (Ko, 2013), and is influenced by building allometry. According to Batty et al. (2008), as buildings grow in size, their shape has to change to enable them to function properly. That is when scaling is linked to allometry. Buildings cannot sustain their volume through increasing their floor areas if they cannot make use of natural light and other forms of externally-supplied energy. This helps to explain why buildings tend to increase in height instead of horizontally.

Compactness may be seen as a proxy for building geometry. The quest for the most efficient building form has been taking place for quite a long time. Martin and March (1975) find that a perfect rectangular parallelepiped (half-cube) would be the most efficient shape, targeted at minimizing heat losses. Ratti et al. (2005) propose a method accounting for ground losses, under which the optimum shape would be a cube. Recent findings from Hachem et al. (2012) confirm that deviations of building shape from the rectangle involve increasing heating loads. Steadman et al. (2000) categorize non-domestic built forms for investigating energy implications and Steadman et al. (2009) point out building depth as an important feature for energy use, as it is related to the limits of passive zones.

Metrics of building compactness are quite simple to define. They are usually a ratio of the envelope surface to the building volume – STV (Ratti et al., 2005; Rode et al., 2014). The STV is significantly correlated ($R^2 > 0.75$) with building energy performance (Fichera et al. 2016).

Bourdic et al. (2012) define building compactness through three different metrics: volumetric compactness, size factor, and form factor. The form factor is useful to eliminate the effect of size and keep only the effect of form. Nevertheless, this expression assumes that the building area grows at a rate of two thirds of the rate of the volume growth. Volumetric compactness is equivalent to the surface-to-volume (STV) ratio (Ratti et al., 2005). The STV is claimed to be the most useful indicator of compactness for estimating heating and cooling needs, as a function of the shape of the building. Anisimova (2011) suggests that STV should be lower than 0.8. The effect of compactness is inverse for heating and cooling (typically, compact buildings have lower needs for heating, but higher ones for cooling), although not necessarily in the same magnitude. Compactness metrics measure the potential for heat transfer through the envelope, which also depends on other factors not linked to the building form, notably construction materials.

Passivity

The passive or non-passive condition is often referred to as a factor of urban texture[3] (Ratti et al., 2005). Solar passive energy use in buildings is more widespread than passive cooling. However, the reason why the latter is not further explored is because it largely depends on smaller scale building elements (Kisilewicz, 2015), and thus it is not directly related to urban form. Passive zones are defined as those which can be naturally lit and ventilated, and that make use of solar gains for heating (Baker et al., 1992). These areas are those within 6 meters (or twice the ceiling height) from the façade (Figure 16). The size of passive areas is deeply dependent on building geometry. Passivity strategies tend to conflict with those for improving building compactness, as there are trade-offs between these two effects (Ratti et al., 2005). While increasing passive zones may increase solar gains, it potentially leads to higher thermal losses due to larger exposed surfaces. The prevailing effect on the building thermal balance, and the choice for the best strategy depends on the local climate.

The broader use of the passive / non-passive ratio has occurred after Ratti et al. (2005), who claim that the relation between passive and non-passive areas in buildings is a better indicator for energy consumption than the surface-to-volume ratio for the latitudes considered in their study. Steadman et al. (2009) argue that building depth, largely determining the limits of passive zones, is an important feature for energy use. Evans et al. (2016) consider the ratio of volume to exposed wall area as an approximation of the average depth of a plan (the ratio is equivalent to half plan depth). They claim that this indicator is likely to be related with the need for air conditioning. This is supported by the findings from Casas Castro Marins and Andrade Roméro (2013).

[3] For differentiating form and texture, see Lynch (1984).

Bourdic et al. (2012) measure this property at the block or neighbourhood scale and call it rate of passive volume. Metrics employed may be applied across different scales. Similarly to compactness, passivity also indicates a potential, because it does not consider aspects such as the shadowing caused by urban obstructions.

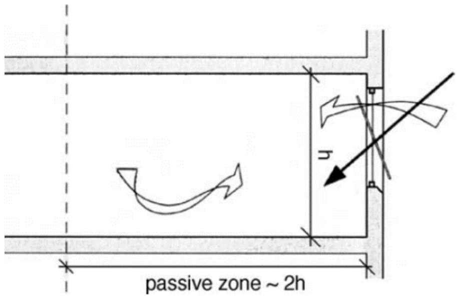

Figure 16. A passive zone (transversal cut)
Source: Ratti et al. (2005)

Shading

As building passivity does not consider obstructions, it should be complemented by a shading indicator. Shading significantly affects the energy balance of buildings. Baker et al. (1992) and Ratti et al. (2005) suggest the urban horizon angle (UHA), which refers to sky obstructions and is used to evaluate the effects of overshadowing from adjacent buildings. Baker and Steemers (2000) define it as the average elevation of the skyline from the centre of the façade being considered (Figure 17). It is measured for each façade, as the height (H) of the opposite buildings divided by the canyon width (W): H/W = tan (UHA). Ratti et al. (2005) apply an algorithm to measure the UHA in complex urban geometries, using the perpendicular line to the façade and a weighted average of six more directions in the range [-67.5º, + 67.5º] from the perpendicular line. These authors also use the obstruction sky view (OSV) angle, which quantifies the luminance of the obstructing façades. It is defined as H/W = cos (OSV). All these metrics involve the relation between street width and building height (H/W), also called urban canyon ratio (Coseo and Larsen, 2014). Street width alone significantly influences the global radiation yield of the urban canyon, with larger widths leading to larger yields (van Esch et al., 2012). Alternatively, the depth ratio is used to consider the effect of mutual shading between building façades (Hachem et al. 2011; 2012). Considering an L geometry, it is measured by the ratio of branch to main wing lengths. In addition, the sky view factor (SVF) describes the openness of the sky to radiative transport at a given ground location (Kim and Guldmann, 2014), and may also be considered as proxy for density (Giridharan et al., 2004). The SVF significantly influences urban air temperatures and the UHI (Oke, 1981), with lower SVF leading to increased temperatures (Chun and Guldmann, 2014).

Shading may ultimately be considered an effect of density (resulting from building’s heights and proximity). It is often treated separately due to its lower scale implications on individual buildings and on the urban microclimate. It is likely that trade-offs exist between cooling loads in buildings, and energy needs for mobility. In addition, shading (especially from trees) may also contribute to more pleasant walking environments in summer.

Robinson (2006) discusses the effectiveness of shading indicators. They are usually calculated for a single building. Alternative metrics, applicable at the urban block or neighbourhood scales would constitute interesting inputs for an energy analysis. For instance, the average UHA of an urban frontage along a street could provide a useful picture of the shading effect derived from the built environment.

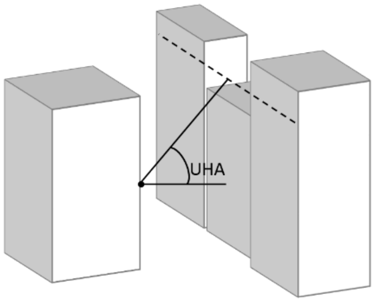

Figure 17. Urban Horizon Angle (UHA)
Source: Adapted from Baker and Steemers (2000)

Knowles (2003) presents the concept of solar envelope to translate the boundaries under which buildings will not shadow their surroundings. Also, Vermeulen et al. (2015) develop a framework for optimizing the urban layout to maximize direct solar irradiation. These studies, however, rely on more complex techniques than the metrics presented above to explore the effect of shading on energy demand. In practice, urban layouts are frequently constrained by the existing structures, where optimal solutions may not always be possible.

Orientation

The orientation of a building determines the amount of solar radiation incident on each of its façades, and consequently the requirements for space heating and cooling (Steemers, 2003; Ratti et al., 2005). In the northern hemisphere, south-facing façades should be favoured to maximize solar gains in winter (Littlefair, 1998; Hachem et al. 2011). East and West orientations gather excessive solar gains in summer, and north-oriented façades gather the lowest solar gains, thus implying higher heating needs (Hachem et al. 2012). Orientation is widely incorporated in several modelling platforms for building simulation – for instance, the renowned LT method (Baker et al., 1992). While it is pointed as a low cost and easily addressed building feature to achieve passive solar design (Morrissey et al., 2011), it has been argued that its effect on building solar potential is not that straightforward (Kanters and Wall, 2014). The optimization of a single building orientation is estimated to have minimal reductions on annual energy use and costs. However, for a whole community or urban area, important savings may be achieved by improving building orientation

(Hemsath, 2016). Additionally, street orientation is claimed to influence the UHI, due to the fact that it determines the shading and ventilation of the urban canyon. However, it does not seem to significantly explain urban air temperatures (Coseo and Larsen, 2014).

There is not much innovation on measuring orientation. It is usually measured in degrees or radians, representing the solar azimuth (e.g. Okeil, 2010; Wilson, 2013). This measure applies to each exposed building façade. Simplifications are needed in order to get a dominant orientation for a single building, such as the longest building axis (Hemsath, 2016) or the alignment in relation to the street, with an east-west axis being preferred for maximizing buildings facing south, and thus increasing solar gains in winter (Ko, 2013; Ko and Radke, 2014; Kanters and Wall, 2016). Streets with an east-west direction are also claimed to potentiate solar gains from increased street widths (van Esch et al., 2012). However, while using street orientation instead of building orientation may simplify the analysis, it may happen that buildings' main façades are not aligned with the streets. In the cases where buildings are not aligned with the street, street orientation is unlikely to be a suitable indicator. Although the orientation of a building or group of buildings is a low scale structural variable, it has been pointed out that it can be measured at the neighbourhood scale (Mitchell, 2005).

2.2.2. Urban networks

Next, urban attributes not included in the "built environment" category are reviewed. They draw on features of urban networks and on their ability to promote specific mobility patterns. Transport networks in cities may be characterized by different attributes, referring to the net itself or to "where" the net leads. The following paragraphs focus on the physical attributes of urban networks, concerning not only street features (referring to road and pedestrian modes), but also additional transport modes.

Connectivity

Connectivity is largely influenced by the spatial configuration of the urban network and is a widely acknowledged urban property influencing travel patterns (e.g. Ewing and Cervero, 2001; Baran et al., 2008). Topologically, it can be interpreted as the degree to which two points communicate with each other. It depends on the number of intersections and on the spatial arrangement of network edges (Cervero and Kockelman, 1997), but it is also dependent on block size (Forsyth et al., 2008). Marshall and Gong (2009) compare two archetypal network structures, tree and grid, pointing out that connectivity can be understood and exist at different scales (macro and micro). At a macro level, it is generally accepted that a greater connectivity shortens distances to be travelled, and potentially leads to reduced energy demand (Litman and Steele, 2005). However, this is not the consensus. Crane (2000) argues that shorter trips may lead to increased trip frequency. At a micro level, a higher connectivity may encourage walking and other soft modes, making urban activities more accessible by these modes (Ewing and Cervero, 2010). Cervero and Kockleman (1997) point out that gridded networks can work at a lower level to improve pedestrian movements. However, at a higher scale they are associated to higher levels of road traffic, as in the case of super-blocks.

Simple metrics of connectivity are the percentage of grid streets within a radius from a given point (Boarnet and Sarmiento, 1998), or the percentage of four-way intersections or the percent of cul-de-sacs (Handy, 1996b). Bourdic et al. (2012) describe connectivity as the number of different ways of going from one point to another. They propose a set of three indicators: i) the intensity of network intersections (number of intersections per area unit); ii) the average distance between intersections, which can be seen as proxy of how walking-friendly a city is; and iii) the cyclomatic number, which is in line with the definition of connectivity presented by these authors. The cyclomatic number represents the number of primary loops in a network, and is given by: $\mu = L - N + 1$, where L is the number of links, corresponding to the different sections of streets between every intersection, and N is the number of nodes, corresponding to the intersections in a road network. In order to be comparable, this number should refer to an area unit.

Chen et al. (2014) present a set of four indexes for measuring overall network connectivity: i) the Beta index (β) gives the average number of edges (e) per node (n) in a given network, i.e. $\beta = e/n$ $(0 \leq \beta \leq (n - 1)/2)$; ii) the cyclomatic number provides the number of circuits to indicate a gap between e and n while counting the number of sub networks q (q = 1 for a fully-connected network), i.e., $\mu = e - n + q$ $(0 \leq \mu \leq (n - 1)(n - 2)/2)$; iii) The Alpha index ($\alpha$) is defined as the proportion between the actual and maximal number of circuits in a fully-connecting planar network: it is given as $\alpha = 2\mu/(n - 1)(n - 2) = (e - n + q)/(2n - 5q)$ $(0 \leq \alpha \leq 1)$; and, finally iv) The Gamma index (γ) is the ratio between the actual and maximal number of edges: $\gamma = 2e/n(n - 1) = e/[3 * (n - 2)]$ $(0 \leq \gamma \leq 1)$.

Connectivity is also a measure provided by space syntax[2] (Hillier and Hanson, 1984). In this context, it is described as the number of lines that are connected to a certain line (Baran et al., 2008). This technique is grounded in graph theory, and assumes that better connected areas attract a higher density of flows. Nevertheless, the concept of connectivity may sometimes be fuzzy. The so-called syntactical measures (under a meta-measure of accessibility) found in the space syntax are closer to the concept of connectivity than to the concept of accessibility, as defined below. For instance, the integration measure corresponds to how easy it is, from each line, to reach all other lines of the urban system. Nevertheless, the space syntax may provide significant advantages over existing methods to measure street connectivity and syntactical accessibility, and to describe part-to-whole relationships of street networks (Baran et al. 2008).

At a micro scale, Moudon et al. (1997) focus on the connectivity and safety of pedestrian facilities when analysing the effect of site design on walking trips. Here, (pedestrian) connectivity is characterized by how well a network links land use parcels or activities within a given area. This is claimed to be a function of route directness and the completeness of (pedestrian) facilities, and to be closely linked to the concept of accessibility. The authors measure route directness as i) the ratio of actual route distance travelled to a straight-line distance, and ii) the walking distance contour, which plots the area from which a pedestrian can reach the centre within a 800 m walk or less. Completeness of pedestrian facilities is computed by the total length of the sidewalk to the total length of block (or street) frontage.

Connectivity metrics should focus on the configuration of the urban network and avoid mixing other attributes, such as the density of network nodes, or the beta index. More empirical knowledge is needed on the effects of connectivity at different scales. In all, pedestrian connectivity is to be favoured in urban areas, while large scale connectivity may have mixed effects.

Accessibility

Accessibility has no single definition. Gould (1969) calls it a “slippery notion” that is difficult to measure. Here, accessibility relates to the ease of reaching desired destinations or opportunities (aligned with Levine and Garb (2002) and Geurs and Ritsema van Eck (2001)). The implications on energy demand depend, to a great extent, on the transport mode considered. Pedestrian and transit accessibility should, thus, be increased. Handy (1993) claims that both local and regional accessibility should be increased, as they are associated to lower levels of non-work travel.

Accessibility is usually linked to a type of travel “cost”, typically distance or time. Handy and Niemeier (1997) consider three types of accessibility measures: the simplest refers to cumulative opportunities, whereas gravity-based and utility-based measures are more complex. Most measures consist of two parts: one concerning impedance, and the other concerning a given activity or trip attraction.

A different classification is proposed by Papa and Coppola (2012), who consider two types of measures: active and passive accessibility. The former is defined as a proxy for the ease of reaching activities located in different zones *j* of the study area for a certain purpose. It is given by the following expression: $A_{act,i} = \sum_j g(W_j) f(c_{ij})$, where W_j is the activity to reach in zone *j, and* c_{ij} is the generalized cost of reaching zone *j* from zone *i.* Passive accessibility is seen as a proxy for the opportunity of an activity located in a zone *i* to be reached by potential consumers coming from all the other zones *j* of the study area for a given purpose. It is defined as: $A_{pas,i} = \sum_j g(W_j) f(c_{ij})$, where W_j are the potential “consumers” of the activity to be reached in zone *i and* c_{ij} is the generalized cost of reaching zone *i* from reach in zone *j.* Likewise, Geurs and Ritsema van Eck (2001) distinguish between activity-based (availability of opportunities to satisfy individual needs) and utility-based accessibility (benefits that individuals may drive from the land use and transport system). Activity-based measures include, amongst others, distance measures, contour measures and potential measures.

Bourdic et al. (2012) simply measure the number of activities within 500 meters from a public transport station in relation to total number of activities from a given area. Additionally, Silva (2013) considers distance limitations in characterizing potential accessibility measures i.e., farther away places from a certain origin are less accessible. She proposes a method – the Structural Accessibility Layer (SAL) – for comparing accessibility levels in the territory. SAL is applied by transport mode to different types of opportunities generating travel. It comprises two accessibility measures: the diversity of activity (DivAct) index and the accessibility cluster.

Also with a geographical perspective, Sevtsuk and Mekonnen (2012a) propose five centrality indexes, while establishing a parallel between these indexes and other existent accessibility measures: *Reach, Gravity Index, Betweenness, Closeness and Straightness*. Despite their usefulness in characterizing the urban environment, the fact that these are classified as centrality indexes shows that accessibility is entangled with other concepts, notably diversity (Ewing et al., 2016).

Selecting one accessibility metric is not an easy task. The choice may depend on the desired level of detail and degree of complexity. In the case of accessibility, contour measures may not properly characterize the urban environment. The *DivAct* considered in the SAL tool (Silva and Pinho, 2010) has been evaluated by mobility and planning experts, who concluded on its robustness, utility and usability (Silva, 2013). In its turn, the *Reach* measure has produced interesting results, which is closer to a person's perception of the urban environment (Sevtsuk and Mekonnen, 2012b). Utility-based metrics are dependent on individual preferences, and thus are less linked to the urban environment in a stricter sense. In the case of an urban form-energy analysis, they may not be the most suitable choice.

Proximity to Public Transport

After the identification of three D's influencing travel demand (Cervero and Kockleman, 1997), three more were added thereafter. Distance to PT is referred by Ewing and Cervero (2010) as the fifth D (the fourth being destination accessibility and the sixth referred to as demand management, involving parking). Proximity to public transport is acknowledged to facilitate the adoption of this transport mode (Kitamura et al., 1997; Dieleman et al., 2002). This may be related to the travel time budget theory, which states that people are willing to spend a certain daily amount of time for travel purposes. Even if the transit system has very good frequencies and is very reliable, if the bus or train stop is not reachable within a short walk from home (or work), it is not likely to be successfully adopted. While door-to-door service may address this issue, the transit system may then become slower. Clearly, this is not a straightforward point.

Proximity to PT usually relies on simple metrics, such as distance to the nearest station or stop (Kitamura et al., 1997). Ewing and Cervero (2010) claim that it is commonly measured as: i) the average of the shortest street routes from the residences or workplaces in an area to the nearest station or stop, ii) public transport route density, iii) distance between stops, or iv) the number of stations per unit area.

Corroborating the importance of the location of transport infrastructure, Marshall and Gong (2009) propose the spinality concept for classifying urban areas according to the spatial configuration of settlements with respect to a strategic transport spinal network. Spinality is described as the extent to which an urban area is aligned along a transport axis. Two indicators are proposed for capturing spinality: i) the *Buffer ratio or B-ratio*, which is the proportion of the built-up area within a given distance of strategic routes, and ii) the *Route length ratio or A-ratio*, which is the proportion of strategic route length to total route length.

While the distance to public transport infrastructure is not the only factor affecting the adoption of this transport mode, it may certainly play an important role. Indicators are generally simple and should be considered in urban form-energy analysis. More complex indicators resorting to location of land uses may fall under the domain of accessibility measures.

Centrality

The distance (of housing) to the CBD is often used to determine energy demand for travel purposes. However, this distance is linked to other concepts presented earlier (e.g. density, diversity, accessibility). The CBD is the area with the highest employment density and number of trip ends (Anderson et al., 1996). Although distances travelled are directly influenced by other attributes of the urban area, notably density, mix of land uses, or network design, the distance to the CBD is often seen as an evaluation criterion by itself. For instance, in centralized systems, areas closer to the CBD are more likely to have higher accessibility indexes. As such, this indicator provides an incomplete description of the urban area because it is dependent on a set of other factors, and so, it should not be analysed in isolation to draw conclusions on urban performance (this is also true for other attributes). However, maybe because it is so intuitive, it is still widely applied in current research.

Greater distances to the CBD are often associated to an increased use of energy for commuting (Alford and Whiteman, 2009; Naess, 2005; Holden and Norland, 2005). This is particularly true for monocentric cities. However, the definition of the “centre” is an intrinsic issue. While this indicator may be quite easily measured in a concentric or radial city (Anderson et al., 1996), it may not be so evident in polycentric cites, and neither are the energy implications. Lee and Lee (2014) argue that a polycentric city may have lower commuting distances, despite being less favourable to public transport commuting. For a comprehensive review on polycentric patterns, see Marshall and Gong (2009).

Ewing and Cervero (2010) consider the distance to downtown as a built-environment variable falling under the category “destination accessibility”. Frost et al. (1998) estimate average travel distances in order to assess the so-called excess commuting in several urban areas. The authors concluded that urban form is a determinant of observed increases in trip length. However, they point out that analysing the commuting efficiency of a city based only in one measure may be misleading. Following Frost et al. (1998) approach, Chowdhury et al. (2013) evaluate commuting efficiency through commuting distances (actual, minimum, maximum) against urban form criteria, typically, the jobs-housing balance.

Interestingly, Brotchie (1984) combines in a single indicator the distance of amenities to CBD and a metric of diversity. The jobs–housing dispersal index (x) is one of the variables taken from Brotchie's triangle, and is the ratio of the average distance of jobs from the CBD (jobs dispersal) to the average distance of workers' households from the CBD (housing dispersal). Mathematically: $x = \left(\frac{1}{E}\sum_j d_j e_j\right)/\left(\frac{1}{H}\sum_j d_j h_j\right)$, where, E and H are the total number of metropolitan jobs and workers' households respectively; e_j and h_j are respectively the number of jobs and workers' households in zone j; and d_j is the network distance from the CBD to zone j. For a monocentric city the index is 0.

Under a slightly different perspective, Lee (2007) collects a set of centralization indexes, which define the extent of concentration of employment near the CBD. Additional centralization measures may be found in Lee and Lee (2014), where they use a principal component analysis to derive a centrality index. Centrality is found to have a significant negative association to VMT. In all, despite having an urban centre that is well defined, walkable and well served by public transport, in order to reduce motorized needs, it is important to keep some smaller clusters of urban services close to housing (as described in the *diversity* section). The right balance, though, is not clear.

Design

Design is related to low scale features of the urban environment that often have a subjective nature (Ewing and Handy, 2009). Design features are related to how pleasant the urban environment is, thus indicating the potential for using soft modes instead of motorized ones. Design stands for the third D influencing travel, which has not been explored enough (Cervero and Kockelman, 1997). Design measures applied by these authors cover a wide spectrum, and can be included in some of the attributes considered earlier. For instance, the "proportion of intersections that are four-way" or the "number of dead ends and cul-de-sacs" may be considered as indicators of connectivity. Similarly, the existence of trees, dealt with before, may fit in the design attribute.

Ewing and Cervero (2001) reinforce the importance of network design in encouraging the use of alternative modes of transport. They claim that "*grids with skinny streets, short blocks, and traffic-calming measures are hardly conducive to long distance car travel. Conversely, grids with six lanes of fast-moving traffic, long blocks, and no medians or pedestrian refuge islands are no panacea for pedestrians.*"

Apart from the configuration of the street network and the presence of trees, additional frequently referred design features are sidewalks and parking. The first is associated to pedestrian-friendly environments (Southworth, 1997) and recognized to be positively correlated with the frequency of non-motorized trips (Kitamura et al., 1997). Sidewalk length and width are both negatively correlated with VMT (Salon et al., 2012).

Parking supply is often assumed to promote driving (Cervero and Gorham, 1995) and create obstructed spaces, through displacing active land uses (Ewing and Cervero, 2001). These authors add that parking affects travel behaviour two-fold, in terms of supply and location in relation to streets and buildings. The relation between parking and VMT may also be examined using parking prices (Salon et al., 2012). Willson (2005) claims that parking supply and policy may improve the effects of transit-oriented development. If properly located, parking may work as a dissuasive factor for driving to final destinations (usually CBDs) and reduce congestion and air emissions.

Existing studies exploring urban design usually find low correlations between the metrics selected and travel demand. However, it is claimed that the effect of urban design on travel is likely to be a collective and cumulative one, involving multiple design features (Ewing and Cervero, 2010) that may have a significant weight together.

Hierarchy

Bourdic et al. (2012) suggest that the scale hierarchy of urban elements is a significant attribute influencing energy demand. This is based on the idea that hierarchic structures are associated to a higher urban structural efficiency (Salingaros and West, 1999). Salat and Bourdic (2011) argue that hierarchically organized urban systems follow power laws, with an important impact on their efficiency: *"the most energy efficient structure for a complex flow-driven system is a highly organized state, based on power law distributions"*. They add that *"in a highly dense and connected city with high levels of complexity, functional mix allows sparing significant amounts of inputs (materials, energy…)."*

These authors propose a metric for measuring the hierarchy of the street network that is based on the width and on the classification of streets, applied at city or district scales. This concept is also implicit on the Design D of Cervero and Kockelman (1997), where they consider arterial speed limits and street widths as properties of the urban space influencing travel demand. Alternatively, (Marins and Roméro, 2013) use the share of road area (road area/ total urban area) to describe the road network.

Batty (2012) claims that urban development patterns may be classified through their fractal dimension, where network structure may be the link for existing agglomeration economies and scaling effects. The effect of hierarchy on urban efficiency is still underexplored. More empirical research on this topic could help uncover desirable scale efficiencies determining energy demand. Additional metrics could help uncover existing relationships.

2.2.3. Summary and discussion

Cities have a complex nature. There are several attributes of urban form acknowledged to influence energy demand. This influence takes place at different scales (the building, the block, the neighbourhood and the whole city). Urban form influences two major urban sectors: housing and mobility. In the first case, urban form mainly determines the building type (and surroundings) and the UHI effect, influencing mostly thermal needs (heating and cooling). In regard to transport, urban form influences modal choice, distances travelled, and trip frequency, with an impact on overall energy needs. While micro attributes are most important in buildings (except for density), for transports it is at the meso- to the macro-scale that effects of urban form are mostly felt.

Conceptually, the literature is consistent in identifying the urban attributes with energy relevance. However, there are no clear boundaries on the understanding of the different attributes. While these may be invoked with different meanings (e.g., compactness has a different meaning depending on the scale of analysis), it may also happen that urban attributes which often occur together are many times taken as synonyms (for instance, accessibility and connectivity). This might be explained by the fact that a single urban attribute may bring others attached. The consequence is the persistence of some ambiguity when dealing with urban indicators, which complicates conclusions on the effect of urban form, particularly on energy demand. An adequate definition of urban attributes is essential for advancing existing knowledge, as the results may vary depending on the choice of indicators and metrics. The literature on urban form and energy has not carefully considered the impact of such choice.

The existing metrics are not evenly distributed over different urban form attributes. There are many ways of measuring an urban property, and a single urban attribute may require more than an indicator to be properly described. A study of the effects of urban form on energy (whatever source or vector of energy is considered) should use variables that describe the object under analysis, i.e. the physical environment. It is here argued that urban metrics should be as simple as possible to be implemented in planning practice. Simple metrics can be as informative as very sophisticated formulas, as long as they are targeted at effectively describing the urban environment. The set of metrics collected is expected to guide future research on the topic.

Moreover, research has been placing its emphasis on a limited set of attributes at a time. Here, it is argued that the influence of urban form on energy is a result of a set of intertwined variables, which should be analysed at the same time under a comprehensive analysis framework. Their overall effect is a result of intra and inter-sector trade-offs. This review goes across the literature, identifying attributes of urban form with energy relevance at different scales, describing how each urban attribute is expected to place its influence. Table 3 illustrates the variation (increase or decrease) in energy needs that each attribute is expected to create, for the three different uses (heating, cooling and mobility). While it is not possible, under the scope of a qualitative review, to produce a robust prescription of how the urban environment should be organized, the main conclusions are summarized as follows:

Density (residential) should be promoted near *public transport* and clustered around commerce and services for reducing private motorized trips (affects *diversity* too). In latitudes where heating is an important energy use, and wherever possible, infill development should be promoted and building heights should be carefully considered in order to prevent blocking solar access.

The desired *diversity* mix may not necessarily be 50/50. Nevertheless, ratios close to 0 and 1 in each neighbourhood should be avoided. In areas that are dominantly residential, creating daily-need services (e.g. a coffee shop, a bakery, a bank…) not only reduces trip needs, but also creates more lively and vibrant urban environments.

Keeping lower scale and connected green infrastructure within the urban core may create pleasant walking environments as well as regulating the urban microclimate, while larger *green areas* in the periphery may work as a green belts preventing urban dispersion, along with other ecological benefits – the city of Toronto being a good example (Green Infrastructure Ontario Coalition, 2014).

At the building scale, wherever heating is a dominant use, *compact* geometries should be favoured, minimizing exposed façades for preventing heat losses to the outside. This may be largely achieved by promoting non-detached housing. A favourable *orientation* should be promoted (south-facing façades in the northern-hemisphere), while trees represent low-cost amenities to regulate excessive solar gains and reduce cooling needs in summer.

Lower scale *connectivity* regarding pedestrian paths should be encouraged (for instance by reducing the size of blocks). Higher-scale street connectivity should be considered carefully, as it is often associated with motorized travel. In order to enable this distinction, urban elements such as streets, should be *hierarchically* arranged. Increased levels of desirable accessibility may be attained, depending on the mode, by improving the *proximity to public transport* infrastructure, or by bringing activities closer to inhabitants, in the case of pedestrians (as a combination of *density* and *diversity* mentioned earlier).

Finally, lower scale *design* elements, such as trees, sidewalks and parking, also exert an important influence. Parking availability in the urban core should be reduced (for instance, replaced by trees), while parking located in the urban boundaries next to key public transport hubs (e.g. park and ride stations) could promote the shift to more sustainable modes. Sidewalks should be proportional to street width, whereas narrower and shaded streets are usually more pedestrian-friendly than large boulevards.

The large bulk of existing studies provides useful insights on how the different elements of urban form affect energy for different urban purposes. However, the estimation of the weight of each indicator, as well as the overall balance of trade-offs, may only be achieved by a comprehensive quantitative framework, and may vary from city to city. The indicators and metrics gathered here are expected to contribute two-fold for the state of the art: i) supporting the emergence of sound innovative analytical frameworks, by collecting a set of urban form attributes with energy relevance, and ii) providing planners with systematic and quantifiable means to design more energy-efficient urban areas.

The following Section 2.3 results from the review performed in Section 2.2 (see also Silva et al. (2017)), and selects suitable indicators and metrics to describe the urban environment, capturing its relationship with energy demand. The reasoning for the selection is presented and, in the case the metrics collected are deemed unsuitable, their shortcomings will be addressed and alternative metrics will be proposed.

Table 3. Expected impact of each urban attribute on each energy use considered

Urban Attribute	*Buildings - heating needs*	*Buildings – cooling needs*	*Travel - energy needs*
↑*Density*	↓ / ↑	↓ / ↑	↓ / ↑
↑*Diversity*	NA/ND	NA/ND	↓
↑*Green areas*	↓ / ↑	↓	↓ / ↑
↑*Compactness*	↓	↑	NA/ND
↑*Passivity*	↓ / ↑	↓ / ↑	NA/ND
↑*Shading*	↑	↓	↓ / ↑
↑*Orientation (Preferred)*	↓	↓	NA/ND
↑*Connectivity*	NA/ND	NA/ND	↓ / ↑
↑*Accessibility*	NA/ND	NA/ND	↓
↑*Distance to CBD*	NA/ND	NA/ND	↓
↑*Design*	↓ / ↑	↓ / ↑	↓
↑*Proximity to PT (Preferred)*	NA/ND	NA/ND	↓
↑*Hierarchy*	NA/ND	NA/ND	↓

Legend: ↑ – Increases; ↓ – Decreases; ↓ / ↑ – Possible trade-offs; NA/ND – Not applicable/Not defined.

2.3. Definition of a set of suitable indicators of urban form for energy analysis

From the review performed in the previous section, several indicators of urban form and respective metrics with energy relevance were identified. The ones fitting the purpose of this research will be adopted in the development of the methodological framework. Conversely, in cases where it was not possible to identify a proper metric for the attributes considered, or where metrics were not applicable at a suitable scale of analysis, adaptations of existent indicators, or additional ones are proposed.

The main challenge at this point is to wrap up the bulk of existing information and to develop a suitable way to translate the urban attributes identified, in order to express the urban environment into a comprehensive and meaningful set of metrics, while simultaneously providing a framework for modelling and supporting the development of future urban policies and strategies.

According to the United Nations Human Settlements Programme (2004), urban indicators should have political relevance, i.e. they should be linked to the political targets defined. This study aims at producing knowledge to be included in strategic planning. Recall that the term attribute refers to a property that is being measured (defined by indicators), while metric refers to an analytical expression – e.g. the diversity attribute, can be defined by an indicator of mix of land uses, employing a metric like the ratio between residential floor space and total floor space. Metrics should be as simple as possible, and provide a quick insight into its meaning, i.e. should be easily translated into the physical reality.

Table 4 presents the urban attributes considered, the indicators deemed suitable to be used in this research, and the respective metrics. The following paragraphs present the reasoning and the framework of such choice.

Table 4. A selection of indicators and metrics of urban form with energy relevance

FOCUS AREA	ATTRIBUTE	INDICATOR	RELEVANCE SCALE	METRIC
Built environment	Density	Ground Space Index (GSI)	Bl, N, C	Building Coverage Area / total ground area
		Floor Space Index (FSI)	Bl, N, C	Gross Floor Area / total ground area
		Building height (F)	Bu, Bl, N, C	Average number of floors
	Granularity	Subdivision indicator	Bl, N, C	# parcels/ total ground area
		Size of block	Bl, N, C	Total area (m^2)
	Diversity	Mixed-use Index (MXI)	Bl, N, C	Residential Gross Floor Area / total GFA
	Green Areas	Spatial Distribution of green areas index	Bl, N, C	$Isd = \frac{Ai}{Si} * \frac{Ai}{\sum_Q Ai}$, where Q are urban blocks, each having an overall area of Si (m^2) and Ai (m^2) of green areas
	Compactness	Surface-to-volume ratio	Bu, Bl, N, C	C = S/V
	Passivity	Proportion of passive areas	Bu, Bl, N, C	Passive areas / total built-up area
	Shading	Urban Horizon Angle (UHA)	Bu, S, Bl, N, C	tan(UHA) = H/W
	Orientation	Favourable orientation	Bu, Bl, N, C	º from South; % Façade length E/W
Urban Networks	Connectivity	Beta index	S, Bl, N, C	$\beta = e/n$ $(0 \leq \beta \leq (n - 1)/2)$, where β is the average number of edges (e) per node (n) in a given street network
	Accessibility	DivAct	Bl, N, C	(DivAct) = $\frac{\sum_y (Acty * fy)}{\sum_y fy}$ ', where y is the activity type, Act_y a value representing the existence or not of the activity type y inside accessibility boundaries (Act_y {0; 1}) and f_y the potential use frequency of the activity type
		Reach	Bu, S, Bl, N, C	$Reach\ [i] = \sum_{j \in G - \{i\};\ d[i,j] \leq r} W\ [j]$, where $d[i,j]$ is the shortest path distance between nodes and in G, and $W\ [j]$ is the weight of a destination node *j*.
	Proximity to PT	Public transport route density	Bl, N, C	# PT stops / total ground area
	Centrality	Distance to CBD	Bl, N, C	Average shortest path between a block and the CBD gravity centre
	Design	Sidewalks	S, Bl, N, C	Average width of sidewalks; sidewalk area / total ground area
		Proportion of street length with provision of trees	S, Bl, N, C	Street length with trees / total street length
		Proportion of street length with provision of cycling lanes	S, Bl, N, C	Street length with cycling lanes/ total street length
		Parking lots per area unit	S, Bl, N, C	# parking places / total ground area

Bu – Building, S – Street, Bl – Block; N – Neighbourhood, C – City

2.3.1. Selection and justification of the indicators

The reasoning for the choice of the indicators selected is presented for the different urban attributes considered. Similarly to the previous section, the factors of urban form influencing energy demand are split into two main focus areas: the built environment and urban networks.

The indicators proposed aim at being measured at an intermediate scale between the city and the building or the street – for instance at block or neighbourhood scale. Indicators typically considered for a single building are presented (as found in literature) because they were considered important in terms of overall neighbourhood energy performance, and thus its application at interim scales will be tested.

Built Environment

Density

Density is cited in literature as one of the most important urban attributes in determining energy demand. It has been argued that describing the density of the urban environment, by using a single metric, may provide an incomplete picture of the physical configuration of the city. For this reason, several metrics are selected in order to properly describe this urban attribute.

A frequent way to describe density is the number of people living or working in a given area. Nevertheless, as the goal of this study is to explore the influence of the built environment on energy demand, it is deemed adequate to select variables of interest referring to the physical configuration of the urban elements. For this reason, population-based indexes are excluded.

In an effort to detach density from other concepts (notably, the mix of land uses and accessibility as found, for instance, in Cervero and Kockelman (1997)), the goal at this point is to consider only the weight of the built-up mass, without accounting for the functional aspects. Some abstraction is asked to reader in this sense. According to Pont and Haupt (2005), density indicators should translate the diversity of spaces that can exist if only density is controlled for.

In line with this, a set of metrics will be used after Pont and Haupt (2005, 2009). The first is the Floor Space Index (FSI), which is claimed to be the metric most frequently used to describe the density of the urban space. The second is the Ground Space Index (GSI), describing the surface on the ground which is effectively built-up. The third is the number of building floors (F). The remaining indicator, Open Space Ratio, is not considered because it is very closely related to GSI, and the metrics selected aim at being non-overlapping.

Overall, density is expected to be inversely correlated to energy needs both in the building and transport sectors. It is advocated to reduce thermal losses to the outer environment (due to lower exposed areas). However, higher densities may also lead to an increased shading effect from surrounding buildings, thus decreasing solar gains. The balance between these two effects is expected to depend on local geographies. Additionally, density may indirectly promote the urban heat island effect, due to a likely existence of continuous sealed surfaces. Considering transports, increased densities typically lead to lower distances to be travelled. It is advocated to bring urban activities closer, reducing the needs for motorized transport. It is also expected that higher densities provide the right conditions for improving the quality of public transport systems.

While the number of floors is expected to promote lower energy needs, both for buildings and transports, the effect of floor area, captured both by the GSI and FSI is not clear. Higher floor areas typically favour improved occupation economies, nevertheless, this may depend on the context at stake.

Granularity

Given the review performed in the previous section, there was an aspect of the urban environment that was not clearly defined by the urban attributes identified in the literature. The consideration of a granularity attribute is related to the need of accounting for the size of key urban elements (blocks and plots), and the way that they are subdivided, and is proposed after Lynch and Rodwin (1958). This attribute may be inherently related to density, as one may argue that higher granularities (smaller elements) imply higher densities (assuming that features like building footprint and height are kept constant). However, this is not always true, and thus the subdivision of urban space becomes an important indicator to describe the configuration of the urban environment.

Bourdic et al. (2012) propose a subdivision indicator, classifying it as a measure of density. Additionally, the size of urban elements has been considered a design feature (e.g. Cervero and Kockelman, 1997). Here, it was considered more appropriate to consider a distinct category, urban granularity, reflecting the need to distinguish between the intensity of land use, and the level of division of the urban environment. These two concepts may not always occur hand-in-hand. Granularity may have distinct effects from density and other design features.

Accordingly, two indicators will be considered to describe granularity: i) the number of plots within a block and ii) the size of the blocks. The first is a subdivision indicator (Bourdic et al. 2012) which describes the partitioning of the built structures (e.g. a large single building *versus* a set of several small ones). This index is proposed as a complement to the density indicators mentioned above. Predicting the effect of this indicator alone is not straightforward. A low number of parcels can either be related to a dispersed urban tissue of single-family houses, or to large parcels with high-rise buildings. Its effect should be considered alongside the size of the block and the indicators of density.

The other granularity metric, the size of the block, has been considered a determinant factor in influencing the adoption of different modes (Ewing and Cervero, 2010). Larger blocks are typically associated to urban settings that are less pedestrian friendly, as distances between each intersection point in the urban space increase.

Diversity

Diversity aims at expressing the variety and distribution of functional activities within a given urban area. The review performed showed that there are several ways of measuring this concept. A renowned study from Cervero and Kockelman (1997) proposes seven different metrics for analysing diversity. The authors found that the dissimilarity index is a more powerful predictor than the entropy index (for non-work trips). Following Cervero and Kockelman's (1997) findings, a simpler adaptation of this metric was sought. The mixed-use index was considered suitable for the purpose of this analysis. It is somehow related to Cervero and Kockelman's index, by considering the proportion of residential floor area to total ground area. It is particularly complicated to establish the boundaries of the area under analysis for the diversity indicator. The effects of diversity are expected to spill over to areas of adjacent neighbourhoods, which may be closer than activities located in the same neighbourhood.

Diversity, referring to the variety and distribution of functional activities in urban areas, has been mostly discussed in literature as one key factor affecting modal choice and travel patterns in cities. The existence of retail activities within neighbourhoods was associated with modal choice and lower VMT for work trips. Overall, diversity of land uses is widely acknowledged to producing more sustainable travel patterns. The existence of mixed functions creates a higher proximity to urban activities, and is also acknowledged to produce important indirect effects such as creating more lively urban spaces. This, too, is advocated to promote the use of soft modes.

Green areas

The relevance of green areas on energy entails the spatial distribution of such areas, not only in terms of their presence or absence, but also in terms of their size. The solution found to capture these two aspects was to adapt the index proposed by Bourdic et al. (2012) on the spatial distribution of green areas, originally proposed for the city scale.

A good mix of built-up and green areas affects the regulation of temperature (and humidity) within the city, limiting the increase of temperatures due to the urban heat island (UHI) effect, mainly felt in dense urban centres. The degree up to which this indicator can be combined with energy savings from higher densities is not yet known. Some authors propose threshold values for density, none validated from real case studies. The existence of dispersed medium-sized green areas have been advocated be more effective for urban cooling than fewer and larger ones.

Moreover, green areas are claimed to create more pleasant urban spaces, thus promoting the use of soft modes. In this sense, the relevance of measuring the spatial distribution together with the surface covered is stressed by the fact that a large green park in a peripheral or segregated part of a city is expected to produce less interesting outcomes than smaller sized parks which are more evenly distributed within an urban area, and whose benefits are more closely felt by residents. In addition to green areas, an indicator on the presence of trees on the streets is considered, and is included in the "design" attribute due to its micro scale nature.

Compactness

As discussed, compactness is considered here at the building scale. Thus, it will be measured as a function of the building geometry. The relevance of building compactness on energy is mostly determined by its influence on the heat flows through the building envelope – increased exposed surfaces most likely lead to higher heat losses to the outside environment. Additionally, irregular geometries with several edges are more likely to increase the existence of thermal bridges.

Building geometry/ shape and building compactness are often described through the relationship between the building volume and its exposed surfaces. The indicators for expressing building compactness are quite consistent in the literature and simple to define. The most frequent index is the STV – surface-to-volume ratio (higher values of this index describe less compact structures that are prone to losing heat to the outside). There are alternatives to the STV ratio (such as the form factor) excluding the effect of size in order to emphasize the effect of form. However, it was deemed that the effect of size could be important to keep, as well that the assumption of a proportion of 2:3 could provide biased characterizations. For this reason, the standard STV was adopted.

Passivity

Passivity refers to the condition of a building being or not passive, i.e. the extent to which a building can be naturally lit, ventilated, and heated as a function of its geometry. It is expected that the effects of passive areas may vary depending on specific design solutions adopted at lower scales, other than those that are usually influenced by urban planning choices (e.g. external shadings or trees).

The measure of passivity adopted follows its renowned advocators (Baker et al., 1992; Ratti et al., 2005) due to its inherent measurement simplicity and widespread use, although with an adaptation, similarly to the rate of passive volume proposed by Bourdic et al. (2012), in order improve its readability at the block scale. In this case, instead of the rate of passive volume, it is considered the rate of passive area. It is the ratio between the passive areas by the total built-up area of the block, where the passive areas are those within six meters from the building façade.

Ratti and colleagues consider the existence of energy trade-offs between privileging passive areas and building compactness. These two attributes are related as a function of building geometry. In order to try to uncover the individual effect of each of these attributes, they will be considered as two separate metrics. The modelling results are expected to contribute to answer the question on which of the two phenomena (compactness *vs.* passive areas) prevails in the global budget of buildings.

Shading

The consideration of a shading indicator aims at evaluating the effect of a building's surroundings in its energy performance, notably by influencing the amount of solar radiation on the building façades, and thus its solar gains. This can either be a negative effect – if solar gains are an important asset to reduce the heating load (presence of overshadowing), or a positive effect – in the case of overheat situations. A shading factor typically indicates the degree of obstruction of a façade due to the characteristics of the urban canyon (e.g. height of buildings in the opposite side of the street and street width).

The urban horizon angle (UHA) is part of the set of indicators proposed by Baker et al. (1992) and Ratti et al. (2005), argued to be determinant for building energy performance. For each façade it considers the height (H) of the opposite buildings divided by the canyon width (W), through the following expression: H/W = tan (UHA). The higher the values of this index the higher the shading effect of surrounding buildings.

This indicator is interesting, as it provides a picture of the urban configuration by considering the relationship between buildings' height and street width. As noted in the previous section, typically wider streets (with low/single-family buildings) are characteristic of a type of development that is considered less interesting and that has high transport costs by favouring road transport – the so-called urban sprawl. As a result, this indicator may capture trade-offs between higher heating needs in denser urban environments (as a result of lower radiation incidences) and lower motorized travel needs.

Orientation

The orientation of a building is a variable that is widely used in building simulation models, due to its influence in solar gains at the level of an individual building or building fraction. It relates to the amount of solar radiation that can potentially reach building surfaces, in the absence of obstacles.

In this case, since the unit of analysis is the urban block, it may be hard to capture differences in the existing patterns of orientation. It is anticipated that, for given urban block, all orientations may take place. Nevertheless, because this has been considered a relevant indicator in the literature, it will be measured and its applicability at the scale of the urban block will be tested.

Orientation is usually measured in degrees or radians, representing the solar azimuth (e.g. Okeil, 2010; Wilson, 2013). The predominant orientation has also been considered as the longest building axis (Hemsath, 2016). However, in the case of buildings with more than one frontage, an axis may be facing the best (south) and the worst (north) orientations at the same time.

Following this concept of "preferred" or most "favourable" orientation, two alternative metrics are proposed to capture buildings' orientation at the block level. The first, is degrees from south –

i.e. the average deviation of all exposed façades from what is considered the best orientation. The second considers the percentage of façade length (measured for all building façades in a block) facing the East to West axis (i.e. East-South-West).

Urban Networks

Connectivity

The connectivity of the street network results from the network's layout, and it is reflected on the easiness of reaching a certain destination from a given origin. A connected urban environment is often associated to a large number of street intersections, and it is typically accredited to create more pedestrian-friendly environments by increasing the chances of changing route direction, i.e., the distances between different points get reduced.

Here, the goal of measuring street connectivity is to capture how the network edges are interconnected, without considering urban land uses. The metric selected should focus on the structure of the street network. Amongst the different metrics reviewed, two options were considered. The number of intersections of the network; and the beta index, which captures the number of edges linked to a given node. The latter was selected because it is more frequently applied in the literature. It represents the possibilities of changing direction in a given area, and has a simple application and reading.

Accessibility

Accessibility is neither a consensual concept, nor easy to define. It can be considered as complementary to connectivity. While the latter considers network design only, accessibility typically considers the easiness of reaching a different urban activities within a certain cost budget (distance or time, for instance) from a given origin, meaning that it also looks at land uses. This is naturally a function of the transport network, but more than that, it assembles the street network to the existing activities in the urban space. Accessibility is also dependent on the transport mode, especially when considering travel time budgets. The number of activities one can reach from a specific place within, say, 15 minutes travel is different if we travel on foot or by car. Higher accessibilities are related to more pedestrian-friendly environments, because it means that a broader range of activities are reachable within a certain travel budget. An alternative way to look at accessibility is to consider the density of activities within a certain radius.

Since accessibility is a complex urban attribute, two different metrics capturing different aspects of the urban environment were selected. The first is the DivAct indicator from Silva (2013), measuring the average number of activity types accessible, weighted by the potential frequency of use. This is a contour measure of accessibility, which considers time as impedance factor for reaching activities.

In addition, the *Reach* index was adopted, from the urban network analysis toolbox (Sevtsuk and Mekonnen, 2012a). This is compatible with the notion of accessibility as a density of activities. *Reach* is equivalent to a cumulative opportunities type of accessibility measure, but is applied on a network instead of the Euclidian space (Sevtsuk and Mekonnen, 2012a). This is considered one the simplest class of accessibility measures, emphasizing the number of potential destinations or opportunities within a radius, rather than their distance (Handy and Niemeier, 1997). Specifically in the case of *Reach*, it enables to include weights. When this happens, it considers the sum of the weights instead of the number of destinations to compute accessibility. In this case, *Reach* does not account for the diversity of land uses, but instead, it enables to estimate the number of buildings (without weights) or weighting destinations by building area or volume, within a specified radius. This metric has proven interesting results in identifying the relative importance of urban areas. Typically more accessible areas, are the ones with a larger amount of built volume per area unit.

Proximity to PT

The proximity of housing and activities to public transport infrastructure may have an effect on the adoption of this mode. Areas that are better served (whether by buses, metro, or other) are expected to attract or generate more trips by public transport modes. While it may be argued that it is not guaranteed that the existence of many public transport routes will take travellers where they want, thinking in terms of likelihood, it is expected that residents with a good offer of public transport infrastructure within a walkable reach from their neighbourhood, have better conditions to choose this transport mode, and vice-versa.

In line with this, it is proposed a simple indicator aiming at capturing the proximity to public transport, adapted from what Ewing and Cervero (2010) call “transit route density”. Since the metrics of accessibility mostly focused on the distance to activities as the impedance factor, the metric selected for evaluating the proximity to PT relies on a different aspect of the urban environment. Instead of computing the shortest paths from the residences or workplaces to a station or stop, the indicator selected measures public transport route density. It is defined as the number of public transport stations or stops in a given urban area.

Centrality

The Distance to the CBD is a classic factor widely disseminated in literature as influencing mobility patterns within urban areas. This is expected to be a factor of higher relevance in monocentric than in polycentric cities. It is acknowledged that urban centrality, or its polarities act as major trip attractors, with trip lengths typically increasing with the distance to these areas. Additionally, with increasing distances to the city centre, the likelihood of using soft modes decreases (considering travel time budgets), and the feasibility of public transport becomes reduced.

Applying this indicator presupposes either considering a monocentric urban area, or an adaptation of the metric to consider the distance to the closest centre in the case of polycentric cities. In either case, the measurement of this indicator is very straightforward and considers the distance from a given area to the (closest) (C)BD.

Design

Design refers to micro-scale features, either from the street network or located in the public space. Design elements are typically targeted at making the urban space more pleasant and are widely acknowledged to influence mobility options. The quality of the pedestrian infrastructure is attributed to increase walking potential, while conversely good car-oriented infrastructure typically promotes the use of private vehicles.

The first aspect, the quality of pedestrian infrastructure, has been measured by the length and width of sidewalks. It is here considered that in the cases where streets are largely covered by sidewalks, what distinguishes the different urban landscapes is the width of the sidewalks. As a result, two distinct metrics are proposed: i) the average width of the sidewalk, and ii) the ratio between the sidewalk area and the total ground area of a given area of analysis.

Also, the quality of the pedestrian infrastructure is largely affected by the presence of trees, considered as a design feature. This indicator will be measured after Cervero and Kockelman (1997), as the proportion of street length with provision of trees. It is expected that for walking purposes, tree presence or absence is more relevant than tree density.

Considering car-related infrastructure, parking is one of the most important design elements. The proportion of lots with on-street, front or side parking, proposed by the same authors seems to be an adequate measure. Finally, it is considered that design not only affects walking and driving, but also other modes, notably cycling. As such, an indicator translating the existence of cycling infrastructure is also proposed, following Cervero and Kockelman's set of indicators: proportion of street length with provision of cycling lanes.

Design is the last category of indicators considered. It was decided not to further explore hierarchy. Work on urban hierarchy has been more extensively developed by Salat and his team. Despite it is here agreed that hierarchy may play an important role in urban efficiency, it is also considered that the most important aspects of hierarchy have been already covered by other indicators, notably the size of blocks and the urban horizon angle (which is a function of street width).

2.4. Synthesis

From the variety of urban indicators and metrics identified in Section 2.2, an array was selected with a view to characterizing the urban environment in a comprehensive way, while simultaneously capturing the possible implications of the physical arrangement of urban elements on energy

(Table 4). For each category of urban form attributes, the key criterion for the selection of the metrics was to ensure that they were not overlapping and that they were defined in a simple and straightforward way. Additional criteria included the representability of the indicator or metric in the literature and proven results of successful application.

All the indicators selected should be measured at the block or the neighbourhood scale. In most cases, this is quite straightforward. In cases where an indicator selected was initially applied at a different scale (higher or lower), the respective metric has been adapted for the block scale. This is the case of the indicators of compactness, passivity, shading and building orientation. They were kept at this stage due to the acknowledgement of their importance in determining energy needs (particularly in buildings). However, it is not certain whether they will yield interesting insights in modelling. The spatial analysis stage is expected to provide a preliminary insight on their suitability.

The major goal of this research is to deepen the understanding of the relation between urban form and energy demand in cities considering two essential urban dimensions: housing and mobility. After the definition and selection of the attributes of urban form with energy relevance, the next step is to collect the data and to measure them, allowing for modelling to take place. Each of these indicators will represent model variables, more specifically, model predictors.

The methodological framework proposed in Chapter 3 is expected to help uncover the overall importance of urban form on the energy demand of the building stock (for heating and cooling) and mobility, as well as the specific contribution of each variable considered. This is expected to enable understanding in which aspects to act upon or which are the best strategies to adopt in a given urban context.

CHAPTER 3. A NEW METHODOLOGY FOR ASSESSING THE IMPACT OF URBAN FORM ON BUILDING AND TRANSPORT ENERGY DEMAND

This chapter proposes a new methodological framework for assessing the impact of urban form on the energy demand for buildings (heating and cooling) and for mobility. It is described in Section 3.2, and grounds on a review of the state of the art, concerning methods for modelling energy demand in the urban context. Such review is presented in the following Section 3.1.

3.1. Methods for modelling energy in the urban environment: a review

Despite the relationship between urban form and energy has long been investigated at different scales and in different geographical contexts (Chapter 2), its effect on the energy flows of cities is not fully understood or quantified (Weisz and Schandl, 2008; Seto et al., 2014; Creutzig et al., 2015), whether considering the effect of urban form in relation to other drivers of energy demand, or the relative importance of the different factors of urban form. Several difficulties may be identified, as summarized by Silva et al. (2016). First, physical features of the urban environment (e.g. housing type) have been correlated to socio-economic factors (Kitamura et al., 1997). Despite there is a large number of variables of urban form to be considered, comprehensive studies are still a few. The degree of interaction among the different urban form variables is also unknown. Ewing and Cervero (2001) recall that the influence attributed to density may derive from other factors of urban form to which density could be associated. Finally, existing research is dominantly sectorial, while it is acknowledged that buildings and mobility should be considered together (O'Brien et al. 2010).

Models are a simplification of the real-world. The choice of a modelling approach depends on the scope and on the purpose of the analysis. Some studies include urban form as a parameter amongst many others (usually defined by one or a couple of variables), as they are not focused on exploring its specific contribution. In the cases where the goal is to infer on the impact of features of urban form on energy demand, the existing research presents some bottlenecks. The first, is an incomplete characterization of the overall effect of urban form, as few indicators are considered at a time (Naess, 2003; Rickwood et al., 2008). The second bottleneck, arises from focusing on buildings and mobility separately. This leads to neglecting existing energy trade-offs between these sectors, and therefore to possible double-counting issues when estimating the effect of specific variables affecting both sectors (e.g., density affects both thermal needs in buildings and mobility). In addition, there aren't many spatially-explicit studies on this topic. As advocated by Grubler et al. (2012), this may be the key to uncover the specificities of urban energy demand. This work will address these issues by proposing a spatially-explicit methodological framework, considering a comprehensive set of urban form attributes with energy relevance, belonging both to the building and the transport sectors.

Urban energy models can be classified depending on the detail of the analysis – top-down *vs*. bottom-up (i.e. use of aggregated data downwards *vs.* use of disaggregated data upwards); or depending on the modelling philosophy – e.g. econometric, engineering-economy (or end-use), hybrid models, scenario approaches, process models, input-output, and artificial neural networks (Bhattacharyya and Timilsina, 2009). Focusing on forecasting, a comprehensive overview of existing models is presented by Suganthi and Samuel (2012); however this review in not limited to the urban context.

Keirstead et al. (2012) identify six categories of urban energy models: technology design, building design, urban climate, systems design, policy assessment and, land use and transportation (LUT) modelling. The authors point urban complexity as a constraint, while arguing for integrated modelling approaches with policy relevance. Anderson et al. (2015) propose no categorization of urban models, but present the most common urban analysis methodologies ranging from spatial analysis to material accounting and simulation models. Two main scales of analysis are considered: the building and the urban scale.

In line with Zhao and Magoulès (2012), the following review considers three categories of models based on the nature of the analytical method: 1 – engineering models, 2 – statistical models, and 3 – data mining models. This is done considering the building and transport sectors, whereas models focusing on urban form will be subject to a more in-depth scrutiny.

3.1.1. Engineering Models

Engineering models are typically more complex and detailed, comparing to the remaining categories, and are often called simulation models. With regard to buildings, engineering models are mostly applied at the scale of a single building or even of a building subset. Larger scales may be covered, if building types are previously defined (e.g. Theodoridou et al., 2011). These models ground on physical principles for estimating the energy balance (typically thermal) of the object under analysis (Zhao and Magoulès, 2012).

Building simulation models are currently well-established methods for determining energy demand at the building scale. A comprehensive directory of building simulation models may be found at BEST Directory (IBPSA-USA, 2016). Their relevance relies on the accuracy of input data. This is why several studies focus on calibrating simulation models (e.g. Sun and Reddy (2006); Kim and Haberl (2015)). Data inputs usually include weather data (typical meteorological year), construction characteristics (materials, fenestration…), occupancy and respective activities, as well as thermal systems description. Aspects of urban form are marginally captured, usually incorporated at the stage of describing the building geometry, with a few examples considering building's surroundings as well. Despite building simulation models may include features of urban form, the effect of morphological parameters or the impact of different spatial planning options on urban energy demand is seldom the focus of the analysis.

In order to explore the effect of building geometry, Pessenlehner and Mahdavi (2003) analysed fifty-four building morphological variations. Thermal behaviour was predicted by simulations in NODEM software, and results were expressed in terms of heating load and overheating index. Linear regressions were used to relate these results to a compactness indicator. It was found that compactness has a significant association with heating load and that its use in building energy standards may be relevant.

With a stronger emphasis on morphological criteria, Ratti et al. (2005) analyse the effect of urban texture on building energy consumption, through the use of the LT model. The LT does not require as much detail as a full dynamic simulation model, but still requires *circa* 30 parameters as inputs. Variables of urban texture considered were: i) passive/non-passive ratio ii) orientation; iii) urban horizon angle (UHA) and; iv) obstruction sky view (OSV). The authors argue that most simulation software so far focuses on building or systems design, neglecting the role of surrounding urban configuration. A variation of at least 10% in building energy consumption for three case studies (Toulouse, Berlin and London) was attributed to texture variables, as remaining variables were kept constant. It was concluded that the passive to non-passive ratio is more important to explain energy variations than surface-to-volume ratio. With a similar approach, Zhao (2011) found that the dispersion degree of buildings, instead, is the variable with highest influence.

Hargreaves et al. (2016) developed a modelling framework combining regional socioeconomic projections and a representation of the variability of land use patterns. The authors used a "tiles" method for converting densities into a representation of the built stock, assuming a gamma distribution, while energy data was estimated by the "Domestic Energy and Carbon Model". The analysis intended to assess the suitability of different options for retrofitting and decentralized supply, under a technological perspective. Also, modelling an intermediate scale between the building and the city, Jones et al. (2007) use the Energy and Environment Prediction tool (EEP) to predict energy use and GHG emissions. This tool is built in a GIS platform and grounds on historical data from surveys. The built environment is divided into groups by a cluster analysis and the data used considering urban form included the size, the shape and the age of buildings. More recently, Shi et al. (2017) draw on simulation-based urban form generation and optimization for energy-driven urban design at district scale, using the City Energy Analyst tool to simulate energy demand at this spatial level.

An additional line of research explores the impact of urban form (mostly vegetation and urban features such as density) on the urban heat island (UHI) effect. This effect is characterized by higher average urban temperatures in relation to the rural hinterlands (Oke, 1987), largely attributed to the urbanized land cover. Although the features of urban form considered in these studies may refer both to the building and transport sectors, the energy implications due to changing temperatures are mainly felt as a result of varying thermal loads in buildings. Under this scope, simulation studies aiming at capturing the UHI effect may be found. Oke (1981) simulated night cooling rates in rural and urban settings, and found that canyon geometry (captured through the sky view factor – SVF) is a relevant factor in determining the existence of heat islands. In line with this, Hu et al. (2016) combine a parametric modelling and optimization, allocating a given amount of floor area to different urban configurations. The UHI effect is also analysed based on the SVF. Wong et al. (2011) assessed the influence of buildings' surroundings to predict air temperature variation and analyse how it affects building energy consumption, using STEVE model. The authors found that urban form variables can have an impact on air temperature of up to 0.9-1.2 ºC. In a different way, Akbari et al. (2012) use a climate model to predict the climate response of urban surface albedo modifications.

With regard to transports, the link between urban form and energy is often established in an indirect way, since model variables are usually number of trips, trip length or mode split. Simulation studies generally assume relationships between urban form and travel, thus predicting travel outcomes based on such assumptions (Handy, 1996b). Land-use transport (LUT) models, developed since the 60's, rely on land use components for predicting travel demand. For a more detailed review on land use, transports and energy modelling, please see Ghauche (2010). A review of existing transport models and the evolution of LUT may also be found in Sivakumar (2007). Cervero (2002) criticizes the bulk of empirical work on LUTs, claiming that they fail at adequately specifying relationships between the built-environment and mode choice (and thus energy demand).

Similarly to the case of buildings, engineering transport models are not deeply concerned with exploring the role of urban form on energy demand. Some examples can be referred, which somehow capture a few aspects of urban form for estimating travel patterns. The MIT model iTEAM (Integrated Transport and Energy Activity-based Model) aims at predicting transport energy consumption. Urban form is captured through the location of households and firms and existing transport infrastructure (Ghauche, 2010). A different approach from Carty and Ahern (2008) applies a cellular automata model based on spatial dynamic systems – MOLAND (Monitoring Land Use/Cover Dynamics). MOLAND uses different digital maps and enables to estimate future transport energy demand for a city through the likely development of land use. A clear advantage of this model is the fact that it is spatially explicit. Carty and Ahern (2008; 2010) examine different scenarios of urban development in Greater Dublin, considering the implementation of a new transport plan and estimate the resulting energy demand.

3.1.2. Statistical Models

The roots of the body of research on urban form and energy grounds on empirical statistical analysis, specifically focused on travel. The seminal study of Newman and Kenworthy (1989) correlates urban indicators and gasoline consumption in 10 U.S. cities. Energy consumption varied up to 40%. The authors concluded that one of the most important factors that influence the variation of energy consumption is the density of urban activities. This study was subject to criticism claiming that the effect of density is overrated, as it neglects the influence of other urban attributes. The fact is that, since then, density has been one of the most prominent variables of urban form advocated to influence urban energy needs (e.g. Banister et al., 1997; Newman and Kenworthy, 2006; Glaeser and Kahn, 2010).

Regression analysis is applied at different scales and contexts (e.g. Kitamura et al., 1997; Bento et al., 2003; Cervero and Duncan, 2006). Cervero (1989) applies a stepwise regression to investigate how jobs-housing imbalances affect mobility patterns (notably walking and cycling trips and freeway congestion) in 18 suburban employment centres. Frank and Pivo (1994) consider both density and mixed land uses for all transport modes. Different statistical techniques are applied, such as simple linear correlation, multivariate regression models, stepwise selection of variables and cross-tabulation. Urban form and mode choice were found to be significantly related, evidencing nonlinear relationships. Although this study has contributed to positively reinforce the relation between these urban form and mode choice, the analysis could benefit if a wider set of factors were considered. Cervero and Kockelman (1997) use factor analysis to examine the influence of the 3D's (density, diversity and design), and Cervero (2002) uses a binomial logit model weighting the influence of the 3D's with factors related to generalized cost and socioeconomic attributes of travellers. The approach to estimate marginal impact of the built environment consisted of building one "basic model" (traditional expression of utility in mode choice) and one "expanded model" (including the built environment). The main findings are that urban environment variables add significant explanatory power to the model (consistent with the 1997 research) revealing that intensities and mix of land use significantly influence travel patterns. The influence of urban design is usually more modest. Soltani and Allan (2006) analyse the effect of micro scale urban attributes on travel. This is done at neighbourhood scale, through a multinomial logit model considering urban form indicators, along with socio-demographics to predict modal choice. Finally, Fang et al. (2015) investigate the relationship between macro features of urban form and aggregated CO_2 emissions, resorting to a panel data model for the period 1990-2010. The authors concluded that features such as the presence of green areas, urban compactness and complexity were significantly related to CO_2 emissions.

Structural equation models (SEM) are a more flexible approach than conventional statistical techniques. Golob (2003) reviews the application of structural equation models (SEM) to travel behaviour research, claiming that SEM has substantial potential in the field of activity-based modelling. Cervero and Murakami (2010) apply SEM to investigate the effect of the built environment on VMT. More recently, Lee and Lee (2014) apply multilevel SEM to assess the influence of urban form in GHG emissions in the U.S. both in the transportation and in the residential sector.

In the case of buildings, Zhao and Magoulès (2012) claim that statistical models serve three key purposes: 1 – to predict energy use over simplified variables; 2 – to predict some useful energy index; 3 – to estimate building parameters related to energy use. Hsu (2015) discusses the strengths and weaknesses of simulation models over statistical ones. The author advocates that statistical models are useful for overcoming shortcomings, such as model complexity.

Kazanasmaz et al. (2014) somehow incorporate form or design in their research. These authors aimed at determining the energy performance of residential buildings in a Turkish city, through the investigation of its relation with architectural features. Such features included: zoning status, orientation, floor counts, area/volume ratio, construction year, net-usable floor area, and window area, among others. The analysis included techniques such as an ANOVA, t-test and a regression analysis. It was concluded from the ANOVA and the t-test that energy use was dependent on five out of eight architectural indicators considered. Engvall et al. (2014) also look for dependencies among selected variables and residential energy consumption. Building design is somehow captured by the "building period" and "type of building" indicators. A hierarchical cluster analysis was previously performed to reduce the number of variables, followed by a regression analysis.

With regard to the UHI, the effect of urban form has also been investigated resorting to regression analysis (Stone and Rodgers, 2001). Here, the variables corresponded both to the building (e.g. year of construction or number of bedrooms) and the transport sectors (e.g. street intersections).

From this review, it is possible to grasp that the use of statistical tools is more recurrent in the transportation sector. This may be due to the fact that existing relationships between urban form and energy in buildings are better characterized; whereas in transports, it is expected the co-existence of more variables with interdependencies that are not fully known.

3.1.3. Data mining

While the previous section is focused on traditional statistical techniques, data mining deals with more complex datasets, and is often an extension of statistical methods. *"Data mining is a step in the KDD (Knowledge Discovery in Database)*[4] *process that consists of applying data analysis and discovery algorithms that produce a particular enumeration of patterns (or models) over the data."* (Fayyad et al., 1996)

Liao et al. (2012) review a decade of data mining techniques and applications from 2000 to 2011. They claim that data mining techniques have given origin to a branch called artificial intelligence. Chen et al. (2000) classify data mining in two main categories: i) statistical models and

[4] "Knowledge discovery in databases (KDD) is a multidisciplinary research field for nontrivial extraction of implicit, previously unknown, and potentially useful knowledge from data" (Tsui et al., 2006)

ii) artificial intelligence methods, also known as machine learning. The latter suggest the existence of a “learning” process from a set of training data from which the “machine” is able to identify patterns and generalize. Data mining has been considered increasingly attractive, mostly due to the increasing availability of computational power, with applications in a variety of fields.

This type of model deals with large amounts of data, and has its foundations in statistics and in computer science. Methods can be included in two main categories: supervised and unsupervised learning. The former uses input data that is linked to the output data fed into the model. The latter, has no correct answers or a clear measure of model success. Figure 18 presents a schematic interpretation of the different data mining techniques based on Tsui et al. (2006).

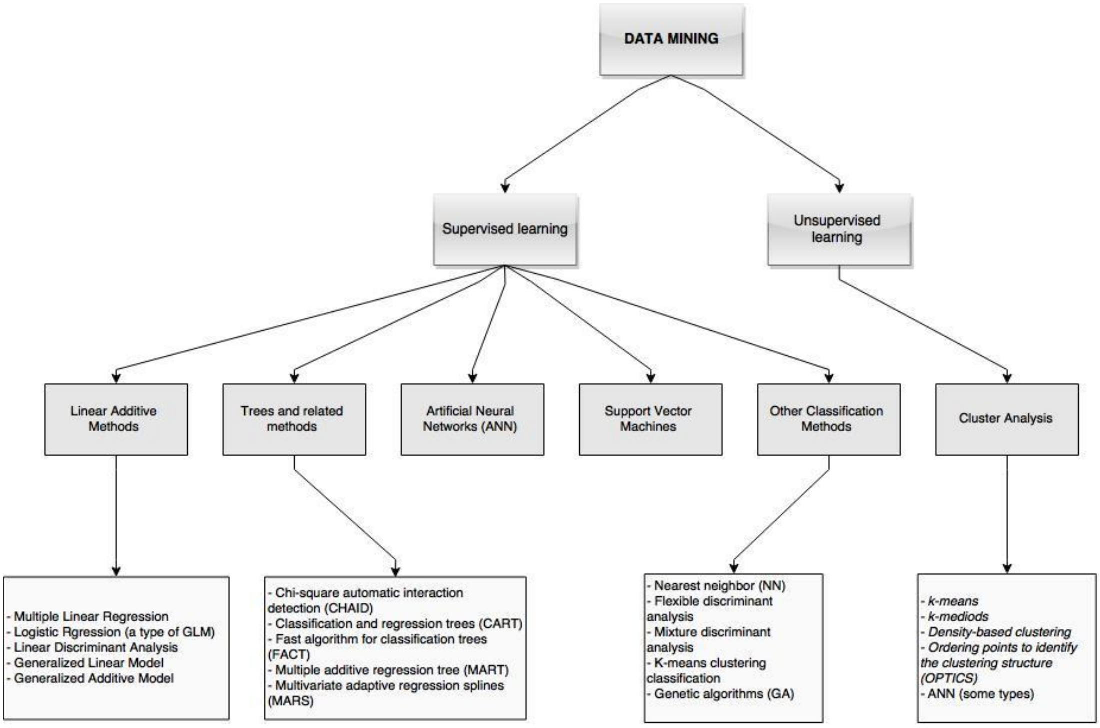

Figure 18. Classification of data mining techniques
Source: Based on Tsui et al. (2006)

The choice of a data mining technique depends on the type of problem. Table 5 presents different types of data mining techniques and provides examples of application (Chen et al., 2000).

Table 5. Information sought in data mining

Type	Application	Example
Cluster	Grouping together items with similar characteristics	Market segmentation
Classification	Development of a profile different groups to decide the belonging of an entity to a certain group	Buyers of expensive sport cars are typically young, urban professionals with high income.
Sequence	Involves events that are linked over an extended period	Ten percent of the customers who order sheets order a comforter next.
Exception	Discovering exception means finding the “unusual”	Detecting unusual credit card transactions
Forecasting	Estimates future values based on data patterns (also known as patterns and trends)	Estimating future sales based on historical records

Source: Adapted from Chen et al. (2000)

Data mining has been applied to predict building energy use. Chou and Bui (2014) applied and compared various data mining techniques (support vector regression (SVR), artificial neural networks (ANN), classification and regression tree, chi-squared automatic interaction detector, and general linear regression) to assess the energy performance of twelve building types. The best performing methods were combined into ensemble models[5]. Input data consisted of physical and design aspects of buildings. The ensemble model (SVR+ANN) performed better for predicting the cooling load and the SVR retrieved better results for predicting the heating load.

Artificial neural networks are the most popular data mining technique (Liao et al., 2012). Karatasou et al. (2006) combine ANN with other statistical processes for building energy prediction. The authors use datasets with environmental variables from two different buildings. Kalogirou (2006) explores ANN for addressing building design issues, enabling stakeholders to get a quick insight on the effect of a certain change in the building performance. Additional applications of neural networks on energy in buildings can be found in Issa et al. (2001); Kalogirou (2000); Yalcintas and Akkurt (2005).

Examples of the application of support vector machines (SVM) include a building load estimation performed by Dong et al. (2005). SVM produced better values considering coefficient of variance and mean squared-error than ANN and Genetic Programming. Zhao and Magoulès (2012) review methods for predicting building energy consumption. They concluded that ANN and SVM can have a highly accurate prediction in nonlinear problems, in contrast to statistical methods. They found that artificial intelligence methods are much suited for building energy prediction.

With regard to applications to the transportation field, Dougherty (1995) performed a review of ANN applied to transports. Fields of application include: parameter estimation; vehicle detection/classification; traffic pattern analysis; traffic forecasting; transport policy and economics; traffic control, among others. None of these explores energy directly. The application of machine learning to transport energy is not as recurrent as it happens for energy in buildings. A couple of exceptions are Geem (2011), who use ANN to estimate energy demand in South Korea using socio-economic variables and transport-related indicators, at a macro level. Murat and Ceylan (2006) use an ANN with a similar approach in Turkey. Urban form variables were neglected in both cases.

Data mining has also been applied to urban form, although without a focus on energy so far. Sokmenoglu et al. (2010) use data mining for identifying patterns in the distribution of urban attributes (e.g. predicting the use of a first floor, given the use of the ground floor and a density index); and Gil et al. (2009) use various features of the urban environment to perform a classification of streets and neighbourhoods into different typologies. With a different scope, Behnisch and Ultsch (2009) present an “urban data mining approach” that aims at clustering and classifying urban geospatial data to find hidden relationships amongst the variables analysed. They apply this approach to a socio-demographic dataset. These three studies largely inspired the

[5] Ensemble models use a combination of models aiming to improve the performance of the resulting model.

methodological framework proposed in the following section to explore the link between urban form and energy demand.

3.1.4. Summary and discussion

There is a wide array of energy modelling approaches including morphological parameters, although many are not focused on exploring the contribution of urban form to the overall energy balance. Existing models vary in scope, structure, complexity, level of detail and data requirements. The way that urban form is included in such models is not consistent, but typically, the studies that are primarily concerned with exploring the effect of urban form have a statistical nature (Table 6).

Table 6. Existing modelling approaches and techniques considering urban form and energy demand

Level of complexity and detail

Engineering models	Data mining	Statistical models
Building simulation	Support vector regression/ machines (SVR/SVM)	Linear correlation
Land-use & transport model	Artificial Neural Networks (ANN)	Regression analysis
Urban climate simulation	Classification and regression trees (CT/RT)	Stepwise regression analysis
	Chi-squared automatic interaction detection (CHAID)	Logit models
	General linear models (GLM)	ANOVA
	Genetic programming (GP)	t-test
		Factor analysis
		Cross-tabulation
		Panel data
		Structural equation models

Incorporation of urban form factors in existing models

Traditionally, energy in buildings and in transports is analysed separately (research on the UHI effect may be an exception, however, the effects on energy are often overlooked). Research in buildings dominantly applies engineering models. While these are very complex and data-intensive, in the case of buildings, the physical relationships are better known. The effect of urban form is not deeply explored in these models, and is typically captured through building geometry, with a few studies also considering building surroundings (urban texture).

In the case of transports, there is a longer tradition of exploring the effect of form attributes on energy demand. This has dominantly been done resorting to statistical techniques. In this field, the interactions amongst variables considered are quite complex and are not fully known. Statistical models have been criticized for lacking accuracy and flexibility.

Data mining has been increasingly adopted, with proven results in a diversity of fields. Energy-related research is concentrated in building energy prediction, for which these tools seem to be a popular alternative to complex engineering models. Applications in transports are scarcer. Some techniques have been suggested to work as design tools, able to inform decision-making. The potential of data mining to uncover the relationship between urban form and energy hasn't been explored yet. The application of these tools to this field could help generate deeper knowledge on a debate with over two decades of existence, and significantly contribute to inform urban policy-making. The following section presents a methodological framework for modelling the relationship between urban form and energy demand resorting to ANN.

3.2. Proposal of a new methodological framework

This section presents the proposal of a spatially-explicit methodological framework for modelling the relationship between urban form and energy demand, and provides the description of how it is structured in terms of the different steps that are part the process and in terms of the techniques used.

The methodology proposed encompasses six steps (Figure 19). The first step consists of the definition of the indicators and respective metrics of urban form with energy relevance (presented in Chapter 2). This step is distinct from the remaining because it takes place at a conceptual level and constitutes the pillar where the following steps will ground. The remaining steps of the methodological framework have a clear operational nature and will be described in the following sections.

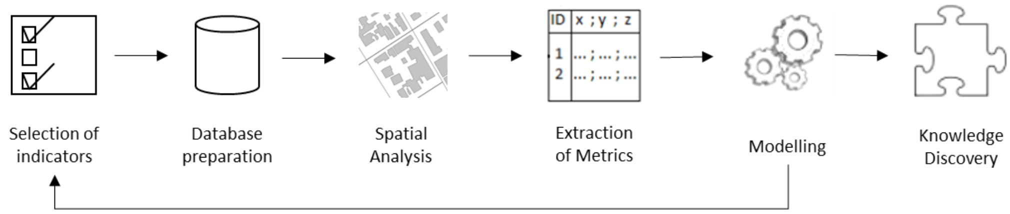

Figure 19. Steps of the methodological framework

3.2.1. Database preparation

A structured database is the first requirement for allowing subsequent steps of the analysis to take place. The database preparation entails two different processes: i) data collection and, ii) assembling and structuring the database. Here, the level of detail wished for should be defined. All the indicators should be measured for a previously defined urban spatial unit. These units should correspond to relatively homogeneous areas in terms of urban form and structure, for instance the urban block or the neighbourhood. It is key to match the data available to the area units considered so that it becomes compatible to be modelled.

Chances are that the database includes data from different official sources, which have to be previously checked for and tailored for the spatial analysis. For the database preparation three main types of data should be gathered: spatial data, statistical data, and data on energy demand. Spatial and statistical data will enable to compute the urban form indicators (predictors) and energy data will constitute the response variables.

3.2.1.1. Spatial Data

Spatial data is a pillar of this methodological framework. The preferred type of spatial data is vector data, in order to enable a good degree of accuracy. Spatial data consists of a georeferenced database with the properties of physical objects, in which each geographical entity has a single identity and independent records for each of the attributes of the database. In addition, spatial data has a specific location and geometric properties, like areas and perimeters, allowing to perform several analytical operations in respect to the shape and physical properties of the objects at stake.

The urban elements needed for the spatial analysis include the land uses, buildings, the boundaries of the urban blocks, the streets, public and open spaces, green spaces, public transport stations, trees… Nowadays, it is common practice that local authorities have cartography on these urban elements.

3.2.1.2. Statistical Data

The collection of statistical data entails two main criteria: The first is that it should enable to compute the indicators from Table 4. The second, is that it should be compatible with the spatial units considered earlier, and thus with the spatial resolution of the analysis (e.g. the urban block or neighbourhood), or at least they should allow estimating the indicators at this scale. The collection of spatial data should be collected form official sources in order to guarantee some degree of quality and accuracy.

3.2.1.3. Energy Data

With regard to energy demand, two types of data could be suitable for feeding the model. The first is “real” data, from official sources at a disaggregated level, for instance based on surveys, metering, or on energy certification schemes. The second type consists of artificial data (inferred from specific models), when the former is not available. Despite being noisier, official data is considered more reliable. Desirably, the data should be disaggregated according to the relevant energy uses, i.e. those that are most affected by urban form: heating and cooling in buildings, and mobility. In addition, energy data should also be georeferenced in order to enable matching the energy needs with the spatial units considered.

Similarly to the indicators of urban form, energy indicators should also hold political relevance. According to Neves and Leal (2010), household energy intensity and transport energy intensity are sustainable energy indicators, fulfilling three evaluation criteria: relevance for local energy sustainability, measurability at the local level, and roles of the authorities. Energy intensity is often expressed in relation to a variable of interest, the most common being population or surface area. For instance, Bourdic et al. (2012) propose the following indicators: energy intensity per resident (e.g. kWh per capita) and surface energy intensity (e.g. kWh per floor area).

Also, in order to assess the effect of urban form, considering energy demand is preferable than energy consumption, because real consumption patterns depend on a larger set of factors (Salat, 2009). Energy demand refers to the energy needed to deliver a certain energy use (e.g. heating or cooling) under specific pre-set conditions. Whether such need is fulfilled, and by which means, translates into the patterns of energy consumption. Actual consumption is a product of a broader set of factors, which are out of the scope of this analysis, notably technological and behavioural factors.

Finally, the database preparation *per se*, consists of merging the different data sources together, and ensuring that all data has a spatial interface and a proper ID, so that it can be easily imported to the geographic information system (GIS) and later exported again into spreadsheet format to be modelled.

Importing the data into a GIS is a way of gathering and storing all the individual datasets, while providing the analysis with a spatial character. This enables a spatial and graphic display of the different indicators considered.

3.2.2. Spatial analysis

The spatial analysis consists of measuring the indicators of urban form that will enter the model as predictors. This step involves some degree of expertise on GIS. The spatial analysis entails some preliminary operations before the measurement of the indicators. Preliminary operations include actions such as clipping, deleting, merging, and joining features and tables. When operating spatial data some mismatches may happen, depending on data resolution and quality. Corrections may be necessary in order to remove conflicts between databases (e.g. road axes without contiguity, or buildings located on top of a road lane), as well as deleting irrelevant data features that may originate noise (e.g. removing building annexes from the building cartography). Figure 20 illustrates an example of layering different datasets for spatial analysis. In this case, four different layers are displayed: building centroids, building footprints, street centre lines and blocks (one feature of this layer is selected, with its boundary in light blue).

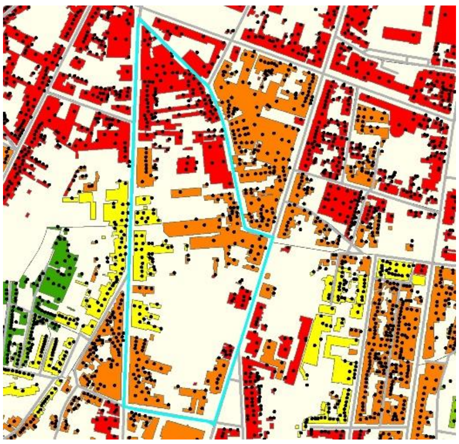

Figure 20. Example of layering in GIS

After spatial features are set, the spatial analysis *per se* consists of measuring in the GIS the urban form indicators previously selected. This is performed resorting to physical properties such as locations, areas, volumes, and distances, which are intrinsic to spatial data; or to the statistical data that has been previously imported to the GIS. This typically corresponds to an encoded layer file itself. The metrics should be computed for each of the area units considered.

Although these results have a graphic visualization, the outputs of this step are also numeric and serve as inputs for the modelling process. This is the main advantage of a spatially-explicit method. Each feature in each layer is linked to an attribute table. This attribute table has as many entries as features displayed in the graphic interface. Each feature has a unique ID and different data fields.

For each indicator, a map can be produced, varying in an appropriate range of intervals for visual inspection. The spatial analysis allows for a multi-scale visualization of the data at stake (e.g. a high-resolution scale such as the urban block, while allowing to see the whole city). At this point, the data on energy demand should also be imported to the GIS (by using the coordinates of each data point), allowing to depict in a map the energy demand trends for the urban area under investigation.

3.2.3. Extraction of the Metrics

After measuring the indicators in the GIS, data should be gathered and then exported into a suitable format for modelling. This is done by using the ID code assigned to the different area units during the spatial analysis.

A suitable format for exporting the metrics is, for instance, an MS Office Excel ™ spreadsheet. Despite most GIS software do not enable to export directly to spreadsheet format, it is possible to do so in two phases. First, it is possible to export into a database management table that is compatible with MS Excel ™ and, in a second instance, to save it as a spreadsheet file. These files are compatible with most of suitable modelling software (e.g. SPSS, R, Matlab,…). At this point, "atypical" area units are removed from further steps of the analysis, although they can be considered for measuring urban form indicators. These are blocks exclusively occupied by green or public spaces, as well as blocks exclusively allocated to services or commercial uses, such as hospitals or faculties. The energy behaviour in these areas would not be comparable to remaining parts of the city, as it is determined by a different set of factors. Removing these areas is expected to allow the model to more accurately predict energy demand in residential or mixed-use urban blocks.

3.2.4. Modelling

The fifth step corresponds to defining and running the model. This research aims at discovering the patterns linking urban form features and energy demand in cities, more specifically at obtaining quantitative knowledge on the influence of urban form on energy demand (for specific related uses). The model is formulated considering energy demand for heating, cooling and travel as a function of a set of urban form variables, as follows:

$$(E_h,\ E_c, ET) = \ f\ (UFi)$$

(Equation 1)

, *where* E_h *are final energy needs for heating in buildings,* E_c *are final energy needs for cooling in buildings, and* ET *are travel needs that may be translated into vehicle kilometre or final energy for travel.* UF_i *are the variables of urban form considered*.

This can be designated as a function fitting or prediction problem (Chen et al., 2000), with continuous variables. From the review of methods for modelling energy demand in cities (Section 3.1), data mining seems an interesting option, considering the research purpose, as well as the type of data in hand. It refers to a large database, where the relationships between the predictors and the response variables are expected to be nonlinear. This type of model seems to offer a good compromise between the level of detail and complexity involved, model flexibility and accuracy, and the desired degree of incorporation of urban form in the analysis. In addition, the application of machine learning, in particular, to the field of urban form and energy hasn't been tested so far.

Considering the specificities of the research problem, Artificial Neural Networks (ANN) arise as a suitable technique to address it. However, it is deemed adequate to previously test simpler techniques closer to traditional statistics, in order to check if they are able to cope with the problem and data at stake. If such techniques perform well (given a set of model fit and quality metrics), it becomes pointless to use a more sophisticated data mining technique, like ANN, if no significant improvements in model quality are obtained. As such, before the application of ANN to the research problem, a couple of additional techniques will be tested: multiple linear regression (MLR) and structural equation models (SEM). This will enable to have a base for comparing the ANN results, as well as providing additional sensitivity on the contribution of the different variables to the model.

The following topics introduce the three modelling techniques to be tested, present their underlying rationale and discuss their suitability as modelling approaches in the context of this research.

3.2.4.1. Multiple Linear Regression (MLR)

A multiple regression is a regression with two or more explanatory variables. Multiple linear regression (MLR) is a renowned statistical method for predicting the values of a dependent variable y, given a set of explanatory variables (x_1, x_2,…, x_i), assuming that these are linearly combined (Tranmer and Elliot, 2008). A MLR model can be translated by the following equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_i x_i + \varepsilon$$

(Equation 2)

, where y is the dependent variable, x_i are the explanatory variables, β_0 is a constant term, β_i are coefficients relating the explanatory variables to the variables of interest, and ε is the error term.

The most common estimation method is the *least squares*, which selects the β_i coefficients that minimize the residual sum of squares (Hastie et al., 2008). The use of MLR enables not only to predict the values of the dependent variables, but also, to infer on the relative importance and the effects of the predictors, which is given by the magnitude and signal of β_i, respectively. While its application is quite straightforward, it is only valid under a linear environment, and thus, it may not be suitable to capture other type of links between model inputs and outputs. Also, it has been argued that the number of predictors influences model accuracy (Austin and Steyerberg, 2015). In cases with a large number of predictors, it is common to apply additional algorithms targeted at selecting the most relevant ones. This is the case of forward- and backward-stepwise selection. The first, starts with the intercept, and sequentially adds predictors that improve model fit, up to a point where the increase in explanation is no longer considered relevant (Hastie et al., 2008). Backward selection works the other way around, by sequentially removing variables that add no significant explanatory power to the model.

In addition to the linear assumption and the difficulty of dealing with large datasets, the application of MLR to the research problem does not allow to model the three outputs at the same time, as initially intended.

3.2.4.2. Structural Equation Models (SEM)

Structural Equation Models (SEM) are based on general linear models (Ullman, 2006), but are usually more flexible. They have the advantage of being a multivariate technique. According to MacCallum and Austin (2000) a SEM represent an hypothesized pattern of directional and non-directional linear relationships among a set of measured and latent (i.e. non-observed) variables. A common application of SEM is path analysis, where the relationships between the measured variables are tested (MacCallum and Austin, 2000). Although SEM uses statistical techniques, it is not considered a statistical method itself (Grace et al., 2012). It enables to evaluate causality relationships and networks of direct and indirect effects, but it is not a prediction technique.

As diagrams are an intrinsic part of this technique, the user is asked to hypothesize the existing relationships between the variables. For this reason, they are considered confirmatory methods rather than exploratory ones (Golob, 2003). One of their disadvantages is precisely the need to previously specify a considerable amount of information to run the model. Although it is based on linear relationships, SEM will be tested in this work because it enables to deal with several dependent variables, as well as exploring interdependencies among the different covariates. As such, SEM will be tested alongside the MLR, as a preliminary modelling approach closer to traditional statistical methods, before moving to more complex techniques from the field of machine learning. This exercise is also expected to yield a better understanding of the nature of the problem, and to serve as a benchmarking procedure for comparing with the results of a more advanced model.

3.2.4.3. Artificial Neural Networks (ANN)

ANN are computational models raising increased interest among the research community. They are a data mining technique (currently the most widespread) under the scope of machine learning. ANN date back to the 1940's with McCulloch and Pitts neurons being mostly used as logic circuits, but it was since 80's that the interest in the field grew. The limitations of single layer nets had been overcome and an increased computational power was available, while the backpropagation method and others emerged as a way of effectively training multilayer nets (Fausett, 1994).

An ANN uses similar principles to the human brain (Jain et al. 1996). They usually consist of an input layer, a layer of output neurons and one or more layers of hidden neurons. ANN relate the inputs and the outputs through a learning process, where an algorithm is able to map the corresponding data patterns. ANN are claimed to be a cost-effective tool for analysing nonlinear problems (able to deal with complexity with relatively little computational and time effort). Despite their proven usefulness and accuracy in solving complex problems and dealing with noisy data, they are often criticized to work as a "black box", i.e. the user is provided with little information on the nature of relationships between dependent variables and predictors (Francis, 2001). Understanding their specificities is essential in order to use them effectively.

ANN are characterized according to three main features: i) the pattern of connections between the neurons, the so-called net architecture or topology, ii) the method for determining the weights on the connections (i.e. the training or learning algorithm), and iii) its activation function (Fausett, 1994).

i) ANN can be single layer nets, with only one layer of weights (referring to the output layer – inputs do not count as a real layers because they perform no computation); or multilayer nets. These are constituted by input units, output units, and the so-called hidden units, which are interim levels of data processing. Depending on the direction the connections, nets can also be classified as a) feedforward nets, where signals flow from the input units to the output units, or b) recurrent nets, where there are closed-loop signal paths from a unit back to itself.

ii) Nets can be a) supervised if there is a target output vector or b) non-supervised in the case of self-organizing neural nets that group similar input vectors together without the use of training data.

iii) The activation function refers to the weighted input signal that activates a given neuron. A nonlinear function, like the sigmoid function, is typically applied (Dougherty, 1995).

The definition of the net topology is an important task. Using too many can cells and layers may overfit the net, while picking too few can reduce the network's ability to map the target outputs – leading to greater errors (Cohen and Krarti, 1995). Kalogirou (2006) advocates that the number of neurons in the hidden layer should be approximately the average of the inputs and outputs. However, this is also dependent on the number of training cases. It is not unusual to find in the literature that the selection of the net architecture has been done by testing different combinations in an iterative process (Zhang and Wang, 2012). Still, it is agreed that multilayer nets are typically more difficult to train than single layer ones. Choosing between different types of ANN depends on several aspects, namely, the goal of the analysis, or the accuracy needed. It may not be a straightforward choice and so, different experiments on topologies, learning algorithms and activation functions are encouraged before relying on one solution.

A feedforward neural net with a one hidden layer (Figure 21) is claimed to be a universal function approximator, able to deal with a large range of problems (Francis, 2001). These nets ground on three stages: a feedforward of the input training pattern, the computation and propagation of the error, and the adjustment of the weights. Considering that the output of neuron j is given by the following general expression:

$$y_j = f_j\ (net_j)$$

(Equation 3)

, where f_j is the activation function of neuron *j* and net_j is the weighted input of neuron *j*.

The net input to neuron *j* is given by:

$$net_j = \ b_j + \sum\nolimits_i x_i\, w_{ij}$$

(Equation 4)

, where b_j is the bias of neuron *j*, x_i is the i^th input vector connected to neuron *j* through the weight matrix *W* = $\{w_{ij}\}$.

The Levenberg-Marquardt algorithm has been many times referred as a very simple, but robust method for approximating a function. This algorithm searches for the model parameters that minimize the sum of the squares of the deviations. This is usually given by the mean squared error (MSE), which is used to evaluate the training process, and for all training patterns and network outputs, it is given by:

$$MSE(x, w) = \frac{1}{2}\sum_{p=1}^{P}\sum\nolimits_{m=1}^{M} e_{p,m}^2$$

(Equation 5)

,where x is the input vector and w is the weight vector. $e_{p,m}$ is the training error at output m when applying pattern p, and is defined as $e_{p,m} = (y_i - \widehat{y_i}\ )$, where $\widehat{y_i}$ is the predicted value of y and y_i is the real value of y.

The update rule for the Levenberg-Marquardt algorithm is given by Yu and Wilamowski (2011) as:

$$w_{k+1} = w_k - \left(J_k^T J_k + \mu I\right)^{-1} J_k e_k$$

(Equation 6)

, where w_k is the weight vector at iteration k, J is Jacobian matrix, I is the identity matrix, μ is a combination coefficient that is always positive, and e is the error vector.

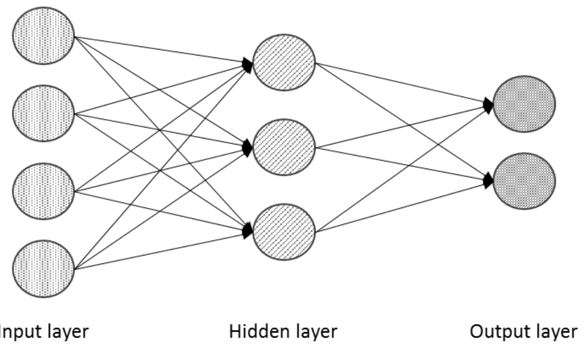

Figure 21. Typical Feedforward Neural Network

ANN seem an interesting modelling option for the research problem described. They enable to deal with a large amount of data, and have been advocated as a very flexible and accurate modelling technique. Applied mathematicians see neural nets as a powerful tool to modelling problems for which the relationships among the variables are not known (Fausett, 1994, pp2), which is the case.

In addition, although machine learning and big data have been on the centre of debate for addressing a variety of problems, it hasn't been used to investigate the effect of urban form on energy demand so far. This will represent a pioneer application to this field. The application of ANN to assessing the influence of a comprehensive set of variables of urban form on energy demand is expected to retrieve different results from the ones obtained from conventional statistical techniques, like the ones presented earlier. In addition, if the relationship between urban form and energy demand is found to be significant, ANN may enable to predict with enough accuracy the energy impact of future urban planning choices.

The application of neural networks is becoming easier with the emergence of specialized software for processing and analysing large amounts of data. The Neural Network Toolbox for Matlab is an option for creating, training and simulating neural nets. Tsui et al. (2006) claim that this is the most complete software package to date. It is an intuitive software add-in for running neural networks.

3.2.5. Knowledge Discovery

The last stage of the methodology is to convert the results of the modelling phase into knowledge. The development of the model has two purposes: i) understanding patterns, and ii) prediction (also called forecasting). The first refers to deepening the understanding of the influence of urban form on energy, and specifically of the urban attributes considered on the thermal energy needs in buildings and mobility. The results from the application of a (or several) modelling technique(s) will enable to retrieve results in the form of weights or coefficients that will be explored. In regard to the second purpose, the model built is context-specific and works as a prediction tool to estimate, from a series of characteristics of the urban environment, the corresponding energy needs of a given urban setting.

There are several techniques that can be used to shed some light on the modelling results. A well-known method is the sensitivity analysis (as applied, for example, by Vartholomaios (2017)), which enables to account for the effect of changes in the values of the urban attributes considered (in specific urban areas or in the whole city), in the overall urban energy performance. Other specific techniques will be presented in the following chapters.

This type of model has a huge potential as a decision-making support tool. It deals with simple metrics computed from data that is generally available from local authorities, and uses a data mining technique with the ability of dealing with large datasets and finding intricate patterns in spatial data. This turns a massive amount of data into structured patterns or rules.

In order to translate the results produced into operational knowledge, it should be interpreted in the light of urban planning and development policies in order to anticipate *how* desired improvements could be achieved, i.e. *which* particular measures could be suitable for attaining more efficient urban development paths.

It is important to note that the goal of this research is not to find an optimal combination regarding the variables of urban form. Caution is needed when prescribing recipes for cities. Instead, by knowing the influence of each variable on energy demand within a specific context, this can turn into an important contribution to the planning practice and policy-making by enabling to account for the energy impacts of urban planning choices in a given urban area.

3.3. Synthesis

This Chapter reviewed the methods for modelling energy in the built environment, concluding that the degree of incorporation of urban form varies significantly among the modelling categories considered. Also, from these three categories, data mining emerged as a promising modelling approach for this research.

Given the above, a new methodological framework for modelling, in a comprehensive way, the relationship between urban form and energy demand has been proposed. Such methodological framework aims at being both exploratory (i.e. characterizing the links between urban form and energy demand) and predictive (i.e. predicting the energy demand for specific end uses, given the local characteristics of urban form).

The methodology is comprehensive in the sense that it entails a large set of urban form indicators, and considers the building and transport sectors at the same time. Also, it is spatially-explicit, allowing to link the data to the territory. With regard to the modelling options, three techniques are considered (MLR, SEM and ANN). Their explanatory and prediction power will be tested and compared resorting to two case studies (Chapter 4 and 5). Its application to two case studies, the cities of Porto and Lisbon, aims at illustrating the applicability of this methodology. These are interesting examples because they represent distinct urban contexts, with different development patterns. The case studies will enable to check both for the coherency of the theoretical model, as well as the feasibility of the methodological framework developed in practice. In addition, they will enable to draw conclusions on the role of urban form on the energy demand of two specific and distinct urban areas.

CHAPTER 4. METHODOLOGICAL APPLICATION TO THE CASE STUDY OF PORTO

The methodological framework proposed in Chapter 3 will be applied to two case studies in Portugal. Its application aims at testing the coherency of the theoretical model, as well as checking the applicability and validating the feasibility of the methodology itself.

The selection of the cases studies was based on several criteria. The first was the consideration of Portuguese cities only. As this is a pioneer application of the methodological framework, which has a large territorial emphasis, it was considered important the existence of some level of previous knowledge on the cities at stake, so that the results from the spatial analysis and the modelling stages could be interpreted in the light of the existing background information. The second criterion was the size of the cities to be considered. Small cities would imply having a reduced sample of spatial units to build the model, and very large cities would probably add unnecessary computational load. Since Portugal does not have large metropolises (compared with the European context), medium-sized cities are just suitable for analysis.

Finally, the last criterion, was the choice of cities with some degree of urban maturity, i.e. cities that have been subject to transformation processes, shaping its physical form over time, allowing for the existence of a variety of urban tissues and urban environments. In addition, since two case studies will be analysed, the two cities selected should differ as possible in terms of socioeconomic aspects and urban profiles. Given the Portuguese context, the cities of Porto and Lisbon emerge as natural choices, as they fulfil all the criteria referred to above.

This Chapter is structured as follows. Section 4.1 provides a description of the case study, considering both territorial aspects and the patterns of energy use in the city. Section 4.2 presents the methodological application to the case study, whereas Section 4.3 discusses the results obtained.

4.1. Case study description

The city of Porto is located in the north of Portugal, being its second most important city following the capital, Lisbon. During the 70s and the 80s, the city experienced an expansion of the third sector, while a trend of population decrease since the 80s has been felt mainly in the city centre, until the current days (Figure 22). Nowadays, Porto has roughly 215 thousand residents, while its metropolitan area has about 1.76 million inhabitants. During the recent decades, the peripheral municipalities have been able to attract residents due to more affordable housing prices and the simultaneous establishment of business and services. The unemployment rate of Porto municipality has steadily increased since the 80s until 2011 (the last census) from *ca*. 7.3% to 17.6%, respectively. It is expected that it may decrease in the next years, as the country recovers from a financial crisis.

In the last years, the city has been the stage of a revitalization process, in a large extent promoted by private capital, and which has been attracting strong touristic flows. The city centre has shifted from an area with decaying and abandoned buildings, to a fashionable district with a high demand for lodging, especially short-term and oriented to tourism, with significant increases in housing prices. Despite some inhabitants are relocating to central urban areas, the pricier housing supply may still be discouraging permanent settlements, visible from the steeper curve in Figure 22, since the 2010's. This may be the beginning of a gentrification process.

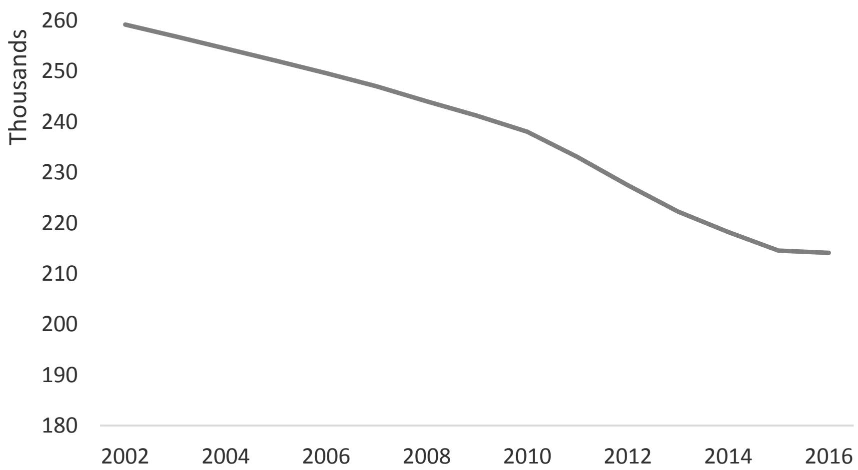

Figure 22. Evolution of resident population 2002-2016. Porto.
Source: INE (2017)

The characterization of land uses in the city of Porto is comprised in its masterplan, the so-called PDM – Plano Director Municipal. It was ratified in 2006 (Câmara Municipal do Porto, 2006a) and revised in 2012 with minor changes (Município do Porto, 2012). This regulatory document considers ten types of uses (Table 7), which are depicted in Figure 23. These include, for instance, historical areas (in brown), areas of continuous building frontages and largely replete plots (in dark red), areas of continuous building frontages in the process of repletion (in orange), detached housing areas (in dark yellow), and areas of isolated buildings (in light yellow). The green areas are broadly represented in several tones of green, and other colours are applied for the different types of existing and proposed areas of public services.

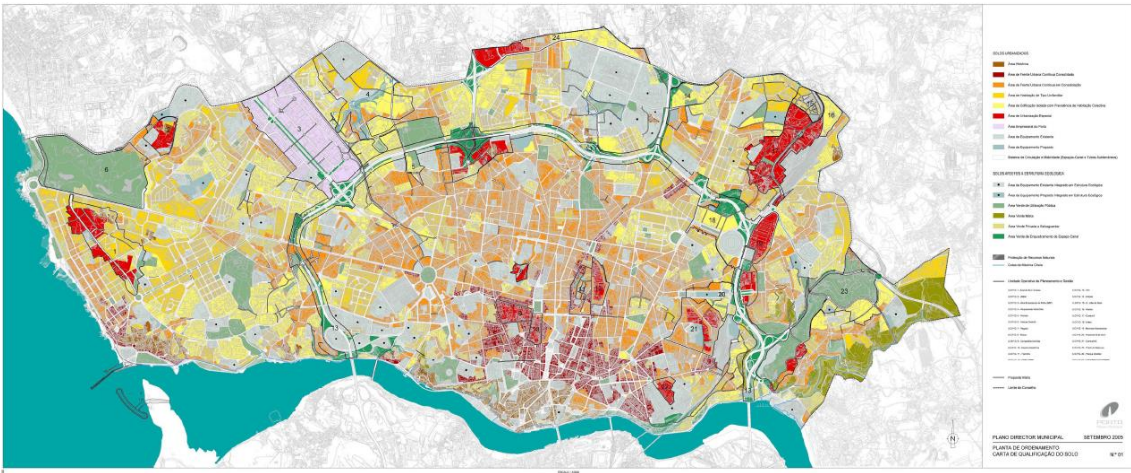

Figure 23. Porto Master Plan
Source: Câmara Municipal do Porto (2006b)

The masterplan entails a detailed spatial classification of the land uses in the city. This is typically done at the block level, sometimes including different land use types in the same block. The classification of the ten land use types in the PDM is dominantly based on morphological criteria, and not so much focused on the urban functions. Table 7 highlights the proportion of the existing land uses in the city of Porto.

Table 7. Land uses considered in the Porto Master Plan

Land use type	**Area (ha)**	**Percentage %**
Historic Areas	72	2
Continuous Building Frontages and Largely Replete Plots	144	3
Continuous Building Frontages and Plots in the process of repletion	734	18
Single Family Housing	426	10
Areas of Isolated Buildings	558	14
Business Park	79	2
Special Urban Development Areas	131	3
Areas of Public Services	574	14
Green Areas	564	14
Transport Areas	847	21
Total	**4129**	**100**

Considering energy use, some key documents have been produced aiming at characterizing the existing patterns, as part of the municipality's commitment as a signatory of the Covenant of Mayors – signatory members must meet and surpass European Union's goals by 2020 on energy efficiency, use of renewables and cut of GHG emissions (Covenant of Mayors). The energy matrix of Porto describes the energy use considering its sources, vectors, sectors and end uses. Figure 24 depicts such patterns in a Sankey diagram, with reference to the year 2009.

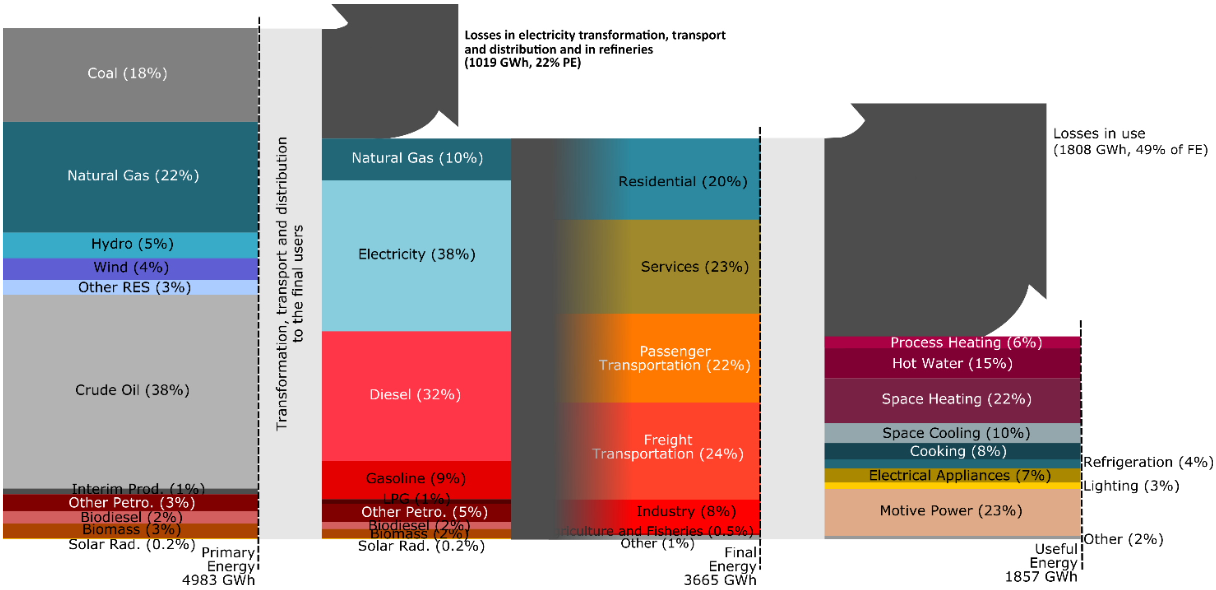

Figure 24. Sankey diagram of the energy use patterns in Porto (2009).

Considering the energy sources, it is evident the weight of fossil sources in the primary energy mix. Buildings are the largest energy users, accounting for a share of 24% and 29% of primary energy, for households and services, respectively (and 20% and 23% of final energy). Transports account for roughly 37% of primary energy (whereas considering final energy, the positions change with the transportation share increasing to 46% of final energy).

It is visible the dominance of electricity (38%) as final energy carrier. In buildings, electricity use escalates to 70% in residential and 80% non-residential buildings. In the transport sector, not surprisingly, gasoline and diesel are the main energy carriers (with 23% and 77%, respectively). In this respect, passenger transport accounts for 22% of final energy use, while freight uses 24% of final energy (Figure 24). With regard to the end uses, in residential buildings, ambient heating amounts to 20% of final energy use, whereas cooling represents about 1%. With regard to transports, about 55% of final energy is used by light-duty road vehicles, from which roughly 74% correspond to passenger trips and 26% to freight. Public transport accounts for 7% of the final energy used within the transport sector.

Considering useful energy, thermal uses hold the largest share. In residential buildings, domestic hot water corresponds to 15%, cooking to 8%, space heating to 22% and space cooling to 10% (Figure 24). Also considering useful energy, the motive power (mostly for mobility purposes) holds the largest share of energy use, with 23% (Leal et al., 2012).

4.2. Data and Methods

4.2.1. Database preparation

For the database preparation three main types of data were gathered: spatial data, statistical data, and official and technical data on energy demand.

4.2.1.1. Spatial Data

The spatial data for Porto was mostly obtained from the local authority (CMP – *Câmara Municipal do Porto*) that made available the following elements:

- The Municipal Master Plan – the so-called PDM (2006), with the corresponding classification of land uses
- Buildings' footprints (2007)
- The street network (2007)
- Green areas (2006) – retrieved from the PDM
- The public transport infrastructure – lines and stations (last update from 2012)

Although the data available is not up to date, it is considered that, overall, the changes in the urban form of the case study until the current days are very small compared to the size of the existing database, and thus this is not expected to compromise the work to be developed. In addition, the spatial units to be considered for the analysis were obtained in vector format from the National Statistics Office (INE – *Instituto Nacional de Estatística*). These features are encoded in such a way that it enables to join statistical data (from the same source) through a common ID field. These spatial units correspond to the lowest level of disaggregation of the statistical data available from the last Census (2011), which have a relatively homogeneous physical structure, the so-called statistical subsection / *subsecção estatística*. They are defined as follows:

> A *statistical subsection* is a "territorial unit that identifies the smallest homogenous construction or unbuilt area, existing within the *statistical section* (unit of analysis immediately above). In urban areas it corresponds to a block, in rural areas to the *place* or part of the *place,* or it may correspond to residual areas that may or may not contain statistical units (isolated)"
>
> *(Translated from INE[6])*

These spatial units are deemed to be a suitable scale for the analysis because they correspond to the urban block, and allow assuming that morphologic characteristics are relatively homogeneous within each spatial unit. As a consequence, it is expected that the influence of urban form on energy demand, may be captured by the existing morphologic variations among the different spatial units, which, in turn, would lead to certain degree of variation on the energy demand of the urban blocks. Overall, for the municipality of Porto there are 1946 spatial units (statistical subsections).

[6] http://censos.ine.pt/xportal/xmain?xpid=CENSOS&xpgid=censos_base_cartogr

4.2.1.2. Statistical Data

The statistical data was obtained from INE, allowing to subsequently matching it to the corresponding vector features in the GIS. INE makes available statistical data for the whole country, and it is a reliable source of statistics in Portugal. The relevant data to be analysed includes mainly characteristics of the built environment (Table 8).

Table 8. Statistical variables linked to the spatial units considered

Domain	Variable description
Building function	# of exclusively residential buildings # of dominantly residential building # of dominantly non-residential buildings
Building height	# of buildings with 1-2 floors # of buildings with 3-4 floors # of buildings with 5+ floors
Building age	# of buildings built before 1919 # of buildings built between 1919-1945 # of buildings built between 1946-1960 # of buildings built between 1961-1970 # of buildings built between 1971-1980 # of buildings built between 1981-1990 # of buildings built between 1991-1995 # of buildings built between 1996-2000 # of buildings built between 2001-2005 # of buildings built between 2006-2011
Population	# of permanent residents

4.2.1.3. Energy Data

In regard to energy demand, it is required to access data both concerning buildings (heating and cooling) and mobility. This is the most difficult type of data to get access to from the three types of data needed, particularly for transports. Local transport authorities are strongly encouraged to collect and make available mobility data for monitoring and assessing the transport patterns at urban level.

As described in Chapter 3, the use of “real” data, from official sources that measure or estimate energy demand at a disaggregated level, was preferred over artificial data, obtained from specific simulation models, with varying complexity degree. A preliminary search for information available online was performed – initially for the two selected case studies, and then for all the main Portuguese cities in the first level administrative subdivision of Portugal mainland (*Capitais de Distrito*). The review included entities like the National Statistics Office (INE – *Instituto Nacional de Estatística*), the General Division on Energy and Geology (DGEG – *Direção Geral de Energia e Geologia*), the national electrical utility with the largest market share (EDP – *Energias de Portugal*) and the webpages of the 18 *Capitais de Distrito* (detailed in Annex II). Although the data wished for was georeferenced information on energy demand (at least at the level of the urban block) in vector format, other formats could also be accepted like excel or access database files. In regard to transports, the data sought included traffic flows or the related fuel/ energy use per transport network edge, or an origin and destination (O/D) matrix with the trip generation for the urban block. However, no trace of data meeting these requirements was found. The lowest level of detail for the data available was often the municipality as a whole, or the parish. This process was repeated for European cities, in order to check for the need of broadening the geographical scope of the case studies. However, it was almost as difficult to obtain the data desired. Although the European Environmental Agency has recent vector data for all European cities – part of the Urban Atlas – no georeferenced data on energy was found. Some cities (e.g. Berlin) have relevant data, especially concerning the energy demand of urban districts, and some annual average daily traffic (AADT) flows for a few primary street edges, however, most of this data is not readily available for download. Some contacts were made in view of requesting such information, none resulted successfully.

Finally, after a few institutional contacts, the National Energy Agency (ADENE – *Agência para a Energia*), responsible for enforcing the building certification scheme in Portugal, made available the corresponding database for the two case studies selected, Porto and Lisbon. This database largely met the data requirements of this research. The energy certification scheme provides as estimation of the thermal energy needs of buildings (instead of the effective energy consumption), which has been advocated in the literature to be more appropriate for studies on the urban form-energy link. In regard to mobility, since there weren't available databases with "real" data, artificial data was considered. Mobility data was retrieved from the best available transport models for each case study. A more detailed description of the data obtained for buildings and mobility is provided below.

4.2.1.3.1. Built environment

The data used for characterizing the energy demand of the built environment corresponded to the nominal useful energy needs for heating and cooling, according to the Portuguese building certification scheme.

The existing data actually concerns two separate databases, each corresponding to a different regulation establishing the framework for building certification. The first database was built under the framework of the EPBD – Energy Performance of Buildings Directive (Directive 2002/91/EC), first published in 2002 and transposed into the national legislation in 2006 (Decree-Law 78/2006 of April, 4th, 2006 on the National Energy and Indoor Air Quality Certification System for Buildings; Decree-Law 79/2006 of April, 4th, 2006, regulating acclimatization systems in buildings; and Decree-Law 80/2006 of April, 4th, 2006, regulating the thermal behaviour of buildings). The second database follows the transposition of the EPBD-recast (EC - European Commission, 2010a) to the Portuguese regulatory system (Decree-Law 118/2013 of August, 20th, 2013, updated by the

Decree-Law 68A/2015 of April, 30th, 2015), and subsequently by the Decree-Law 194/2015 of September, 14th, 2015).

In order to extract relevant information, no pre-certificates were considered, nor were building projects (only effectively built structures were extracted). Also, only residential buildings were considered, since non-residential buildings are more complex and have a larger set of drivers influencing their energy needs (as described in Chapter 2).

After selecting the relevant data from both databases, the format of the coordinate system was made uniform (transformed into decimal degrees format) in order to be imported to the GIS. From an original sample of nearly 18.000 certificates made available by ADENE, roughly 12.500 were used, as they had valid entries and were properly georeferenced. Further stages of analysis were developed in the GIS and correspond to the spatial analysis described below.

Still, it is worth noting that there are significant differences on the method for calculating the energy needs between the two different regulations. The methodological differences affect the corresponding energy needs mainly due to the fact that in the first regulatory framework the temperature set point (indoor comfort temperature) was 20 ºC, and in the second regulation the set point was 18ºC.

In order to make the two databases comparable, the database corresponding to the former regulation was converted into the new one. The sample was large enough to provide insights on the average energy needs in the two cases. For this, the conversion factor considered was the ratio between the average needs for later regulation (SCE2) and for the former (SCE1) - SCE2/SCE1 both for heating (N_{IC}) and cooling (N_{VC}). This was performed for each construction period, in order to ensure that the differences would be due to the calculation method, instead of efficiency improvements in time. The results of such a conversion are in line with Moreira (2014) and are depicted in Figure 25 and Figure 26.

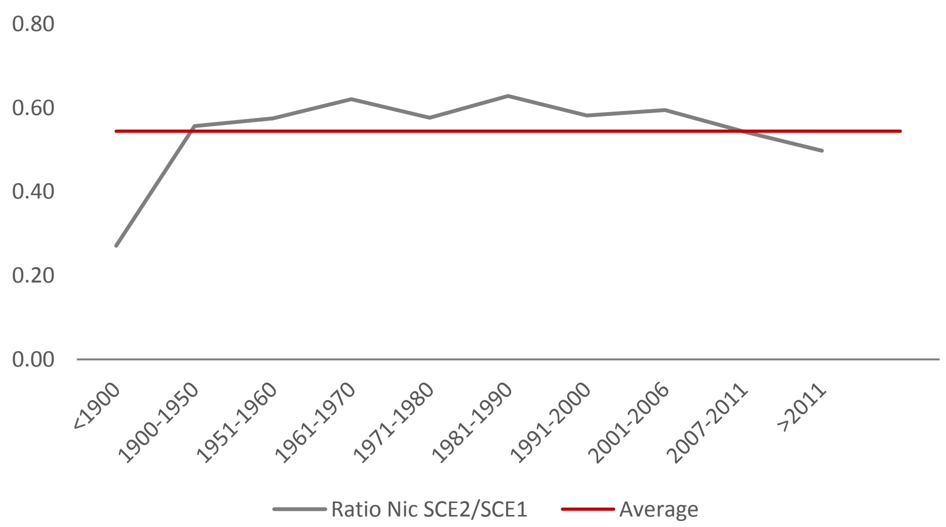

Figure 25. Ratio between the average nominal energy needs for heating of the second regulation (2013) and the first one (2006). Porto.

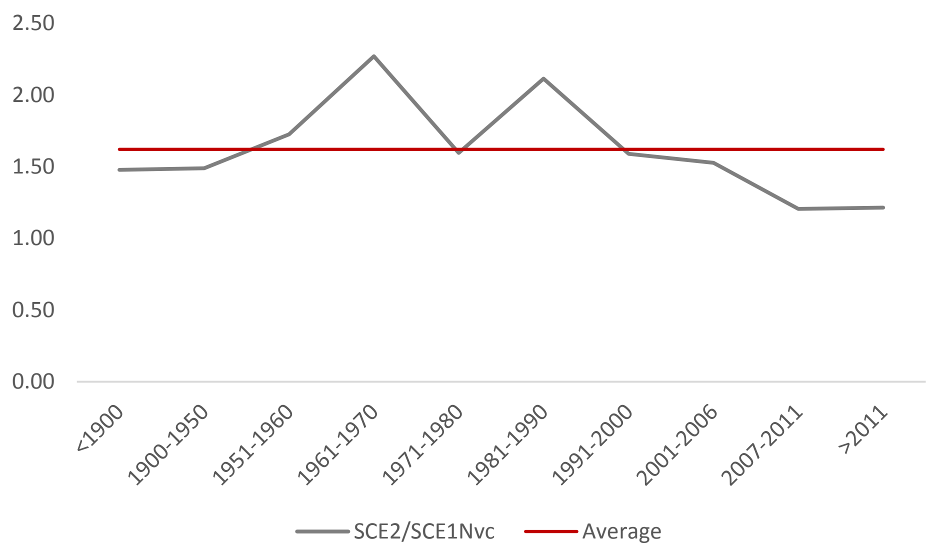

Figure 26. Ratio between the average nominal energy needs for cooling of the second regulation (2013) and the first one (2006). Porto.

While the heating needs decreased from SCE1 to SCE2 (set point varied from 20ºC to 18 ºC), the needs for cooling increased. While the needs for heating are quite constant (except for the first construction period, that was also less represented), with a decrease after 2006 – the enforcement of the first regulation of building energy performance, the needs for cooling vary more widely, but also present a reduction after this period.

4.2.1.3.2. Urban Networks

The mobility patterns considered in this approach include only private motorized vehicles for passenger transport. There are three fundamental reasons why public transports (PT) were not included in this analysis: the first is that the use of PT is expected to be predominantly influenced by the characteristics and location of the public transport infrastructure itself, which is relatively "fixed". It has been claimed that urban form primarily influences auto trips and walking, while the effect on the trips made by public transport is less important (Ewing and Cervero, 2010). The second reason is the fact that public transports currently hold a reduced share of energy use for mobility purposes. Finally, the last reason has a more practical nature. The data available regarding the use of public transport in the city was very limited, and it was not available in the format desired (it was not georeferenced and didn't have enough spatial disaggregation). The existing data consisted of the number of validations at each metro station (there was no data on trip destinations, and the validations were not distinguished into trip origins and line changes). Also, it was not possible to obtain data for the trips by public bus. Since the spatial coverage of the metro stations in the municipality is quite limited (i.e. the territory is not equally served by the metro and there aren't many metro stations in the city), it would be impractical to allocate this data to the scale of analysis considered for the whole city.

In addition, freight is left out of the analysis for the same reason that non-residential buildings were not considered for characterizing the energy needs of the built environment. Freight has more complex factors determining the corresponding fuel / energy demand (notably the nature of the freight business), where urban form is not expected to play a relevant role. Also, freight is not typically an urban energy use, as it often takes place at a larger scale than the city (e.g. metropolitan, regional, national…).

Considering private vehicles, there was no official information on traffic flows for the city of Porto at the level of detail desired. The alternative was to use a traffic assignment model calibrated for the case study under analysis, and which has been adopted in official publications to characterize the traffic flows in the city (CMP, 2007). SATURN is a well-established traffic assignment model (Van Vliet, 1982), that has been calibrated for the road network of Porto, based on traffic counts (year 2005), by an expert team at the University of Porto. This model has also been used to support technical studies ordered by the local municipality. The application of such a model enables to get a picture of traffic flows in the city with a quite good definition. Several street edges are characterized with traffic flows (in pcu – private car units) on both ways, and an O/D matrix with nearly ninety traffic zones within the city is also available (still, traffic zones are larger than the spatial units for the analysis).

Since the traffic flows are allocated to network edges, it would probably be more challenging to use this data for the characterization of the spatial units, as their boundaries coincide with the network edges. Instead, an O/D matrix, with 87 traffic zones within the city, and 22 outside the city's boundaries has been imported to the GIS. These were downscaled into the spatial units considered, by applying a population ratio-based normalization to estimate the annual average daily traffic (AADT) flows. One important characteristic of the traffic zones of this transport model is the fact that their boundaries coincide with major streets in the city, and coinciding also with the boundaries of the spatial units under analysis (the urban block). This allowed for a straightforward and quite accurate downscaling process. The specific operations performed in the GIS are described in the following section.

4.2.2. Spatial Analysis

The Spatial Analysis refers to the process of measuring the indicators and metrics of urban form according to Table 4 (Chapter 2). These were measured resorting to a geographic information system (GIS) in order to build a dataset of urban form indicators attached to the physical characteristics of the territory, i.e. a geospatial dataset. The software used was the ArcGIS 10.1.

Before the analysis, some "atypical" spatial units, such as public and green spaces, were removed. Although green areas are used to measure specific indicators, the urban blocks occupied only by green and public spaces are later removed, as they will not enter the model. In addition, some previous operations are required, to ensure the usability and coherence of the spatial data. Examples include, for instance, removing building annexes (buildings with a footprint lower than 20 square meters, and manual deletion), removing buildings located on top of the street network, and network nodes that were not effectively connected.

Although the results of this methodological stage have a numeric dimension, and will serve as inputs for the modelling stage, it is more insightful to provide the reader with the results displayed in a map, taking advantage of adopting of a spatially-explicit method. As such, a map is produced for each indicator, varying in an appropriate range of intervals for visual analysis. The following topics present the maps produced for each indicator, the procedure, and the rationale adopted for measuring them. This is done for each indicator belonging to the two focus areas: the built environment and urban networks. The results obtained are discussed as well, wherein some specific areas of the case study may be referred. For additional insights on the location of areas mentioned in the interpretation of the maps, please see Annex III.

4.2.2.1. Built environment

4.2.2.1.1. Density

Density is measured through three different indicators after Pont and Haupt (2005): the ground space index (GSI) – often called compactness, the floor space index (FSI) – also called intensity and, building height – number of floors (F).

<u>Ground Space Index (GSI)</u>

The GSI (Figure 27) is computed as the ratio between building coverage and the total ground area of an urban block. For this, two layers of analysis are needed, one with the spatial units and another layer with the buildings. The corresponding areas are automatically calculated in the GIS. In order to compute the ratio, it is necessary to sum the area of building footprint located within the boundaries of each spatial unit or urban block (through a “spatial join” operation) and divide it by the area of the corresponding urban block.

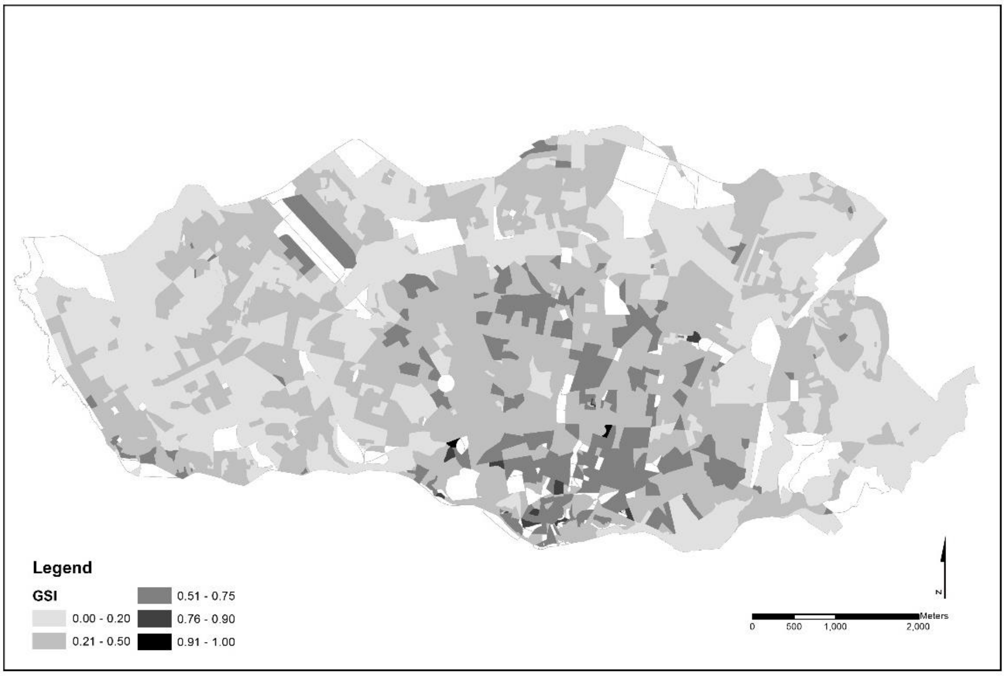

Figure 27. Density, Ground Space Index. Porto

Overall, Porto is not a dense city (considering European standards and even the Portuguese capital, Lisbon). Nevertheless, denser areas are located in the city centre, where largely more than half of the block area is built-up. Besides the city centre, denser areas are located around key streets such as *Rua da Constituição*, or some small old blocks in the western part of the city. These are also visible in blocks nearby the city's industrial / business district. White areas in the map represent blocks without buildings, such as parks, squares, rotundas, or alternatively, areas designated in the PDM as urban equipment (e.g. a football stadium), which will not be considered in the analysis.

<u>Floor Space Index (FSI)</u>

The FSI (Figure 28) is computed similarly to the GSI, through the ratio between the building gross floor area (GFA) and the total ground area of the urban block. The procedure for the FSI requires the same layers as for GSI. The product of the building footprint by the average number of floors provides an approximation of the existing gross floor area. Afterwards, the sum of the GFA in each block is divided by the total ground area of the corresponding block.

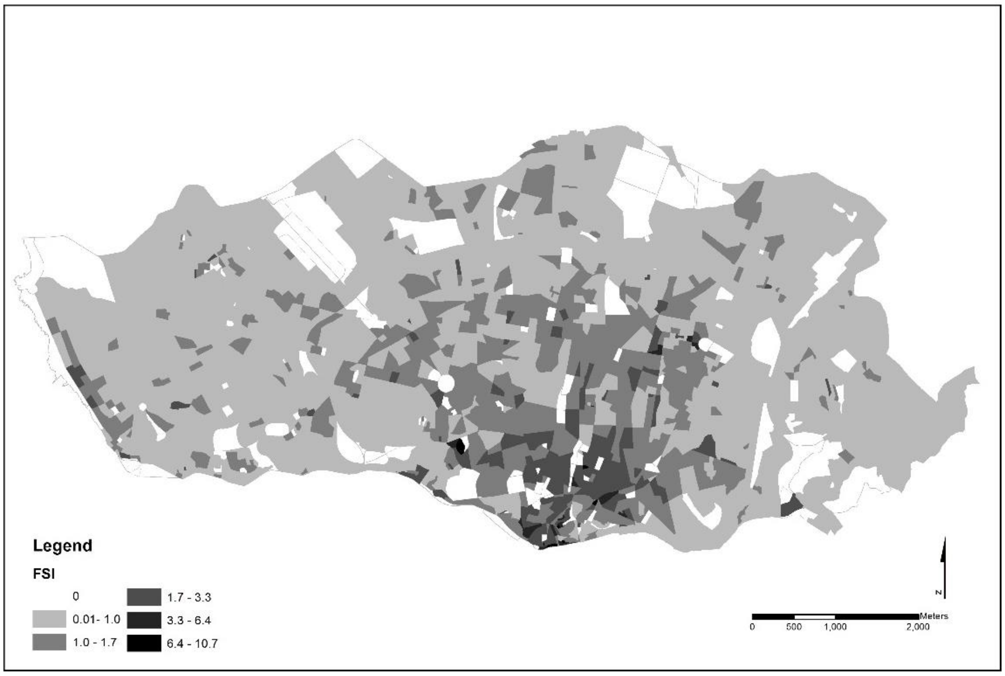

Figure 28. Density, Floor Space Index. Porto

More than the GSI, the FSI reveals the dominant character of the city centre in terms of denser built-up mass. The FSI combines the effect of height with the effect of degree of clusteredness of buildings. As such, from this map, it is not evident whether higher densities are due to higher buildings. The answer will be provided by the next indicator (building height). Higher levels for this indicator correspond to the type of construction found in the city centre, with attached buildings seldom having more than five storeys.

Building height (F)

The average number of floors was estimated from the statistical data available on the number of floors. The statistical data describe the number of buildings with a number of floors within an interval (as described in Table 8 in the previous section). The approximation was made considering that the average number of floors was the sum of the product of the average height of the interval by the number of buildings of that interval, divided by the total number of buildings in the urban block: $Avg\ number\ of\ floors\ = \frac{\sum_i (bi * Avh\ i)}{\sum_1^i bi}$, where b is the number of buildings in a category interval i, and Avh is the average building height of the interval i.

Although there are more sophisticated approaches using real buildings' heights / Digital Elevation Models (e.g. Tenedório et al., 2013), these were not pursued for two main reasons. The first is related to the scale of analysis being the urban block (not the building), and so a higher level of detail would have become diluted for the block scale. The second reason is that the spatial data on buildings heights was quite noisy (sometimes difference between ceiling and ground was negative), and hence considered not to be a very reliable source.

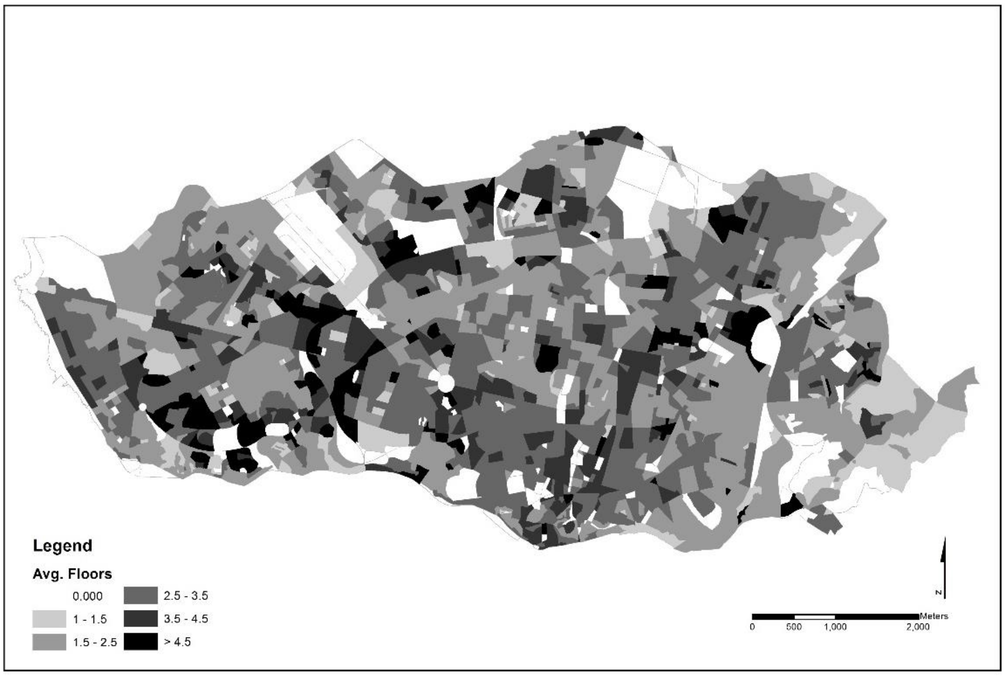

Figure 29. Density, Average building floors. Porto

Figure 29 offers a quite different spatial pattern from the two density indicators depicted above. Whereas the urban core remains quite dense, the highest values of average building height are located mostly in peripheral areas, which have not been considered as dense, given the previous indicators (GSI and FSI). A conspicuous example is, for instance, the *Pasteleira* neighbourhood, and other nearby urban blocks in *Lordelo do Ouro*.

4.2.2.1.2. Granularity

Granularity is measured by the subdivision indicator (Bourdic et al., 2012) and by the size of the blocks, as follows.

<u>Subdivision indicator</u>

The subdivision indicator (Figure 30) is given by the ratio between the number of plots and the area of the block. Although there was no data available on plots/parcels, previous studies support that, in the case of Porto, it is possible to assume that a building typically corresponds to a plot (Oliveira and Silva, 2013b).

Two options were considered for calculating this indicator. One, was to overlay the buildings' layer with the blocks, another was to use the INE statistics on the number of buildings. The latter option was discarded because of a statistical gap on the collection of data regarding the existing buildings. Buildings that are exclusively non-residential are not covered by the census procedure, and thus are not accounted in the existing statistics, which could represent a significant distortion mainly in the areas of the city centre.

Resorting to an overlay operation it is possible to generate a count field in the attribute table of the block layer (referring to the number of buildings within the block), which allows to compute the subdivision indicator, dividing this field by the block area.

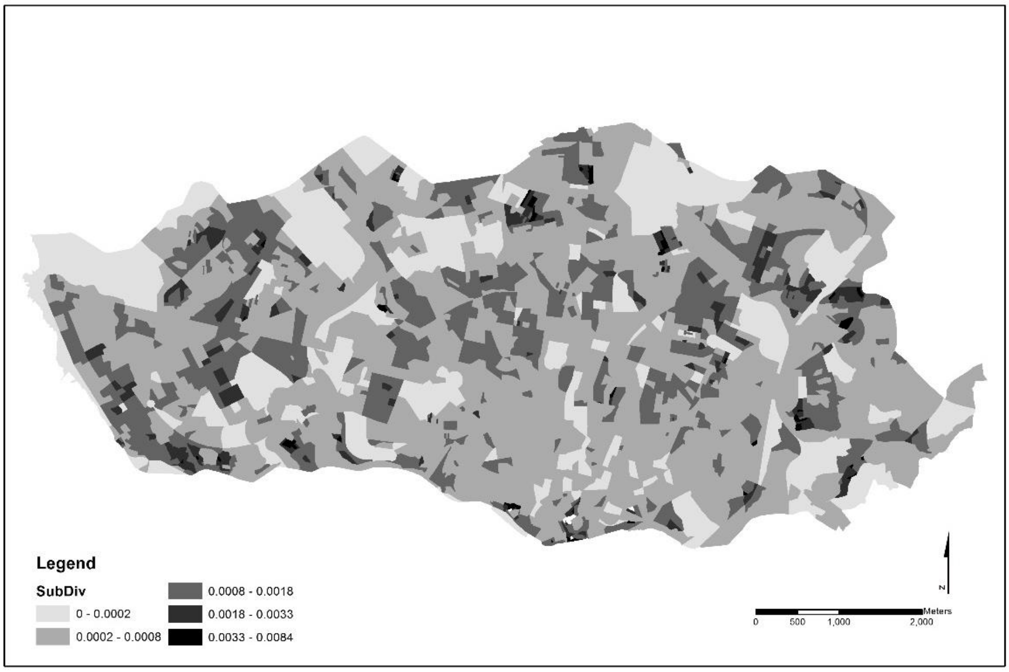

Figure 30. Granularity, Subdivision Indicator. Porto

There is not a clear spatial trend for the subdivision of blocks. Higher values for this indicator are either found in older areas of the city, such as *Foz* (located in the West, in the seaside), or located in specific neighbourhoods with detached and semi-detached buildings, like *Bairro Gomes da Costa*, *Campo Alegre* or *Contumil* (each with a different urban character).

Size of the Blocks

The size of blocks (Figure 31) is very straightforward to measure. The GIS enables to automatically measure the geometry of the features displayed.

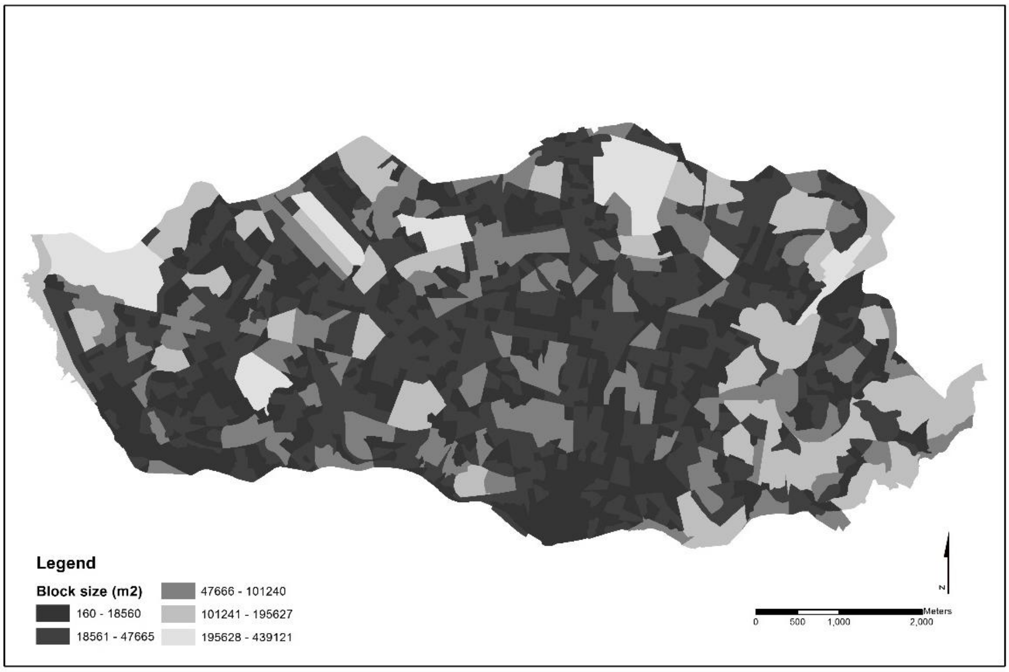

Figure 31. Granularity, Size of the Blocks. Porto

Figure 31 shows that smaller blocks are typically located in the city centre, and other older areas of the city such as *Foz*. Small blocks are also found around key urban axes such as *Rua Costa Cabral* or *Rua da Constituição*, or in neighbourhoods like *Aldoar* or *Gomes da Costa*. The larger blocks are mostly located in the northern and eastern areas of the municipality, which are clearly not as consolidated as the remaining, and typically correspond either to specific land uses, like green areas, the industrial district, and urban equipment, like hospitals or stadiums.

4.2.2.1.3. Diversity

Diversity is measured by the MXI – mixed-use index (van den Hoek, 2008), which considers the ratio between residential gross floor area (GFA) and the total GFA in the urban block (Figure 32).

Similarly to what happened for the estimation of the number of floors, the statistics on urban functions (Table 8) do not exactly match the data needed. Two main issues arise, from the existing data: buildings that are exclusively non-residential are not considered, and there is only information regarding the number of buildings in the different functional categories, making it difficult to allocate gross floor areas to land uses. In order to determine the residential gross floor area (GFA) for the computation of the index, the following assumptions were considered:

- Exclusively residential buildings (EER) – 100% GFA is residential
- Dominantly residential building (DRB) – only one floor is non-residential (typically, the ground floor).
- Dominantly non-residential building (DNRB) – only one floor is residential.

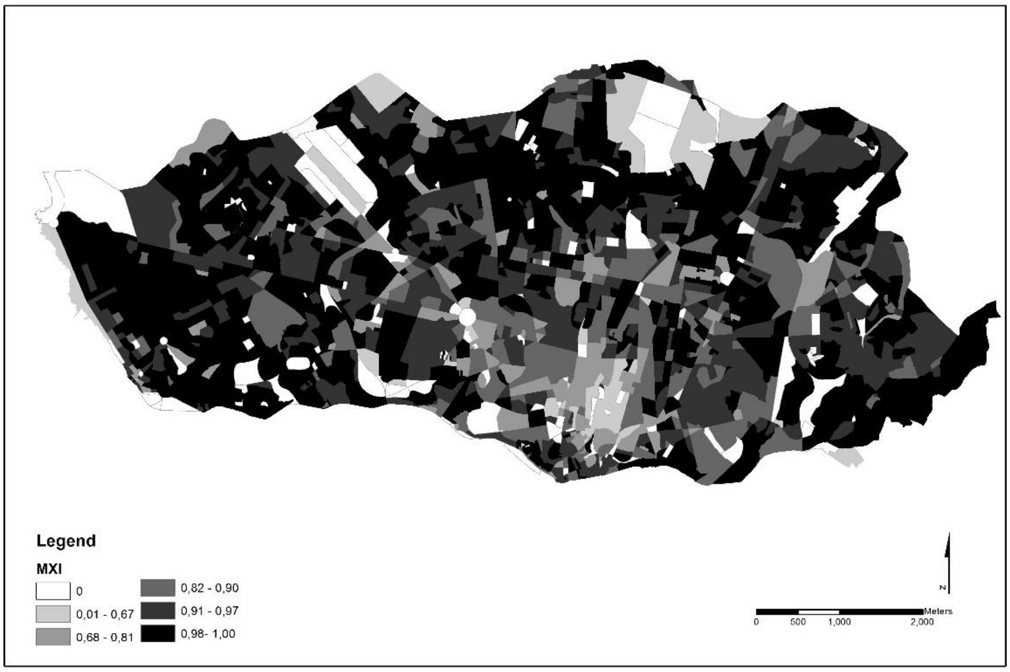

Figure 32. Diversity, MXI. Porto

Higher values for the MXI reveal areas that are dominantly residential (depicted in darker colours). As expected, the downtown (city centre) has lower values, but it is possible to find some other smaller scale polarities, for instance on the second business district around *Rotunda da Boavista*. Blocks depicted in white are either areas without buildings (such as squares), or areas with buildings that are not accounted in the existing statistics (as described above), like an urban block occupied only by a hospital or the industrial district.

4.2.2.1.4. Green areas

The index used to evaluate the existing green areas (Figure 33) was adapted from Bourdic et al. (2012). The data used on the location and size of green areas was retrieved from the local Master Plan. The corresponding land use categories considered in the PDM are:

- Private green areas
- Mixed green areas
- Public Green Areas

Two additional types of green areas, as classified in the PDM (areas for the protection of natural resources and green areas bordering road axes) were left out of the analysis. The first type, aren't necessarily green, as it is the case of coastal and riverside areas. The second type, although these may be green, they are not used by the people, as they are locked in the middle of large and traffic-intensive roads.

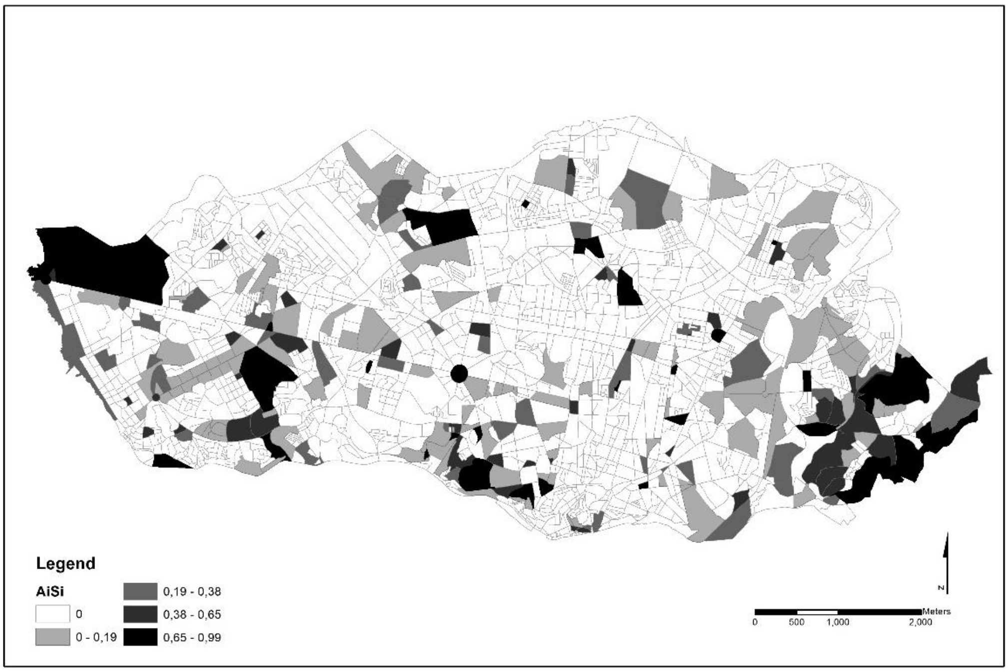

Figure 33. Spatial distribution of green areas. Porto

According to this index, the darker the colour the higher the importance of the green area in relation to the block and to the city. This seems to represent quite well the relative importance of the green areas of Porto. Darker areas such as *Parque da Cidade*, *Palacio de Cristal* or *Quinta do Covelo*, play a significant role in recreational and leisure terms in the municipality.

4.2.2.1.5. Compactness

The building compactness (Figure 34) is characterized by the STV – surface to volume ratio (Ratti et al., 2005). The surface area (S) was determined for each building, as the product of the building perimeter by the average height of the block. Only exposed façades were considered. The volume (V) is computed by the product of the footprint area by the average building height.

In order to transfer this data to block layer, instead of considering the simple average compactness of all the buildings in the block, it was computed the average compactness, weighted by the size of the buildings footprint area of the buildings in the block. This enables to give more importance to larger or attached buildings, as their compactness effect typically affects more households, than small or multi-family buildings (and revealed better results in the modelling phase).

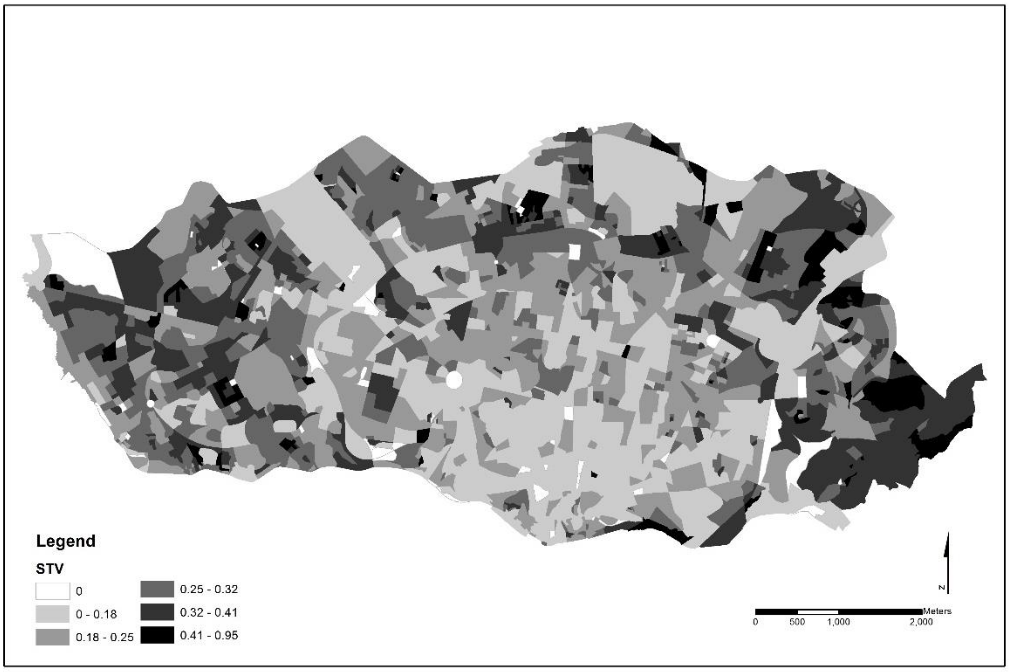

Figure 34. Compactness. Surface to Volume ratio. Porto

Since the compactness indicator is the surface-to-volume ratio, it means that the higher the STV, the lower the building compactness. Higher values of STV are depicted in darker colours. The results are in line with the ones from density, as well as the description of the urban environment of the city from Porto master plan, i.e. areas with higher compactness levels are found in historical and consolidated areas (with attached buildings), whereas areas of isolated buildings, mostly located in the outer urban tissues are visibly less compact.

4.2.2.1.6. Passivity

Passivity is measured by the proportion of passive areas in an urban block, calculated by the ratio between these areas and the total built-up area of the block. The passive areas were identified by buffering the building areas within six meters from the façade. In order to estimate the total passive areas of a building, passive areas were multiplied by the number of floors. Then these areas were summed for the whole block, and divided by the total built-up areas.

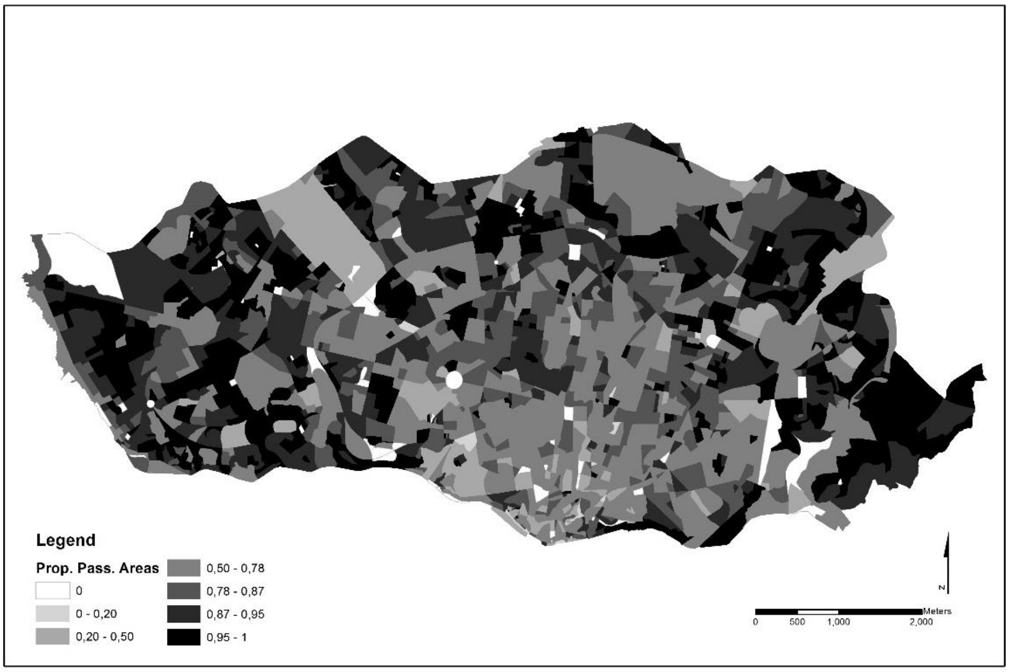

Figure 35. Passivity. Proportion of passive areas. Porto

The map depicts lighter coloured areas as having fewer passive areas. It is interesting to note that this map is quite similar to the one from the compactness indicator, confirming the findings from Ratti et al. (2005) on the link between buildings' compactness and passive areas.

4.2.2.1.7. Shading

Shading is measured for each building façade by the UHA, as the arc tangent of the average height (H) of the opposite buildings divided by the canyon width (Ratti et al., 2005).

This procedure resorted to additional estimations due to the lack of detailed data on street width. A new layer was created, consisting of the space between the boundaries of the urban blocks for each street edge, and street width was approximated by the ratio between the area of the polygon and its length.

The street layer had been previously manipulated in order to include the code of the adjacent statistical blocks for left- and right-hand sides of the street in order to enable importing the corresponding generated data into this layer through a common ID code. Afterwards, the H/W ratio was computed for each street edge facing a block. The UHA is determined through the arc tangent of the previous ratio to get the UHA (in degrees). Finally, in order to get a single measure for the whole block, the average UHA was determined for all urban frontages delimiting a block.

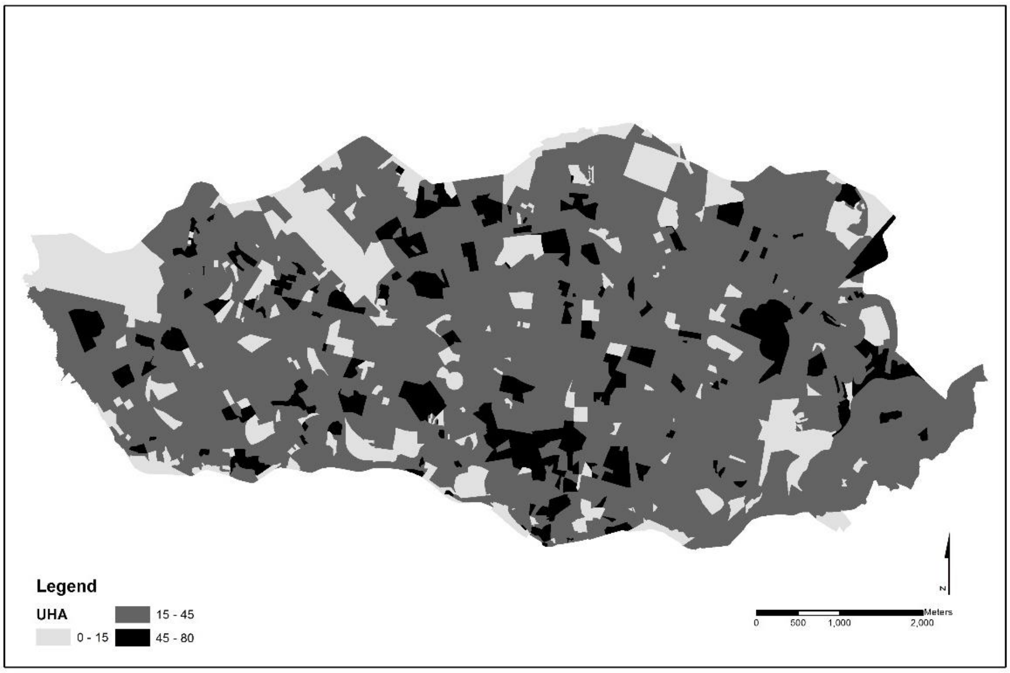

Figure 36. Shading. UHA. Porto

In order to allow for the interpretation of the results obtained, the following ranges were considered (Baker and Steemers, 2000).

< 15º - low obstruction

15º to 45º - moderate obstruction

> 45º - heavy obstruction

Despite some areas with darker colours in the map effectively correspond to areas with narrower streets with higher perceived obstructions, the results obtained were not completely satisfactory, because there isn't much discrimination throughout the city. If fact, buildings with over 5 floors are not very common, and so the existing variations correspond to low to moderate obstructions. Another explanation may be the fact that this is an indicator originally proposed for a single building that was adapted to the block scale, as an average of the UHA of its street edges. As it is difficult to retrieve enough insight from the map produced, it is not deemed feasible to be considered for the modelling stage.

4.2.2.1.8. Orientation

Orientation was measured for exposed façades only. Building polygons were converted to lines, and the azimuth of each line was determined through the *EasyCalculate* add-inn. In order to transfer this data to the block level, it was needed a way to get to a single value for each unit of analysis. Two approaches were tested:

- The average deviation of the orientation of each façade from an optimal solution, i.e., degrees from south, weighted by the façade length.

- The percentage of façade length facing angles from east to west (including south), i.e. the ratio between total façade length E-W and the total façade length of whole urban block.

As the first option didn't retrieve enough discrimination through the territory, the second approach enabled to get a better picture of urban bocks with better orientations, in relation to those with a significant percentage of façade length facing north (worse cases).

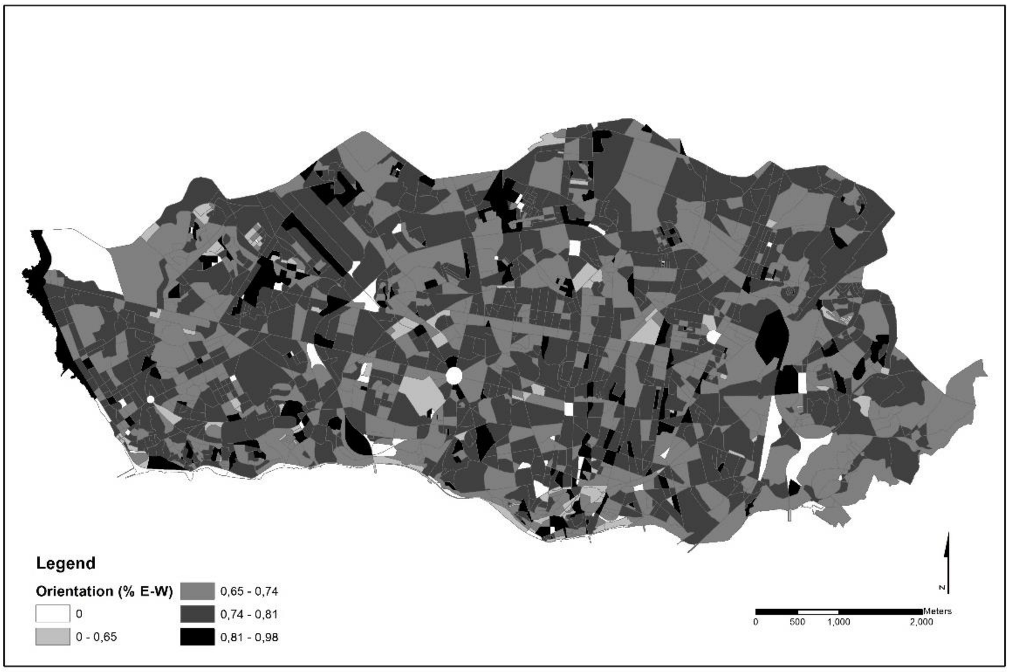

Figure 37. Orientation. Percentage of façade length facing east, south and west. Porto

The map depicts the percentage of façade length facing orientation angles from east to west (including south). Darker areas have better orientations overall, i.e. ranging between east, south and west. Although it is possible to identify some blocks with preferred building orientations, note that the discrimination begins at a percentage higher than 65%. In this case, an urban block includes all different orientations in quite similar proportions. It is not evident whether the existing differences at this scale, are enough to influence the thermal performance of the different urban blocks. In addition, and conversely to the remaining indicators, orientation does not translate into any slight spatial trend, and the results do not reflect the existing urban tissues in the city. For these reasons, and in spite of its relevance for the thermal performance of a single building or building fraction, this indicator will not be considered for the modelling phase, as it is not properly captured at the scale of the analysis. Aggregating orientation data for an urban block seems to imply losing the sense of its application.

4.2.2.2. Urban Networks

In order to measure urban network indicators, some preliminary operations were performed. The ID code of the adjacent blocks for left- and right-hand sides of a street were attributed to each street edge, which enables to import data to the block layer through a table join. Additionally, as some indicators need to run the street network as a network dataset, it was important to check for and to fix network connectivity problems.

4.2.2.2.1. Connectivity

Connectivity was measured through the Beta index (β), giving the average number of edges (e) per node (n) in a given network. The process for the analysis is described as follows. The layer corresponding to the street network (lines), is converted to points, i.e. points are created in the place of the network junctions/nodes. A manual correction was performed in order to delete dead ends, and false nodes arising from design problems of the street network cartography.

Afterwards, the point layer is overlaid onto the streets in order to count the number of street edges linked to each node. Each street edge has two nodes (or one if it is a dead end). In order to get a connectivity value for the street edge, it was computed the average of the connectivity of the two nodes delimiting the edge. In the end, each block has an average beta for the streets delimiting its boundaries.

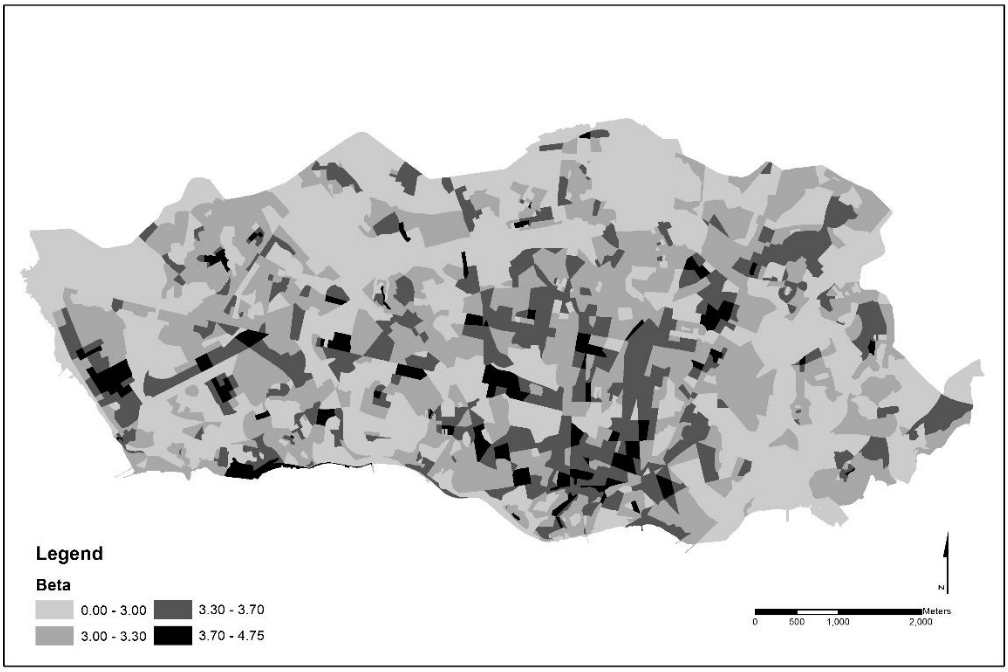

Figure 38. Connectivity. Beta Index. Porto

Figure 38 evidences that blocks in the city centre are typically better connected, as well as those in the area of *Foz* (typically with a grid-like network), and in neighbourhoods like *Gomes da Costa*, or those around *Praça Francisco Sá Carneiro.* There seems to be a link between the values obtained for the connectivity indicator and the type of road network, with areas with a grid-like network usually presenting higher beta values. A visual analysis allows identifying, through common sense and local knowledge some degree of relationship between this indicator and the traffic flows in the city.

4.2.2.2.2. Accessibility

Two indicators are considered for measuring accessibility: the *DivAct* and *Reach*.

<u>DivAct</u>

The Divact index has been previously applied to the city of Porto by Silva (2013). The author made available the data for this indicator, and thus there was no need to compute it from scratch. In any case, this could have been done resorting to information on the location of activities and housing in the city, and the existing transport networks for each travel mode (car, public transport and walking).

The DivAct index for private vehicles will not be considered because it does not provide much insight. All the city territory is accessible by car, with DivAct_car values very close to 1 in most of the urban blocks. The DivAct for public transport (DivAct_PT), offers a better spatial differentiation, but it is still visible that most of the municipality has a high accessibility by public transports (Figure 39). In this case, the time impedance considered for travelling by public transport is twenty minutes. Finally, the pedestrian DivAct (DivAct_Ped) truly provides a sense of local accessibility. The time impedance for calculating the pedestrian index is a ten-minute walking reach.

The pedestrian DivAct is expected to be inversely related to the need of using private motorized vehicles (PMV). Areas with lower values for this index, where walking becomes unfeasible to reach a certain number of activities, are expected to have higher PMV trips.

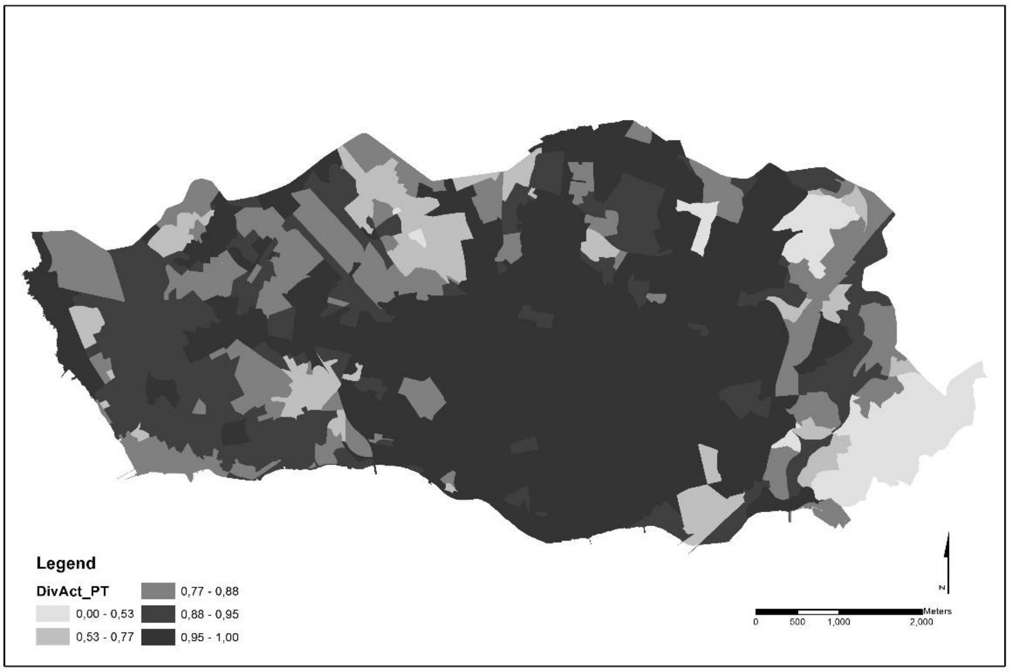

Figure 39. Accessibility. Public Transport DivAct. Porto

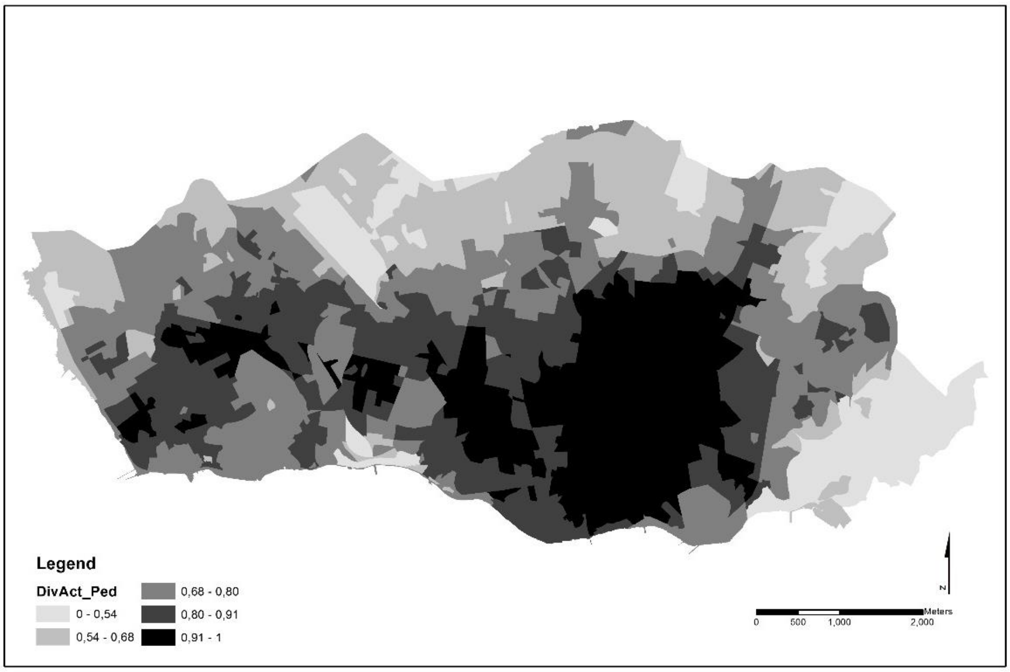

Figure 40. Accessibility. Pedestrian DivAct. Porto

Figure 40 depicts the pedestrian DivAct. Darker colours represent areas where walking enables reaching a larger number of urban activities within a given time budget. It is evident the strong accessibility of the urban core, together with other areas that have a good provision of commerce and services along key urban arteries, notably *Boavista* and *Foz*.

Reach

The Reach index (Figure 41) was measured by installing and running the urban network analysis toolbox. The first step is to create a network dataset. Although the *Gravity index* was also tested, the *Reach* index retrieved more interesting results. In fact, these indexes are related. When the parameter *beta* is zero, the gravity and the reach indexes are the same (Sevtsuk and Mekonnen, 2012a). The criteria considered to compute the index included a radius on the network of 500 meters, and a weight field referring to the built volume.

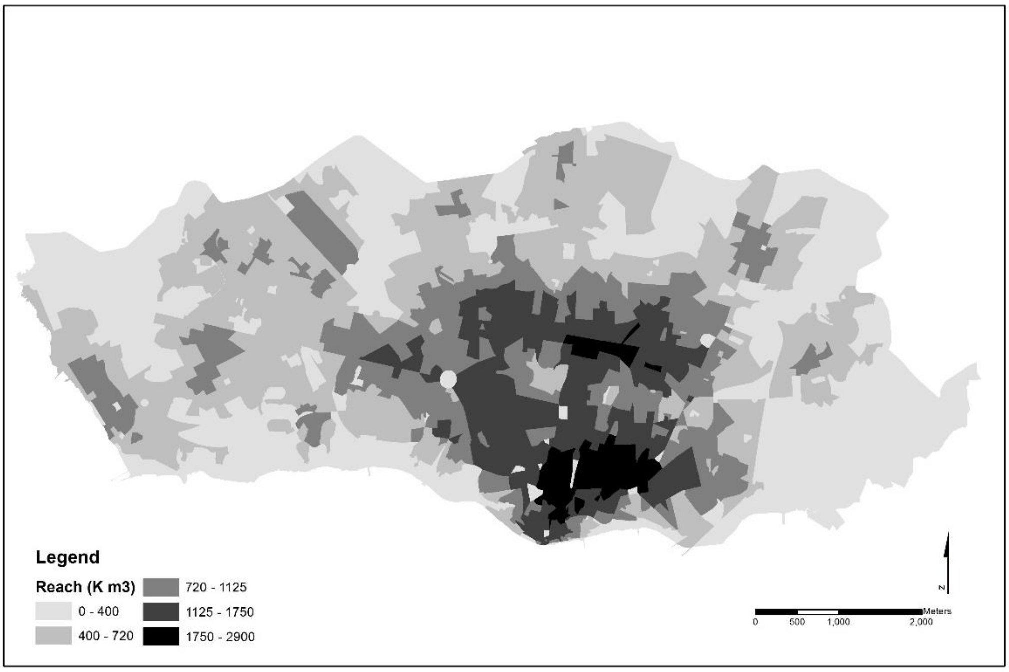

Figure 41. Accessibility. Reach. Porto

The map depicts the amount of built volume reachable within 500 meters on the network. Conversely to the DivAct, *Reach* does not reflect the location of activities. It reinforces the importance of the built environment in the city centre, as well as in other street axes like *Constituição* and *Costa Cabral*. It is interesting to note that it somehow matches previous results from other indicators (notably the one referring to diversity and accessibility), although it is based on a very different rationale. This supports the existence of interconnections between different urban attributes.

4.2.2.2.3. Public transport route density

This indicator is computed as the number of public transport stops/ stations, divided by the area of the block. Two types of public transport (the two most important) are considered: buses and the metro system. Since most stops are located in the border of the blocks layer, as it often coincides with the street centreline, it was necessary to execute a buffer from the stop point (with 10 meters) so that for each stop, located in the border of two (or more) different blocks, all overlapping blocks could be accounted for. The buffers were overlaid with the block layer in order to count the number of stops intersecting an urban block.

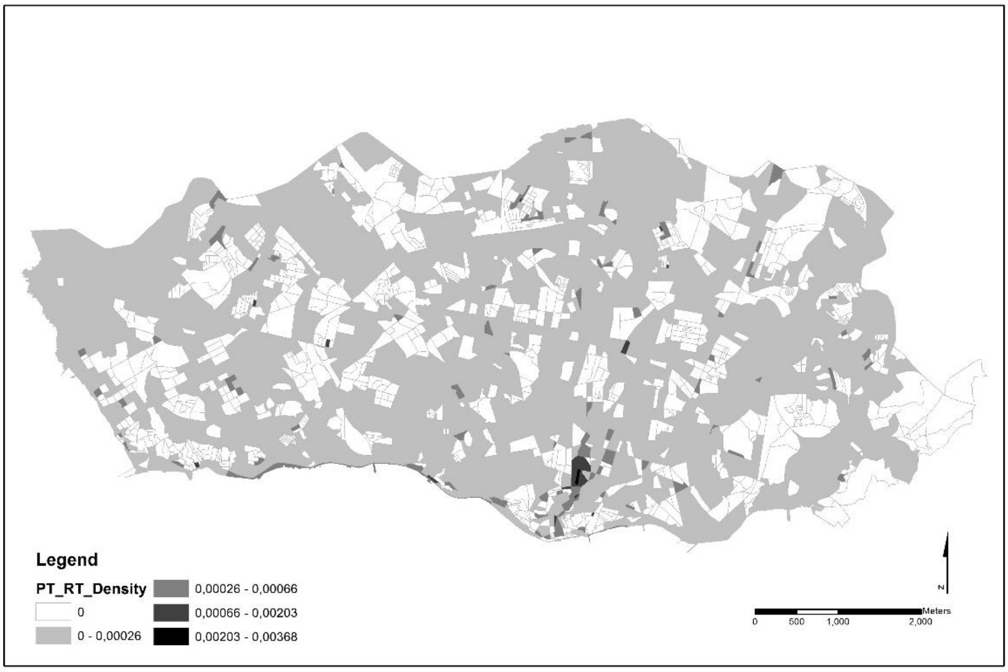

Figure 42. Public Transport Route Density. Porto.

Figure 42 shows that despite the whole municipality is almost entirely served by public transports, it is evident that few areas have higher densities. Apart from the urban core, it possible to note other areas that are well served, like *Praça Marquês do Pombal*, as a result if a strong trip attraction around this area.

4.2.2.2.4. Centrality

The centrality indicator (Figure 43) reflects the distance (in the network) to the CBD. It was measured by using the network analyst toolbox. Similarly to the computation of Reach, a network dataset was created previously to the analysis. The analysis consisted of the creation of an O/D cost matrix. The origins considered are the centroids of the urban blocks, and the destination (the CBD) corresponds to *Avenida dos Aliados,* located in the city centre. In the end, the distance cost data was imported to the layer of the urban blocks.

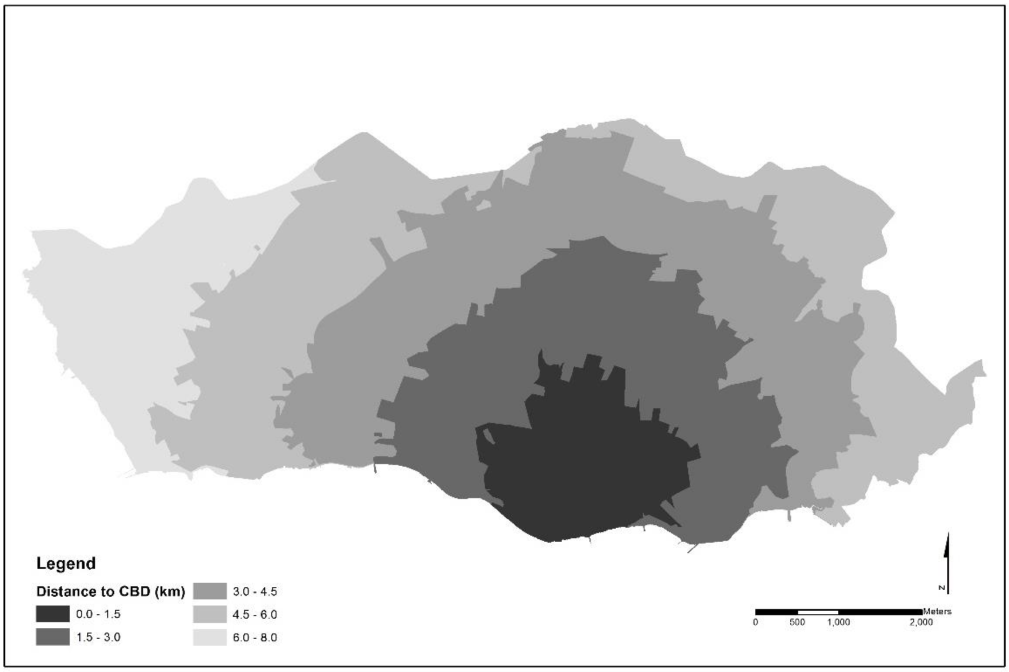

Figure 43. Centrality. Distance to CBD. Porto

The centrality map reflects the distance to the CBD (*Avenida dos Aliados)*. The map produced displays distance clusters, with darker colours meaning shorter distances to the CBD. These areas are expected to have lower energy needs for travel, since they have a greater proximity to a likely (work) destination in the city.

4.2.2.2.5. Design

The design attribute entails four different indicators, considering the following urban elements: sidewalks, trees, cycling lanes and parking.

Sidewalks

Two indicators were considered in order to assess the quality of the sidewalks. One, was the average sidewalk area per block, but was not further considered because it is dependent on the block size, probably not reflecting how pedestrian-oriented the block is. The other is the ratio between the area of the sidewalk and the area of the block (Figure 44).

Data concerning sidewalks wasn't available at any extent or under any format. The measurement of this indicator grounded on a time-consuming task of editing a CAD file in order to get a workable layer of the sidewalk borders, for all the urban blocks. In order to get data on the sidewalk area, the following steps were performed. A street layer with the ID of the blocks on both sides of the street was used. Then, it was necessary to identify the nearest sidewalk to each street edge (since only one feature is retrieved from this operation, it is assumed that there wouldn't be major differences between the sidewalks facing two sides of the same street). As the layer of sidewalks generated from the CAD is in polygon format, the polygon area is straightforwardly obtained from the features' geometry. Finally, the indicator computed is the ratio between the area of the sidewalk polygons and the area of the block.

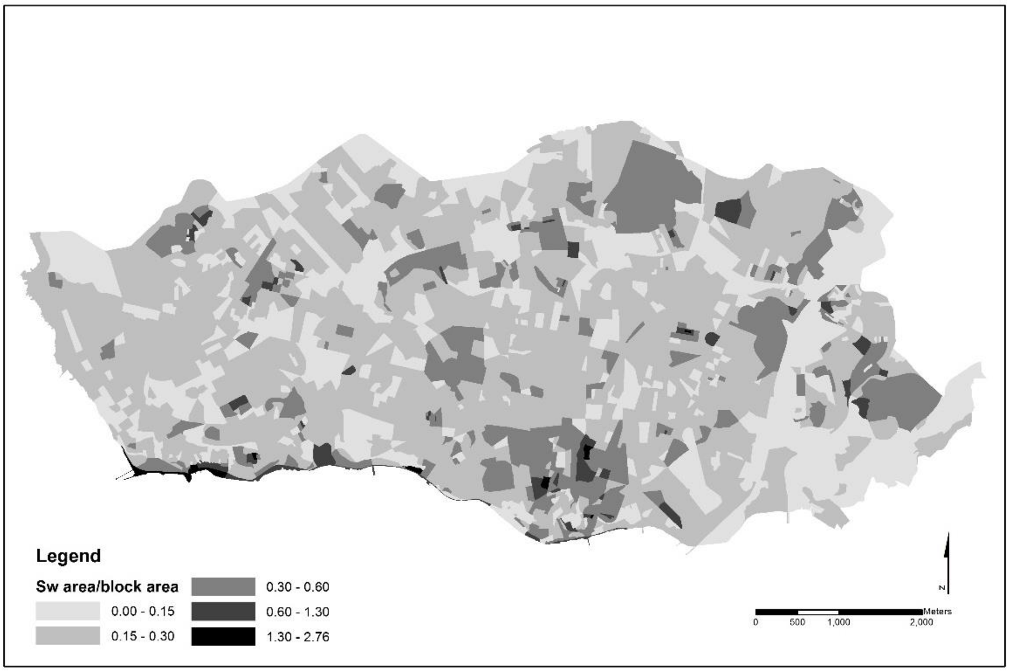

Figure 44. Design. Sidewalk area / block area ratio. Porto

The purpose of this map is to allow for the analysis of whether the areas with larger sidewalk infrastructure correspond to pedestrian-friendly zones. This link is visible in the city centre where sidewalks are thought to accommodate a large number of pedestrians (including some pedestrian streets). This is also evident in some leisure-oriented areas, like the ones on the riverside, as well as around key urban squares like *Rotunda da Boavista* or *Praça Francisco Sá Carneiro*. However, large sidewalks may also be found in wide and traffic intensive urban arteries. The modelling stage is expected to reveal the overall influence of sidewalks.

<u>Provision of trees</u>

The presence of trees is measured as the proportion of street length with provision of trees. Departing from a layer considering the streets with trees, this information was transferred to the layer of the complete street network, where the presence of trees was signalled. Having calculated the overall street length, it was then possible to compute the indicator as the ratio between the length of street with trees and the total street length. Again, this was overlaid with the layer of the blocks in order to get an average for spatial unit.

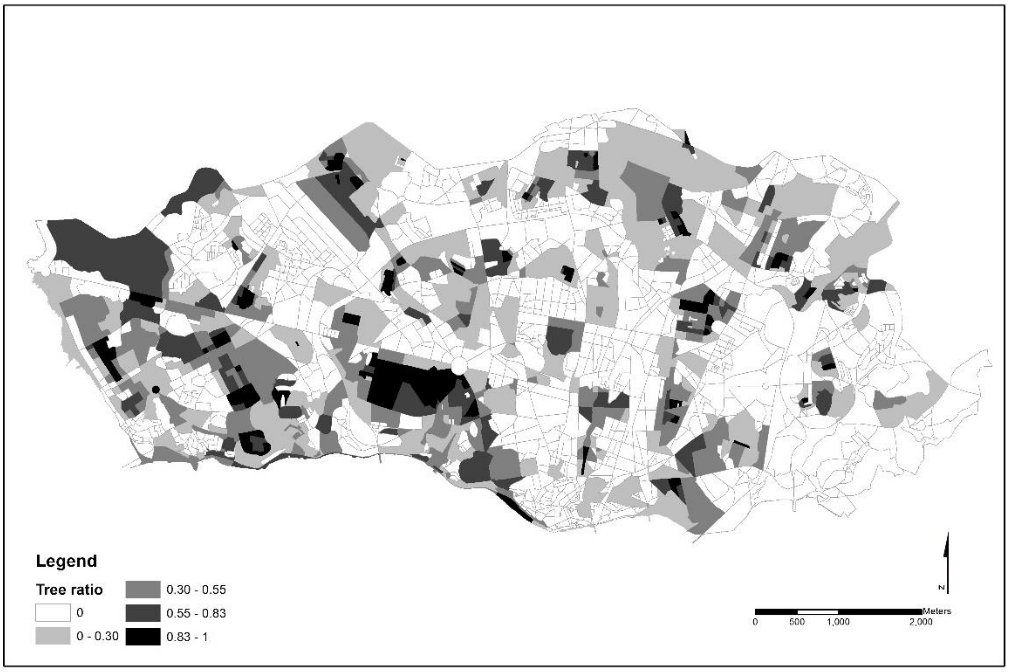

Figure 45. Design. Proportion of street length with trees. Porto

Figure 45 depicts the proportion of street length with trees facing each urban block. There is a large share of the territory without trees in the street. Except for the city centre and some residential neighbourhoods, trees are frequently located in streets where significant daily pedestrian movements are not expected. The examples include either around recreational areas, like the riverside or the seaside, or along major and road-intensive traffic axes, such as *Avenida da Boavista*, most likely as a traffic mitigation measure.

<u>Provision of cycling lanes</u>

The presence of cycling lanes is measured as the proportion of trip length with provision of cycling lanes. A new layer with the existing cycling lanes was created from scratch according to the information provided by the municipality. The procedure adopted was very similar to the one of the provision of trees, allowing to compute the ratio "length of street with cycling lanes" to "total street length".

Figure 46 evidences that Porto is lacking robust cycling infrastructure. The existence of cycling infrastructure is mostly oriented towards leisure uses, as it is typically located in peripheral areas like (again) the seaside and the riverside. Their location does not support biking in everyday trips as they do not serve the areas with higher trip attraction potential (e.g. the city centre), the exception being the university neighbourhood *Asprela*, on the North-eastern part of the city. However, the utility of cycling lanes in *Asprela* has been discussed, as they are too narrow, with no physical separation between the lane and the road, and are frequently blocked with improperly parked cars[7].

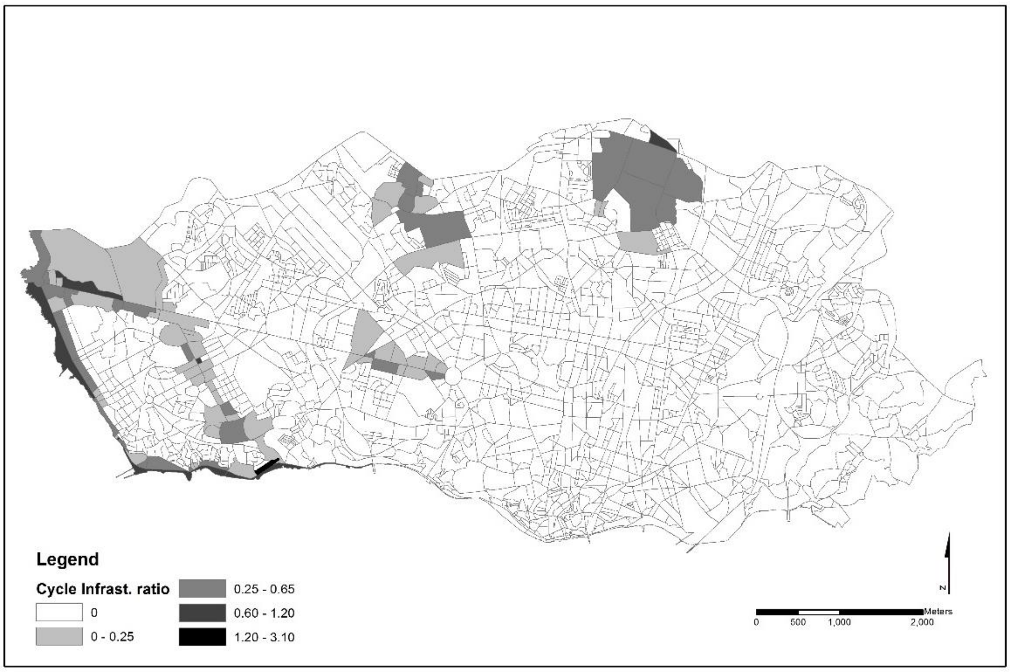

Figure 46. Design. Proportion of streets with cycling lanes. Porto

Cycling infrastructure is not yet consolidated in the city of Porto. In fact, the modal split for cycling in Porto is still residual. Whereas the use of an indicator on the provision of cycling infrastructure makes sense in many cities worldwide, the specificity of the case study does not suggest interesting results from its application. It will not be considered for building the urban form /energy model, since it is not expected to have a significant effect on the existing mobility patterns in this case.

<u>Proportion of plots with parking</u>

Here, the indicator selected is the proportion of plots with parking. However, it was not possible to obtain data to fully characterize the parking availability in the city. The municipal authority provided information on paid on street parking and on parking facilities (mostly run by private entities). It is well known that the effects of parking in encouraging auto use are mostly felt from unpaid parking. Also, paid parking is a small portion of the overall existing parking capacity, for the city of Porto. For this reason, this indicator had to be dropped at this point, although it is expected that the existence of more complete data would allow obtaining very interesting results.

[7] Since the assessment of these indicators until the time of writing the thesis, there has been some investment on additional cycling infrastructure, with more evident daily utility. A notable example being the one in *Rua da Constituição*. Nevertheless, these increments are probably not yet significant to provide the indicator on the provision of cycling lanes with a robust character to be modelled.

4.2.2.3. Energy

4.2.2.3.1. Built environment

For the characterization of the energy needs of the built environment (for heating and cooling), the building certification database for the city of Porto, with over 12.800 usable certificates, was used. The certification data was imported to the GIS, by using the corresponding coordinates.

Figure 47 shows the spatial distribution of the existing certificates. Almost all urban blocks with residential buildings have energy certificates. The white background polygons with grey boundaries correspond to the urban blocks, the grey polygons correspond to existing buildings, and each orange dot corresponds to a building certificate. The areas without certificates in the map, are mostly areas without (residential) buildings or few areas without building certificates emitted.

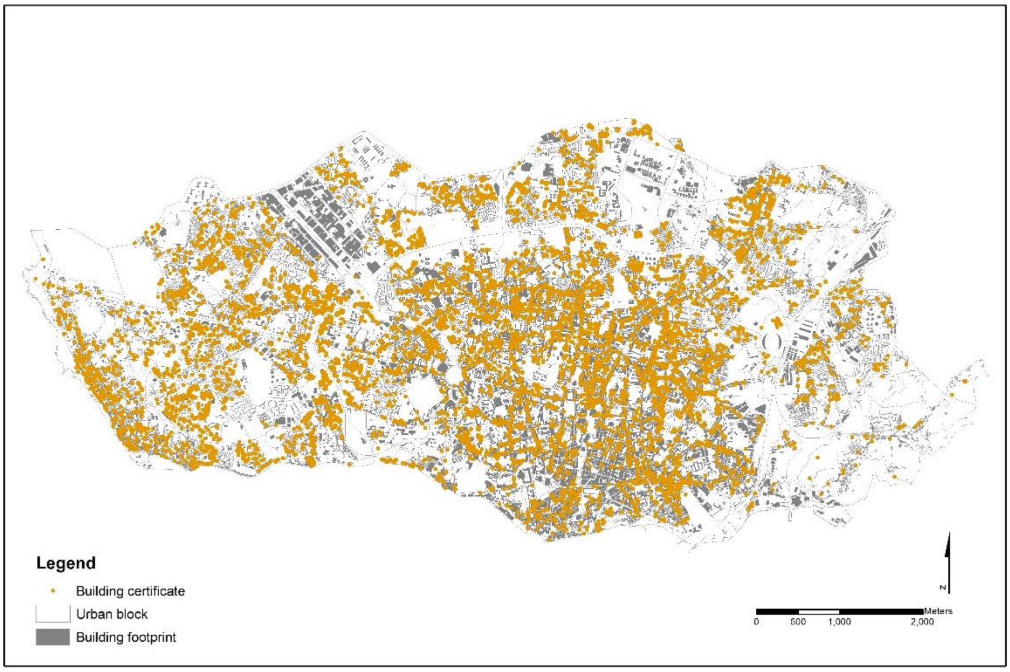

Figure 47. Spatial Coverage of the buildings certification system database for the Porto case study.

After having matched the energy needs of the former regulation (2006) to those of the second regulation (2013), both databases were merged into a single GIS layer. This was overlaid with the layer of the blocks, which enabled to determine the average nominal useful energy needs for heating – Nic (Figure 48) and the average nominal useful energy needs for cooling – Nvc (Figure 49). These have been converted into final energy in the modelling stage, by using the average conversion factor of useful to final energy of the Porto municipality (according to the Porto energy matrix), for heating and cooling, respectively (Annex IV).

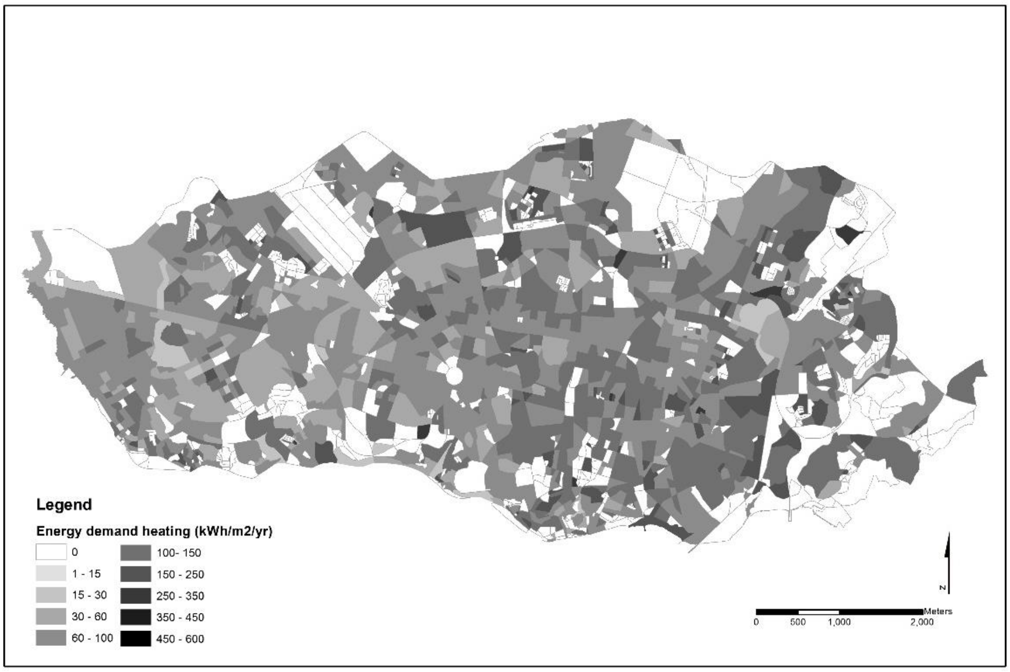

Figure 48. Average nominal energy demand for residential heating (kWh/m²/yr). Porto

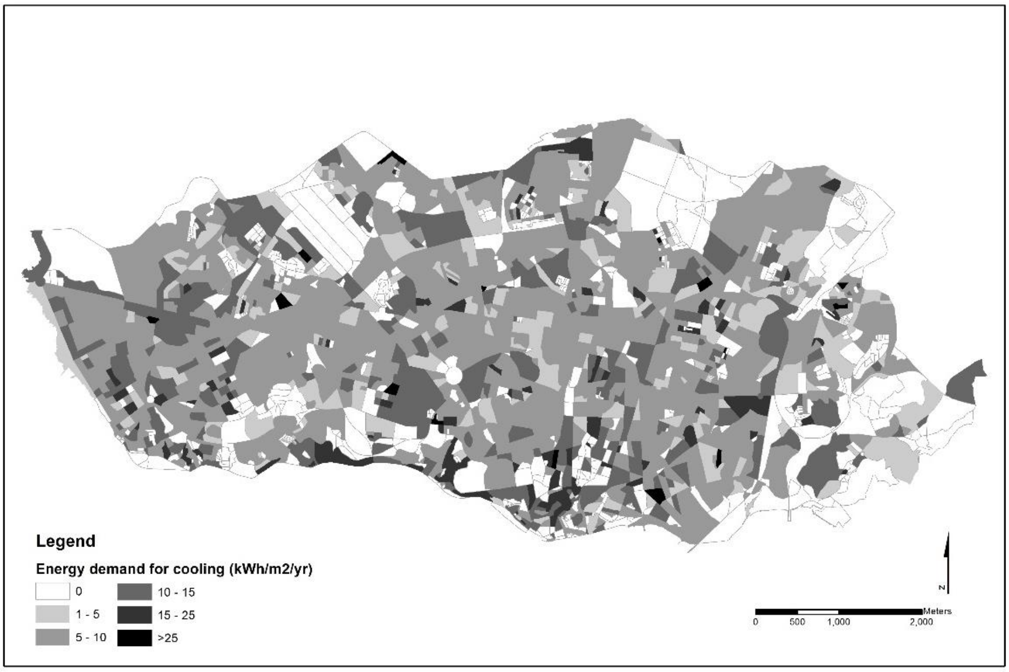

Figure 49. Average nominal energy demand for residential cooling (kWh/m²/yr). Porto

As expected, given the climatic conditions of the case study, the energy needs for heating are significantly higher than those for cooling (Figure 48 and Figure 49). While there isn't a conspicuous spatial trend for heating, it is possible to identify that the highest needs for cooling are located in the old urban areas of the city centre (more compact), and in blocks along the river, which are facing south.

4.2.2.3.2. Urban Networks

As mentioned above, the data source for characterizing the mobility patterns was an O/D matrix extracted from the SATURN model, calibrated for the city of Porto. Such matrix entails 87 traffic zones within the city, and 22 zones outside the city's boundaries (to enable considering in and out flows, to and from the municipality, respectively). The matrix gives the estimated number of trips (in private car units – pcu) for each origin/destination pair in the morning peak hour (08.30h-10.30h). This is not the ideal characterization of the mobility patterns, but still, it is the best available information for the case study. Resorting to a few assumptions, it allows estimating the travel demand at the block level for the city of Porto.

The O/D data was imported to the GIS, so that the trips (O/D) could be allocated to the territory. The centroids of the traffic zones were computed to allow for the development of the following steps. Since mobility, and thus, energy needs, depend not only on the number of trips generated, but also on the distances travelled, the later had to be estimated. For this, the reference distance between each O/D pair was calculated as the shortest path between the centroids of the corresponding (O/D) zones. For each traffic zone, the number of trips was multiplied by the corresponding trip length (in km), which resulted in the indicator for characterizing the private car mobility (vehicle kilometre travelled).

In order to downscale the data from the traffic zones into the spatial units considered, a couple of options using a ratio-based normalization were considered (following (Horta and Keirstead, 2017): one based on the resident population and another based on the built-up area. Since the data available refers to the morning peak hour, the resident population was considered for downscaling trip origins (assuming that most people leave their homes in this period – the proxy being resident population); and the built-up area was considered for trip destinations (assuming that the destinations are more a function of the built environment). Finally, it was assumed that the evening peak hour is the inverse of the morning peak hour (a common procedure in traffic modelling), and that these two periods together correspond to 14 % of the total daily traffic, approximately 7% each. This is in line with what has been pointed out in the literature. TRB (2000) claim that typical volumes for the morning peak hour in urban areas is 9% of the daily traffic (based on the US context) and Ferreira (2010) has identified an average proportion of 6% for the city of Porto. The AADT was represented per square meter of floor area, in order to produce a relative measure (rather than an absolute one), similarly to the ones used for the built environment. Figure 50 depicts the results obtained.

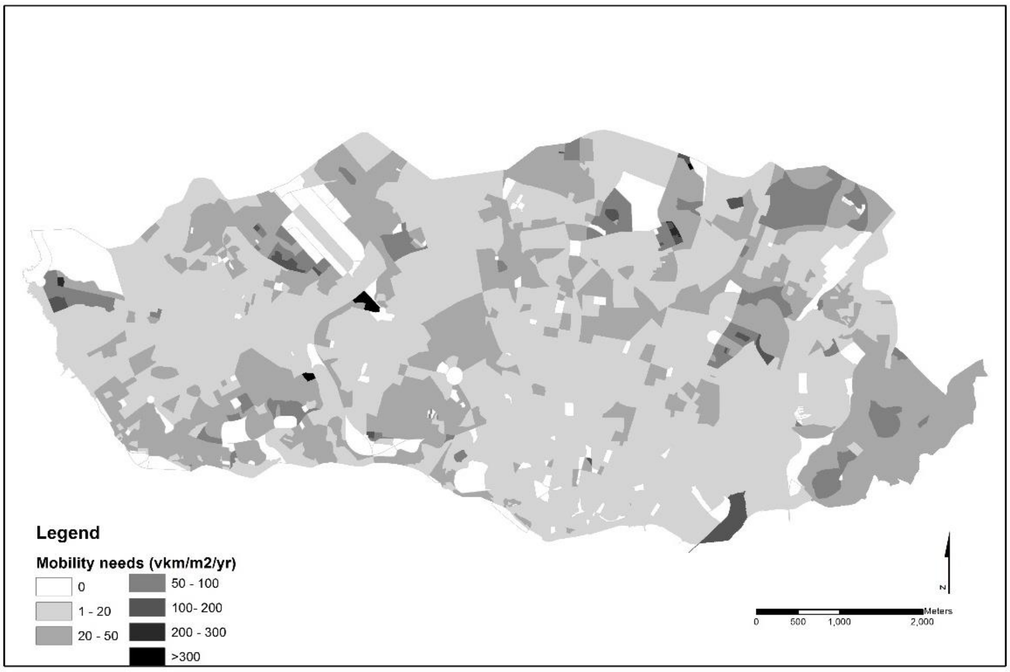

Figure 50. Average demand for motorized mobility (vehicle.km/m2/yr). Porto

4.2.3. Extraction of Metrics

After the spatial analysis, where the indicators of urban form and energy have been measured and mapped, the subsequent stage corresponds to gathering and merging all the data produced into a suitable format, compatible with the modelling process. This may be a time-consuming process.

Still, before extracting the indicators and metrics computed, it was deemed suitable to remove the urban blocks (i.e. data entries) without buildings (e.g. public spaces, green areas…) and other blocks considered “atypical”. This was considered important either because these areas do not have an associated energy consumption figure, and because the spatial units to be modelled should be comparable, in terms of the expected influence of urban form on energy. Although green and public areas are expected to influence energy demand, depending on their proximity to built-up structures, they should not be included in the analysis as independent units.

Matching the data from the different layer maps created for the representation of the indicators of urban form can be done in two ways. It can be done in the GIS, before extracting the data, or after the extraction of the metrics in a software compatible with database management.

In the first case, the attribute tables of each layer map (.mxd files) are merged resorting to the ID code of the spatial units analysed. This was performed for all the indicators of urban form, as well as for the energy indicators referring to the built environment and to mobility patterns, through a “join attribute table” operation. In the end, the relevant fields of the attribute table are extracted in .dbf format.

In the case of merging tables after the exporting the individual .dbf files from the ArcGIS, these should first be saved in a spreadsheet format. Then, again, the merging takes place through the ID field. It is key to ensure that the data entries match the corresponding ID of the urban block when merging tables, or else it will lose its spatial nature. The format of the interim structured spreadsheet (e.g. MS Excel) should be selected so that it is compatible with the modelling software to be used in the next stage. In this case, MS excel seems to be a suitable option, because it has a widespread application and is compatible with most of the modelling software considered for addressing the research problem, as described in the following section.

4.2.4. Modelling

Given the review of modelling approaches to be incorporated in the methodological framework (Chapter 3), Artificial Neural Networks (ANN) were considered an interesting and suitable technique for modelling the research problem. Recall that the model is formulated considering energy demand for heating, cooling and travel as a function of a set of urban form variables, according to *(Equation 1).*

Still, before the application of the ANN, a couple of statistical methods will be applied. These are a Multiple Linear Regression (MLR) and Structural Equation Models (SEM). This preliminary statistical analysis aims at providing additional sensitivity on the relative explanatory power and significance of the predictors, thus influencing the selection of the variables to be included in the ANN model, as well as having a basis for comparing the ANN results.

Then, as many of the relationships are expected to be nonlinear, ANN will be tested. MLR and SEM may still be too restrictive for modelling the data at stake. Whereas SEM may provide useful insights on the existing relationships between the variables considered, it does not have a prediction character, conversely to ANN. The analysis goes from simpler techniques closer to traditional statistics towards more complex approaches from the artificial intelligence field, reflecting a preference for simplicity. Non-linear regression was not considered, as it requires previous model specification, and there isn't enough knowledge on the nature of the existing relationships.

In the end of the modelling process, the different modelling techniques will be compared considering the determination coefficient (R^2) and selected fit measures. The application of these three techniques is expected to enable selecting the best modelling option(s) for this problem, as well as to conclude on the influence of each of the attributes of urban form on energy demand. The selection of a final model will allow to perform the subsequent stages of research, considering the assessment of alternative urban development pathways.

The average conversion factors of useful to final energy for space heating and space cooling (according to the Porto energy matrix) are given in Table 68 (Annex IV). Table 9 presents the summary statistics of the dependent and independent variables considered (according to *Equation 1*). A total of 1831 urban blocks were modelled. In general, the variables of urban form evidence a large variability, given the figures of the standard deviation. With regard to energy, the needs for travel (ET) show a particularly high variability, comparing to energy for heating (E_h) and cooling (E_c).

While there are some missing values for buildings, in areas where there are no certificates available, mobility needs are better characterized throughout the territory. The following sections describe the rationale for the application of the modelling techniques considered (MLR, SEM, and ANN), followed by the results obtained in each case.

Table 9. Descriptive Statistics of the variables considered

Code	Variable description	N	Minimum	Maximum	Mean	Std. Deviation
E_h	Final energy needs for heating ($kwh/m^2/yr$)	1307	16.8	354.4	130.3	53.3
E_c	Final energy needs for cooling ($kwh/m^2/yr$)	1307	.02	9.8	2.8	1.4
ET	Final energy needs for travel ($kwh/m^2/yr$)	1831	0	990.3	25.7	37.7
GSI	Ground Space Index	1831	0	4.29	.35	.28
FSI	Floor Space Index	1831	0	10.70	.93	.87
F	Number of Floors	1831	0	9.00	2.69	1.16
SS_Area	Size of block	1831	160	369567	19030	26882
SubDiv	Subdivision Indicator	1831	.00006	.03119	.00123	.00170
MXI	Mixed-use Index	1831	0	1.00	.91	.20
AiSi	Spatial Distribution of green areas	1831	0	.99	.03	.12
STV	Surface-to-Volume Ratio	1831	0	.66	.26	.10
Connect	Beta index	1831	0	4.75	3.12	.53
DivAct_PT	Divact Public transport	1831	0	1.00	.92	.13
DivAct_Ped	DivAct Pedestrian	1831	0	1.00	.80	.15
Reach	Reach (within 500m radius)	1831	0	2801019	732065	495987
PT_RD	Public transport route density	1831	0	.001535	.000065	.000129
Centrality	Linear distance to CBD	1831	21	7870	3715	1809
Tree	Proportion of street length with provision of trees	1831	0	1.00	.18	.29
SW	Sidewalk area / block area	1831	0	0.704	.040	.001

4.2.4.1. Multiple Linear Regression (MLR)

Three MLR models, one for each dependent variable in relation to the relevant urban form variables, were considered, followed by a (forward) stepwise analysis. This consists of adding independent variables, step by step, in order to improve the quality of the model. This was performed in IBM SPSS Statistics 23. The three regression models tested are described as follows:

$$Eh = f\ (GSI, FSI, F, SS\_Area, SubDiv, AiSi, STV, and\ Tree) \qquad \textit{(Equation 7)}$$

$$Ec = f\ (GSI, FSI, F, SS\_Area, SubDiv, AiSi, STV, and\ Tree) \qquad \textit{(Equation 8)}$$

$$ET = f\ (GSI, FSI, F, SS\_Area, SubDiv, MXI, AiSi, Tree, Connect, DivAct\_PT, DivAct\_Ped, Reach, PT\_RD, Centrality, SW) \qquad \textit{(Equation 9)}$$

The transport model includes more variables because the number of attributes of urban form influencing mobility identified in literature is also higher, in relation to the ones affecting the built environment. For evaluating the models built, two criteria will be considered. The first is the explanatory power, which is given by the coefficient of determination (R^2). It may be defined as the proportion of variance of the dependent variable(s) associated with the predictor(s), with values closer to one indicating a larger explanatory power of the model *(Equation 10)*. In addition, using goodness-of-fit measures allows for the evaluation of model quality/ fit. For the MLR, the standard error (SE) is the error involved in the prediction. The model significance (Sig.) is also an important measure to account for. It refers to the probability of rejecting the null hypothesis (where the predictors do not influence the response variables), with values closer to zero indicating a better fit. In order allow for comparisons between the results obtained for the MLR and the results from ANN, some additional accuracy metrics were computed to verify model accuracy: the mean absolute percentage error – MAPE *(Equation 11)* and the root mean square percentage error – RMSPE *(Equation 12)*. For further considerations on prediction errors please see Lan et al., (2012).

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{Y})^2}$$

(Equation 10)

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i} \times 100\right|$$

(Equation 11)

$$RMSPE = 100 \times \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i - \hat{y}_i}{y_i}\right)^2}$$

(Equation 12)

, where $\hat{y}_i$ is the predicted value of y and y_i is the real value of y.

4.2.4.2. Structural Equation Models (SEM)

The SEM, including the specification and mapping of the relationships between the variables, were built in the software Amos 23. This implied previously creating a SPSS database, which works as an interface for storing the data. In order to explore different possibilities, two models were considered:

SEM1) A model using all the variables considered as in *Equation 1*.

SEM2) A model using the stepwise approach above, such that the variables included were:

$$(Bh, Bc, T) = f\ (GSI, FSI, F, SS\_Area, SubDiv, STV, DivAct\_Ped)$$

(Equation 13)

The accuracy measures for SEM differ from the ones for the MLR and ANN. For this reason, comparing the results obtained for the SEM and the remaining modelling techniques is not straightforward. However, it is possible to infer on the overall model suitability and to compare the different SEM scenarios.

In this case, the two accuracy measures used are the RMSEA – Root Mean Square Error of Approximation and the CFI – Comparative Fit Index. These are common measures for evaluating the fit of SEM, however, they tend to penalize model complexity, favouring models with less parameters. RMSEA *(Equation 14)* is an absolute fit index based on the chi-square, with values closer to 0 being better. CFI *(Equation 15)* compares the developed model with the null model. CFI is normalized and ranges between 0 and 1, with higher values indicating a better fit.

$$RMSEA = \sqrt{max\left[\frac{(X^2/df)-1}{n-1}, 0\right]}$$

(Equation 14)

$$CFI = 1 - \frac{max\left[\left(X^2_{model} - df_{model}\right),\ 0\right]}{max\ [(X^2_{model} - df_{null})\ ,\ (X^2_{model} - df_{model}), 0\ ]}$$

(Equation 15)

In *Equation 14* and *Equation 15*, X^2 is the chi-square and df are the degrees of freedom. *Model* is the model being evaluated and *null* refers to the null model, reflecting the null hypothesis which considers that the dependent variables are not related with the explanatory variables.

4.2.4.3. Artificial Neural Networks (ANN)

The architecture of the ANN model for this research includes urban form variables as model inputs (predictors), while the outputs are energy demand for heating in buildings (E_h) and cooling (E_c) and mobility (ET), according to *Equation 1*. The model was built in MATLAB R2015a, which is a software with a very complete package for running neural networks that can be edited by the user. The data was normalized within the range of -1 and 1 before being modelled. This is done in order to meet the requirements of the hyperbolic tangent sigmoid transfer function (Figure 51). In addition, a log normal transformation was applied to the target variables, which led to an improved model performance.

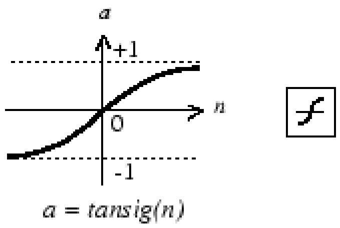

Figure 51. Tan-Sigmoid transfer function
Source: Beale et al., (2014)

Different network architectures were tested. Starting with a default number of 10 neurons, the number of neurons in the hidden layer was gradually increased up to 15 neurons (larger number of neurons increase model complexity and make the interpretation of the network weights more difficult).

The training algorithms were selected according to their suitability to the problem. Three different algorithms were tested: the Levenberg-Marquardt (LM) backpropagation algorithm, the Scaled Conjugate Gradient (SCG) algorithm and, the BFGS quasi-Newton backpropagation. While LM is advocated to be a fast convergence algorithm usually retrieving lower MSE values, it requires higher storage capacity. SCG is advocated to perform well in networks with a large number of weights. BFGS is claimed to be similar to LM but with lower storage requirements. However, computation requirements may increase geometrically with the number of weights (Beale et al., 2014).

The data sample for training, validating and testing the model was randomly split, within a proportion of 80%, 10% and 10%, respectively. The training phase is used for computing the gradient and updating the weights and the biases of the net. The validation phase is targeted at avoiding overfitting. The validation errors are monitored during the training process, in order to be kept at a minimum (before the point where they begin to rise again due to overfitting). Finally, the testing dataset, works as a reference for the validation one. If the error of the test phase reaches a minimum at a very different iteration, it may evidence a poor division of the data.

In order to facilitate comparisons between the different networks, a script was developed in order to run a pre-specified number of network trainings (e.g. 100, 200, 1000,…) where the weights are randomly initialized, and selecting the net with the lowest MSE – mean squared error *(Equation 5*).

From the modelling options tested, a net with 15 neurons in the hidden layer and with a Levenberg-Marquardt (LM) training algorithm delivered the best results (Figure 52). The results obtained from the different networks were compared alongside with key evaluation criteria similar to the ones from MLR. A coefficient of determination (R^2 – *Equation 10*) enables to infer on the explanatory power of the model, while prediction errors enable to evaluate the prediction power. The MAPE and the RMSPE were calculated using the testing dataset and for each of the dependent variables considered (*Equation 11* and *Equation 12*, respectively). The MSE *(Equation 5)* was determined considering all variables together, both for the global model and for the testing dataset.

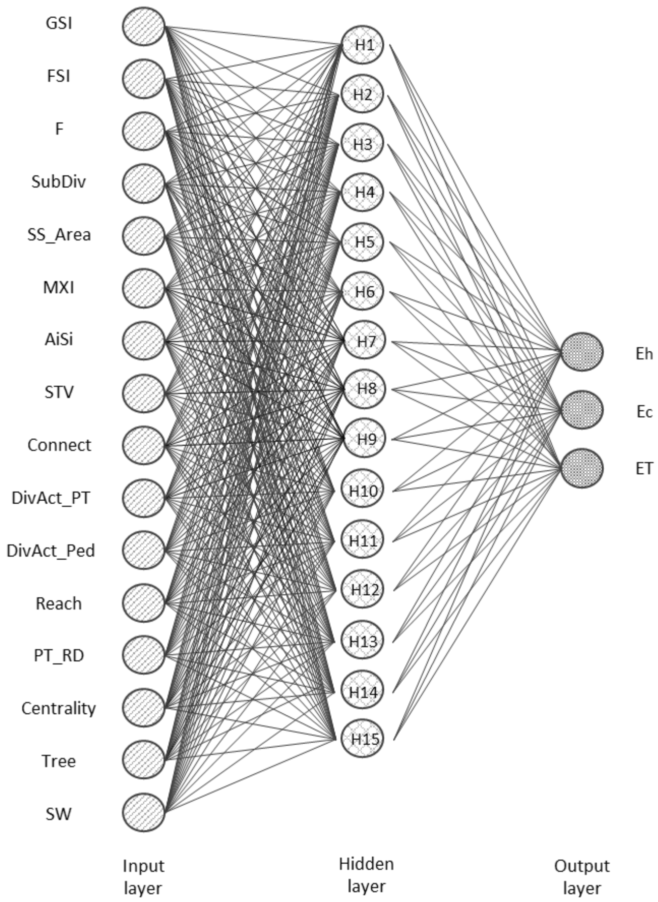

Figure 52. Architecture of the ANN model selected

In the end, in order to understand how much each predictor contributes to explain the variability observed on the dependent variables, different methods are applied to extract knowledge (structured information) from the best performing ANN model.

4.2.4.4. Results and discussion

In order to conclude on the suitability of the modelling techniques, the accuracy metrics presented will be analysed. The explanatory power is given by the R^2 and the prediction power is evaluated resorting to accuracy metrics (in relation to a specific response variable (E_h, E_c, ET) or to the whole model, i.e. E_h, E_c, and ET modelled together).

4.2.4.4.1. Multiple Linear Regression (MLR)

Three MLR models were built considering each of the response variables individually as a function of the corresponding urban form variables. The results obtained are presented in the following paragraphs.

$$Eh = f\ (GSI, FSI, F, SS\_Area, SubDiv, AiSi, STV, and\ Tree) \qquad (Equation\ 7)$$

Table 10. Multiple Linear Regression. E_h as dependent variable. Model Summary

Model	R^2	SE	MAPE	RMSPE	F	Sig.
E_h	.218	34.9	32.7%	64.7%	45.3	.000

Table 11. Multiple Linear Regression. E_h as dependent variable. Coefficients

Model	Unstandardized Coefficients		Standardized Coeff.	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	103.981	8.486		12.254	.000		
GSI	12.743	14.056	.066	.907	.365	.115	8.727
FSI	9.216	4.312	.158	2.137	.033	.110	9.064
Floors	-13.751	1.663	-.374	-8.271	.000	.294	3.396
SS_Area	-4.772E-5	.000	-.034	-1.191	.234	.754	1.327
SubDiv	1198.762	1384.522	.029	.866	.387	.534	1.874
New_AiSi	-10.049	9.733	-.027	-1.032	.302	.897	1.115
STV	79.852	17.128	.187	4.662	.000	.374	2.676
Passivity	2.695E-5	.000	.022	.895	.371	.992	1.008
Tree	-6.391	3.622	-.044	-1.764	.078	.951	1.051

The model for heating needs is significant at a probability level of .05 (Table 10), and presents errors within an acceptable range, as well. This MLR model (E_h) was the one evidencing the strongest relationship, with an R^2 of 0.218. This may not be considered a very strong correlation, meaning that roughly 22% of the variability of the dependent variable (E_h) is explained by the independent variables included in the model. However, for a linear model with several independent variables, and acknowledging that urban form is not the only factor determining energy demand, this may be considered a reasonable result. Even if almost 22% variation of energy demand for heating in buildings is a product of urban form, if it is possible to better control these 22% with more efficient planning policies, it would most likely lead to meaningful energy savings. Still, it is expected that the use of a more flexible modelling technique may enable discovering hidden patterns in the data, and thus evidencing more significant relationships between the variables.

The variable with the highest explanatory power (Table 11) is the number of floors (with a higher number of floors leading to lower energy needs for heating), followed by the STV (higher STV mean less compact built structures, implying higher needs for heating). Also, note that the variable measuring the proportion of passive areas is the one evidencing the lowest relationship (Beta = .022), and the one of the least significant for this model. Also, it is unexpectedly directly related to heating needs in buildings. This fact, helps answering the question posed by Ratti et al. (2005) on what would be the balance between the two contradictory effects of compactness and passivity. In the case of Porto, it seems that the effect of compactness is most important, and this explains why these two measures of building geometry are directly related to heating needs in buildings. Accordingly, the results suggest for the removal of this variable (“proportion of passive areas”) from the model – yet the result obtained is kept in Table 11 for providing the reader with some more insight.

$$Ec = f\ (GSI, FSI, F, SS\_Area, SubDiv, AiSi, STV, and\ Tree) \qquad (Equation\ 8)$$

Table 12. Multiple Linear Regression. E_c as dependent variable. Model Summary

Model	R^2	SE	MAPE	RMSPE	F	Sig.
E_c	.025	4.28	66.5%	892.6%	4.21	.000

Table 13. Multiple Linear Regression. E_c as dependent variable. Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	9.667	1.040		9.295	.000		
GSI	-2.709	1.723	-.127	-1.573	.116	.115	8.727
FSI	1.616	.528	.252	3.059	.002	.110	9.064
F	-.651	.204	-.161	-3.196	.001	.294	3.396
SS_Area	-5.744E-6	.000	-.037	-1.169	.242	.754	1.327
SubDiv	262.174	169.682	.058	1.545	.123	.534	1.874
New_AiSi	.163	1.193	.004	.137	.891	.897	1.115
STV	-.418	2.099	-.009	-.199	.842	.374	2.676
Passivity	-3.013E-7	.000	-.002	-.082	.935	.992	1.008
Tree	.052	.444	.003	.118	.906	.951	1.051

The MLR model for cooling evidenced the weakest relationship, which was somehow anticipated as cooling needs may be more dependent on non-structural solutions (such as shading devices) than to urban form factors. Another possible explanation is that cooling loads and urban form are related in a dominantly nonlinear fashion, or it is possible that data on cooling demand is noisier, leading to more difficult conclusions. This was somehow noticed in earlier stages, specifically, from the analysis of Figure 67 and Figure 68 (in this chapter) and is evidenced by the high value obtained for the RMSPE in this model, which makes it unfeasible for prediction purposes. Additional modelling techniques are expected to enable to better conclude on the effect of urban form in cooling needs.

It is visible that for the MLR cooling model (E_c) the indicators of density are the ones with the highest explanatory power, whereas the low significance of the variables related to the presence of green areas and trees does not enable to draw meaningful conclusions about their effect.

$$ET = f\ (GSI, FSI, F, SS\_Area, SubDiv, MXI, AiSi, Tree, Connect, DivAct\_PT, DivAct\_Ped, Reach, PT\_RD, Centrality, SW)$$

(Equation 9)

Table 14. Multiple Linear Regression. ET as dependent variable. Model Summary

Model	R^2	SE	MAPE	RMSPE	F	Sig.
ET	.099	35.96	70.6%	86.8%	13.3	.000

Table 15. Multiple Linear Regression. ET as dependent variable. Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	36.041	10.744		3.355	.001		
GSI	21.919	9.193	.166	2.384	.017	.102	9.769
FSI	-11.791	3.106	-.273	-3.796	.000	.096	10.401
Floors	4.656	1.213	.143	3.837	.000	.357	2.801
SS_Area	.000	.000	-.098	-4.034	.000	.839	1.192
SubDiv	-2.777	610.686	.000	-.005	.996	.651	1.535
MXI	25.563	4.688	.133	5.452	.000	.836	1.196
AiSi	8.971	7.405	.028	1.211	.226	.898	1.113
Connect	.765	1.678	.011	.456	.649	.893	1.119
DivAct_PT	2.625	7.979	.009	.329	.742	.669	1.496
DivAct_Ped	-51.823	8.630	-.202	-6.005	.000	.438	2.285
Reach	-2.309E-6	.000	-.030	-.817	.414	.360	2.780
PT_RD	-4714.727	6755.632	-.016	-.698	.485	.924	1.083
Centrality	.000	.001	-.023	-.705	.481	.477	2.096
Tree	-2.755	2.964	-.021	-.929	.353	.940	1.064
Sidewalks	14.128	16.864	.019	.838	.402	.943	1.060

The model for travel resulted on an overall weaker relationship than expected with an R^2 of roughly 0.1 (Table 14). Nevertheless, some single variable coefficients for trip generation were similar to what literature has been pointing, around 0.20 (Ewing and Cervero, 2010). Again, the variables of density evidence a relevant influence (although not all in the same direction) and the pedestrian accessibility seems to be the most important variable for reducing motorized travel needs (Table 15) along with the MXI (higher values point to a greater dominance of residential areas). Although evidencing lower coefficients, the variables "Reach", "PT_RT_Density" and "Tree" are also inversely related to motorized travel needs.

The following section describes a MLR modelling process built similarly, i.e. a model for each of the three response variables and with the same predictors, this time including a stepwise approach for the selection of the significant variables in each model.

4.2.4.4.2. Stepwise Multiple Linear Regression (MLR)

A stepwise approach was tested for the same MLR models described earlier, in order to investigate which variables do not add significant explanatory power to the model (under a linear environment), and which could eventually be eliminated from the analysis. This method enables to identify model terms that may be removed from the original model formulation.

Table 16. Stepwise Linear Regression. E_h as dependent variable. Model Summary

Model	R Square	SE
1	.165	35.99
2	.185	35.57
3	.212	34.99
4	.214	34.96

a. Predictors: (Constant), F
b. Predictors: (Constant), F, FSI
c. Predictors: (Constant), F, FSI, STV
d. Predictors: (Constant), F, FSI, STV, SS_Area

The stepwise approach for E_h evidences that four out of eight variables enable to achieve an R^2 very close to the initial model formulation (with a difference of .04). For the remaining variables, only the one referring to passivity will be effectively removed from further stages of the analysis, as the results obtained are in line with previous suggestions from the literature and confirm its redundancy in relation to the compactness variable. The remaining variables will be further explored in additional modelling techniques.

Table 17. Stepwise Linear Regression. E_c as dependent variable. Model Summary

Model	R Square	SE
1	.012	4.29
2	.016	4.29

a. Predictors: (Constant), GSI
b. Predictors: (Constant), GSI, SubDiv

The stepwise approach for E_c suggests that this is the energy use least influenced by urban form, with only two variables selected (Table 17). However, since many of the urban form variables are common to the E_h model, they will be kept in the following modelling exercises (with the three response variables being considered at the same time).

Table 18. Stepwise Linear Regression. ET as dependent variable. Model Summary

Model	R Square	SE
a	.052	36.75
b	.077	36.27
c	.084	36.14
d	.090	36.04
e	.094	35.97
f	097	35.91

a. Predictors: (Constant), DivAct_Ped
b. Predictors: (Constant), DivAct_Ped, MXI
c. Predictors: (Constant), DivAct_Ped, MXI, SS_Area
d. Predictors: (Constant), DivAct_Ped, MXI, SS_Area, FSI
e. Predictors: (Constant), DivAct_Ped, MXI, SS_Area, FSI, F
f. Predictors: (Constant), DivAct_Ped, MXI, SS_Area, FSI, F, GSI

The results obtained for the transport model suggest that mobility is the energy use that is influenced by a larger set of variables. Still, the overall coefficient of determination is quite low.

One explanation may be that mobility needs may be dominantly influenced under a nonlinear environment. This has to be further explored.

Overall, the stepwise MLR presented very close results to the ones from the simple MLR. This suggests that under a linear environment, few predictors evidence a significant explanatory power of energy demand, with accessibility, diversity of land uses, and density being the most prominent. This justifies the dominance of existing research in these topics.

4.2.4.4.3. Structural Equation Models (SEM)

Structural Equation Models (SEM) were the second modelling technique applied to the research problem. Its advantage in relation to MLR is that it enables to model all the predictors and the response variables together (with the links specified by the user) and that it is a more flexible technique. Two modelling options were explored:

SEM1) A model including all the variables of urban form, according to *Equation 1*.

SEM2) A model considering covariations derived from the stepwise approach, such that the variables included are:

$$(Eh, Ec, ET) = f\,(GSI, FSI, F, SS\_Area, SubDiv, STV, DivAct\_Ped) \qquad \text{(Equation 13)}$$

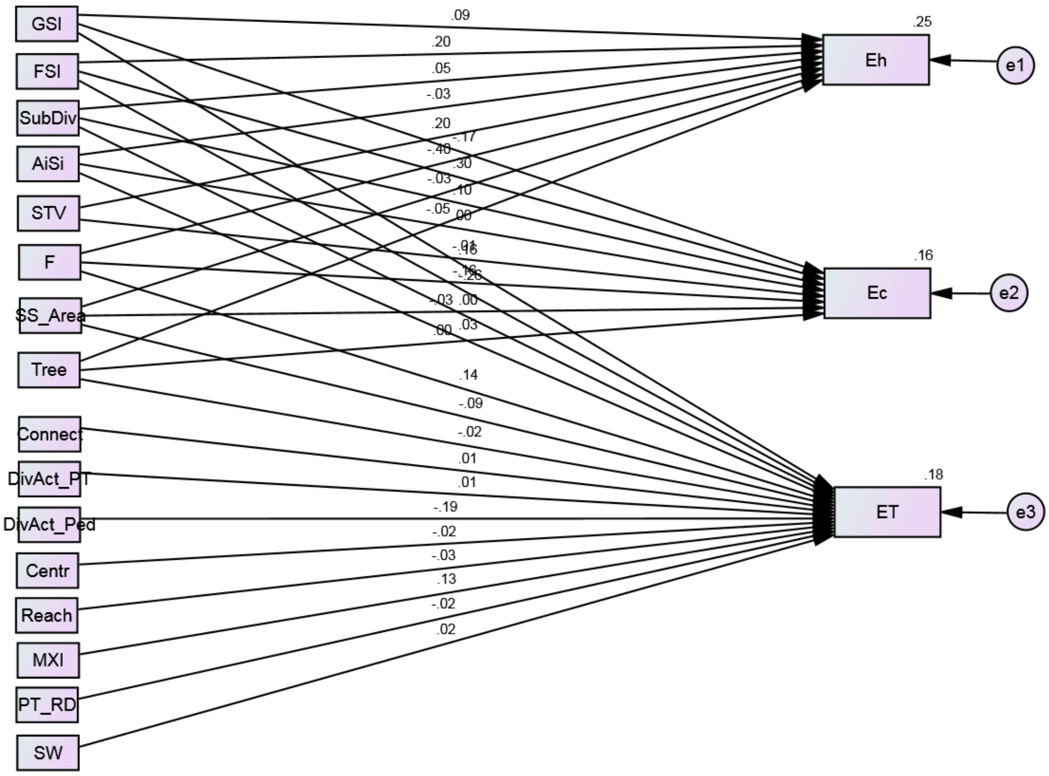

Figure 53. SEM considering all variables under an input-output framework

Table 19. Fit metrics for SEM 1. Porto

SEM1	RMSEA	CFI
	0.211	0.042

The model depicted in Figure 53 entails the same individual relationships as modelled in the Multiple Linear Regression performed earlier, but this time, as it is one advantage of the SEMs, it enables to consider E_h, E_c and ET as outputs at the same time. One interesting finding is that the coefficients of determination of each dependent variable increase significantly from the ones obtained in the MLR, especially for the response variables performing worse (E_c and ET). This is an encouraging finding for modelling all variables from buildings and transports together, instead of considering them in an isolated way.

Despite the graphic representation of the SEM does not enable to perceive the individual regression weights due to a high number of variables involved, it is important to refer that the contribution of the independent variables on explaining the variation of the depend ones is very much in line with the ones obtained in the univariate multiple linear regression (MLR).

Both models were significant at the level 0.01. Table 19 and Table 20 show that while SEM2 (Figure 54) retrieved much lower coefficients of determination for all the variables, its performance (model fit) is better, comparing to the one from SEM1 (both considering the RMESEA and the CFI). This suggests that removing variables *per se*, may help improve the model fit, but is not the solution for modelling the effect of urban form on energy demand. SEM2 evidences that some variables of urban form are interrelated (notably those respecting density). The first model provides a more comprehensive and expectedly realistic picture of the relationship between urban form and energy. In either case, the model fit is not completely satisfactory. A possible interpretation may be that SEM is still not flexible enough to fully address the relationships between urban form and energy demand in cities.

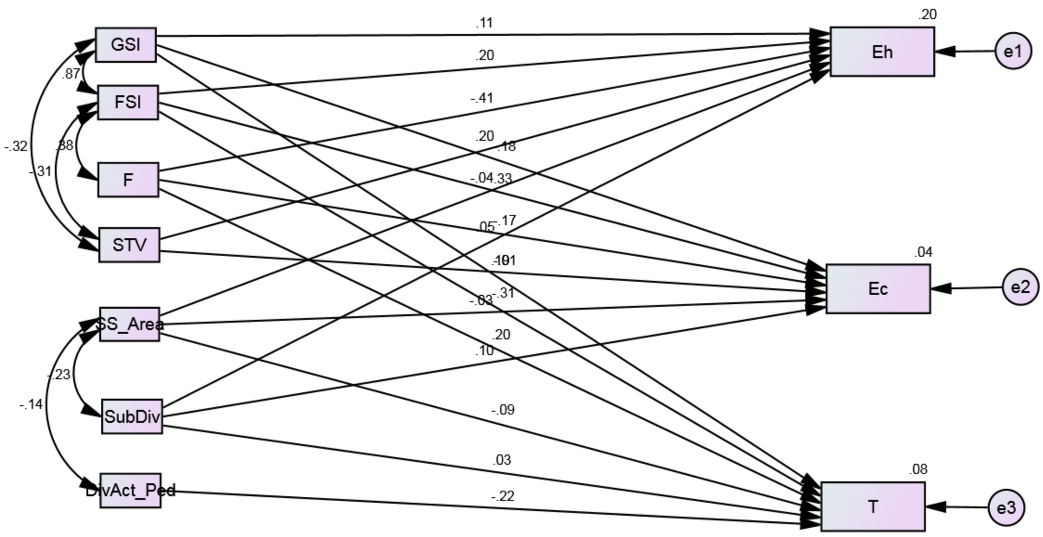

Figure 54. SEM with fewer variables, grounded on the stepwise MLR

Table 20. Fit metrics for SEM 2. Porto

SEM2	RMSEA	CFI
	0.233	0.704

The results obtained allied to the limitation of SEM of not allowing for prediction analysis, leave room for testing an additional modelling technique. The application of SEM provided further insights for understanding how variables relate to one another, in relation to the MLR performed earlier, and confirmed that (still under a linear environment) despite density-related form factors are more prominent for determining the overall energy demand, the contribution of other factors should not be neglected (evidenced by the increased the coefficients of determination). At this point, however, four indicators (shading, passivity, orientation, and cycling) were dropped along the analysis. These will not be included in more complex modelling techniques for three fundamental reasons. The first is that shading and orientation are not properly measured at the block scale, being more relevant when analysing a single building. The second is that passivity evidenced a disappointing relationship and it is suspected to be capturing the effect of compactness. The last reason refers to the specificity of the Porto case study. The cycling indicator does not have enough expression in the city territory to be included in this analysis, although it may, in other cities, represent an important factor to be considered.

4.2.4.4.4. Artificial Neural Networks (ANN)

The advantages and applicability of ANN to the research problem have been discussed in Chapter 3. This is a flexible technique with proven prediction accuracy, enabling to model several outputs at a time. Before reaching the final model and the results presented below for the Porto case study, several modelling options were considered:

- A first experiment was made considering a univariate ANN analysis, built in a similar way to the individual MLR models for each of the three response variables. This enables to compare the accuracy of ANN with MLR without changing the model structure.
- Different network architectures were tested by considering different number of neurons in the hidden layer, as well as training algorithms.
- Finally, further variables were added to the base model (including only urban form variables), which aimed at assessing the incremental explanatory power obtained by considering non-urban form variables.

Table 21 compares the coefficients of determination for each response variable, obtained from the univariate ANN models (i.e. ANN models with a single response variable) and those obtained from the techniques applied earlier (MLR and SEM). It shows that except for cooling, the application of ANN (even if univariate) enables to identify relationships of higher magnitudes for heating and mobility (which are the two most important urban energy uses influenced by urban form). Whereas the R^2 for cooling is comparable to the one obtained from the MLR, it is lower than the one from SEM. This may suggest that cooling patterns are better modelled along with heating. In regard to the significant increase in the coefficient of determination for transport (ET), it may be explained by the existence of important nonlinear relationships that MLR and SEM weren't able to uncover. It seems that ANN is able to find relationships between the data at stake, that the linear models couldn't. This encourages the application of ANN for modelling all the variables together.

Table 21. Comparison between the different R^2 obtained from each of the modelling techniques applied.

	MLR	**SEM**	**ANN univ.**
E_h	0.22	0.25	0.27
E_c	0.02	0.16	0.02
ET	0.09	0.18	0.36

The next step was to consider a comprehensive model, with all the predictors from Table 9, as well as the three response variables at the same time (E_h, E_c, ET). Starting with the default number of 10 neurons in the hidden layer, these have been increased to 13 and to 15 neurons. A larger number of neurons was tested, but once the model fit did not improve significantly, such options were discarded in order to avoid excessive model complexity and a more difficult interpretation of the network weights.

Different training algorithms were tested, as well. The Levenberg-Marquardt (LM) backpropagation algorithm was the most successful training algorithm among those tested (the remaining being the Scaled Conjugate Gradient (SCG) and the BFGS quasi-Newton backpropagation). Table 22 presents the accuracy metrics and the coefficients of determination for the best LM-ANN models, with 10, 13 and 15 hidden neurons.

Table 22. Accuracy metrics of different LM-ANN for each response variable

# Neurons	Variable	**R^2 test**	**MAPE**	**RMSPE**	**R^2 global test**	**MSE test**
10 neurons	**E_h**	0.32	30.9%	49.0%	0.82	0.042
	E_c	0.18	41.9%	70.8%		
	ET	0.17	46.8%	63.4%		
13 neurons	**E_h**	0.37	28.7%	40.4%	0.78	0.047
	E_c	0.10	44.3%	79.3%		
	ET	0.35	41.7%	63.0%		
15 neurons	**E_h**	0.48	29.1%	44.9%	0.78	0.038
	E_c	0.12	47.3%	79.1%		
	ET	0.37	43.3%	62.9%		

Table 22 shows that, overall, a larger number of neurons in the hidden layer enables to obtain models with greater accuracies (i.e. lower errors), not only considering each of the individual variables, but also the whole model. Additionally, the results from the ANN model with 10 neurons, are very close to the ones obtained with SEM. With an increasing number of neurons, and thus increased model complexity and computational cells, it is possible to see that the model begins to predict better for both heating and mobility (while losing some accuracy in predicting the cooling needs).

For the selection of the best model, the determinant criteria included a good global model performance (given by the MSE), while privileging a better accuracy for heating and mobility. This is due to the fact that these two energy end uses are the most important in determining the overall urban energy demand (the needs for cooling have a significantly lower share of final energy use). As such, the best model was the LM-ANN with 15 neurons in the hidden layer, not only because it presents the lowest MSE for the global model, but also because it was able to find individual relationships of higher magnitudes for heating and mobility without losing the respective accuracy (Table 22).

In addition, the selection of the best model took into account not only the accuracy metrics from Table 22 (MSE, MAPE and RMSPE), and the coefficient of determination, but other model features. The normality of the errors was checked for resorting to an error histogram (Figure 55), the minimum MSE for the validation and testing datasets being obtained at close iterations (Figure 56), and similar coefficients of determination for each of the modelling phases – training, validation and testing (Figure 57).

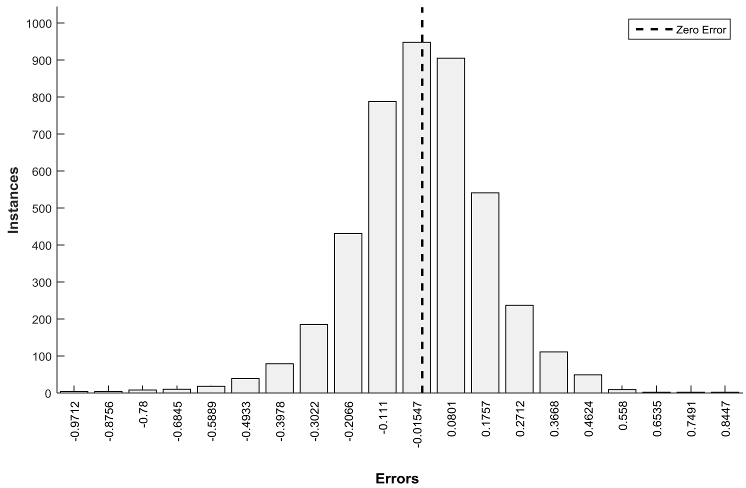

Figure 55. Error histogram of the ANN model. Porto.

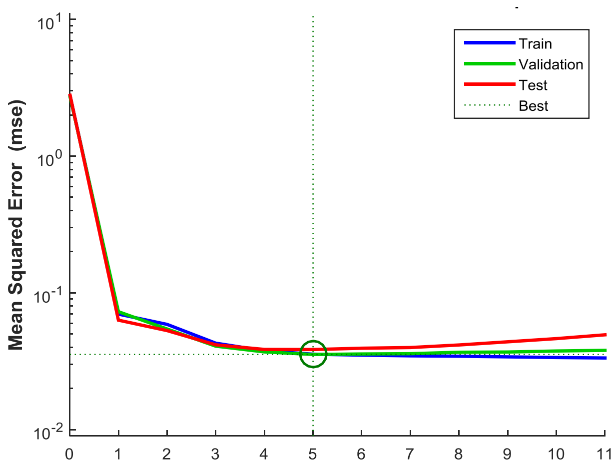

Figure 56. Mean Squared Error of the three datasets at different iterations. Porto.

Minimum mse values in close epochs for test and validation datasets (Figure 56), which have similar curves suggests a good split of data samples.

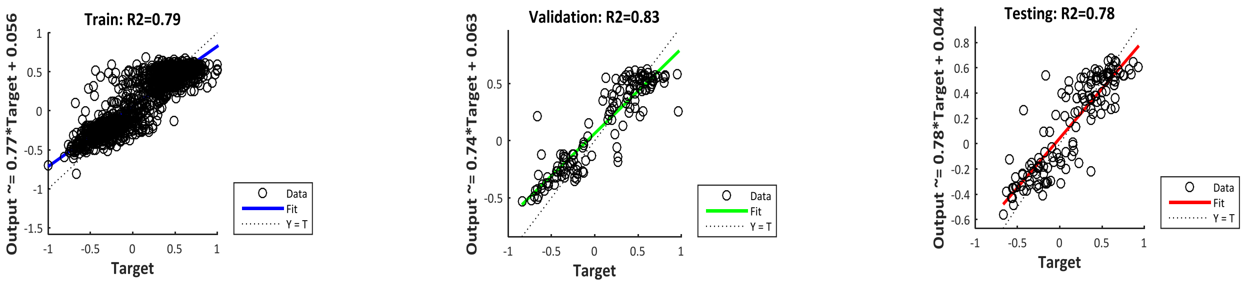

Figure 57. Relationship between the real values (targets) and the modelled values (outputs) of the global model. Porto.

Obtaining close coefficients of determination for each of the different modelling phases (Figure 57) reveals that the model has enough generalization capacity, i.e. that there is no overfitting.

This pioneering application of ANN to model thermal energy needs in buildings and mobility needs altogether retrieved promising results. On the one hand, the results corroborate the existence of significant relationships between the urban form variables and energy needs, with the coefficient of determination presenting a significantly higher magnitude than those obtained from the previous methods. On the other hand, it showed that a model relying on urban form variables only (i.e. based on indicators available at an early stage of an urban development plan or project) enables to estimate with enough accuracy the energy demand for the urban area at stake (especially considering that urban form is not the only driver of energy demand), and at a high resolution level. In addition, the values obtained for the individual prediction errors were more satisfactory than those obtained in the other techniques, and the global ANN model fit is quite satisfactory, as well.

The R^2 obtained for the global model supports studies claiming that the combined effect of several urban form variables could be quite large (Ewing and Cervero, 2010). In this case, it may explain about 78% of overall energy needs for buildings and transports together. As noted earlier, in the case of buildings the data refers to energy needs obtained from the building certification scheme. Considering real consumption would likely retrieve weaker relationships, as it is likely to be more dependent on technology and behavioural factors, instead of on urban form. Also, the results suggest that the energy needs for cooling (E_c) are those least influenced by urban form, for the latitude explored in this case study. This is visible by the lower R^2, as well as from the higher prediction errors, notably the RMSPE that penalizes large individual errors. Here, urban form primarily influences heating needs in buildings (about 48%) and mobility needs (about 36%). This strongly supports the adoption of urban planning and urban form-oriented policies targeted at energy conservation.

It is acknowledged that there are other variables influencing energy demand (e.g. behavioural/ social and economic factors) not included in this model. This is the reason why the coefficient of determination is considerably lower than 1. The goal of this work is not to build an extremely accurate prediction model, but instead, to focus on the contribution of the variables of urban form, and to check for their combined influence on specific urban energy uses. As shown, the results obtained from the application of this methodology to a real case study have confirmed the relevance of urban form attributes regarding urban energy performance. Such a model may work as a case-specific tool, with relevance for local early stage decision-support in urban and energy planning.

Acknowledging that social/ behavioural and economic factors are also drivers of energy demand, a supplementary modelling exercise was performed, consisting of adding socio-economic explanatory variables to the ANN model built before. The variables initially considered were:

- Resident population;
- Average construction period of buildings;
- Percentage of active population;
- Purchase Power (PP) / Gross Domestic Product (GDP)

However, the level of detail at which the model is being applied leads to some constraints on data availability. The closest indicators to the variables initially considered were: the resident population; the average construction period of buildings; and the percentage of active population (as proxy of the occupancy of dwellings and mobility patterns of active *vs.* non-active population, i.e. employed *vs*. children, unemployed and retired people). The economic indicators (PP and GDP) were only available for the city as a whole. After running several iterations, this last modelling option was dropped because it didn't return significant improved results (higher coefficients of determination or lower errors), comparing to the base model including only variables of urban form. Table 23 presents the results for the best ANN model including social indicators. It shows that not only were the individual relationships and respective prediction errors less interesting, but also that the overall model accuracy significantly decreased (given by the higher MSE) by adding the new variables. These results may be explained by the fact that, thermal energy needs in buildings, as given by the building certification system, reflect the characteristics of the building itself, instead of real occupancy patterns (more related to the resident population and the percentage of active population). As for the construction period, one can consider that the urban form indicators used for the base model already describe the existing building types, which may turn this indicator somehow redundant. In the case of mobility, one may infer that economic and behavioural factors play a more significant role, which isn't captured by the indicators that were available.

Table 23. Accuracy metrics for each response variable of the model with social indicators

Model	Variable	**R^2 test**	**MAPE**	**RMSPE**	**R^2 global test**	**MSE test**
Base Model + social vars.	**E_h**	0.34	29.7%	50.2%	0.79	0.050
	E_c	0.27	40.2%	63.9%		
	ET	0.28	46.9%	67.5%		

The next methodological stage, knowledge discovery, is developed for the best performing model. The process of extracting information from the ANN model, along with the respective results is described and illustrated in the following section.

4.2.5. Knowledge Discovery

Notwithstanding the successful results regarding the ANN model fit, it is also important to consider the model's ability to explore the links between the different predictors and response variables. As pointed out earlier, one of the critics pointed to ANN is the fact that it behaves like a black box. Up to date, there isn't a consensually agreed or accepted method to extract information from ANN on the influence of the different variables considered, i.e. in order to understand how much each predictor contributes to explain the variability observed on dependent variables. For further discussions on the topic please see Gevrey et al. (2003); Olden et al. (2004) and Fischer (2015).

Olden and Jackson (2002) refer three common methods for determining the relative influence of different predictors in ANN: i) the Neural Interpretation Diagram (NID), ii) Garson's algorithm, and iii) sensitivity analysis. The authors explain that the relative contributions of independent variables to the model outputs are a result of the magnitude and direction of the network connection weights, where larger weights correspond to larger effects of the prediction process.

Following Olden and Jackson (2002), this research applies the three methods proposed by the authors, to retrieve knowledge from the neural network model. First, the Neural Interpretation Diagram (NID) and the Garson's algorithm (Garson, 1991) are applied. This is followed by a sensitivity analysis, aiming at exploring the variation of a few response variables of the model in relation to specific predictors. This is not done for all the possible combinations of independent and dependent variables, but instead to some selected pairs of variables. As a complement to this analysis, the urban development alternatives, or scenarios (in Chapter 6) will provide additional sensitivity to the behaviour of the model variables. It will assess the effect of changes in specific indicators of urban form, in order to predict the respective impact on energy demand.

NIDs (Özesmi and Özesmi, 1999) represent the network connection weights in a diagram. The magnitude of the weights is represented by the thickness of the links. Tracking the magnitude and the direction of the weights from the input variables to the outputs is done in two steps, first considering input-hidden weights and then hidden-output weights. More neurons in the hidden layer turn the interpretation more difficult. An alternate approach may also be referred to as the connection weight approach, as in Olden et al. (2004). Figure 58 depicts the NID for the case study of Porto, with positive weights represented in blue and negative weights in black. However, due to the large number of variables and neurons, and the fact that the connections represented in the NID do not link the inputs directly to the outputs, this method offers little insights on the nature of the links between the model variables.

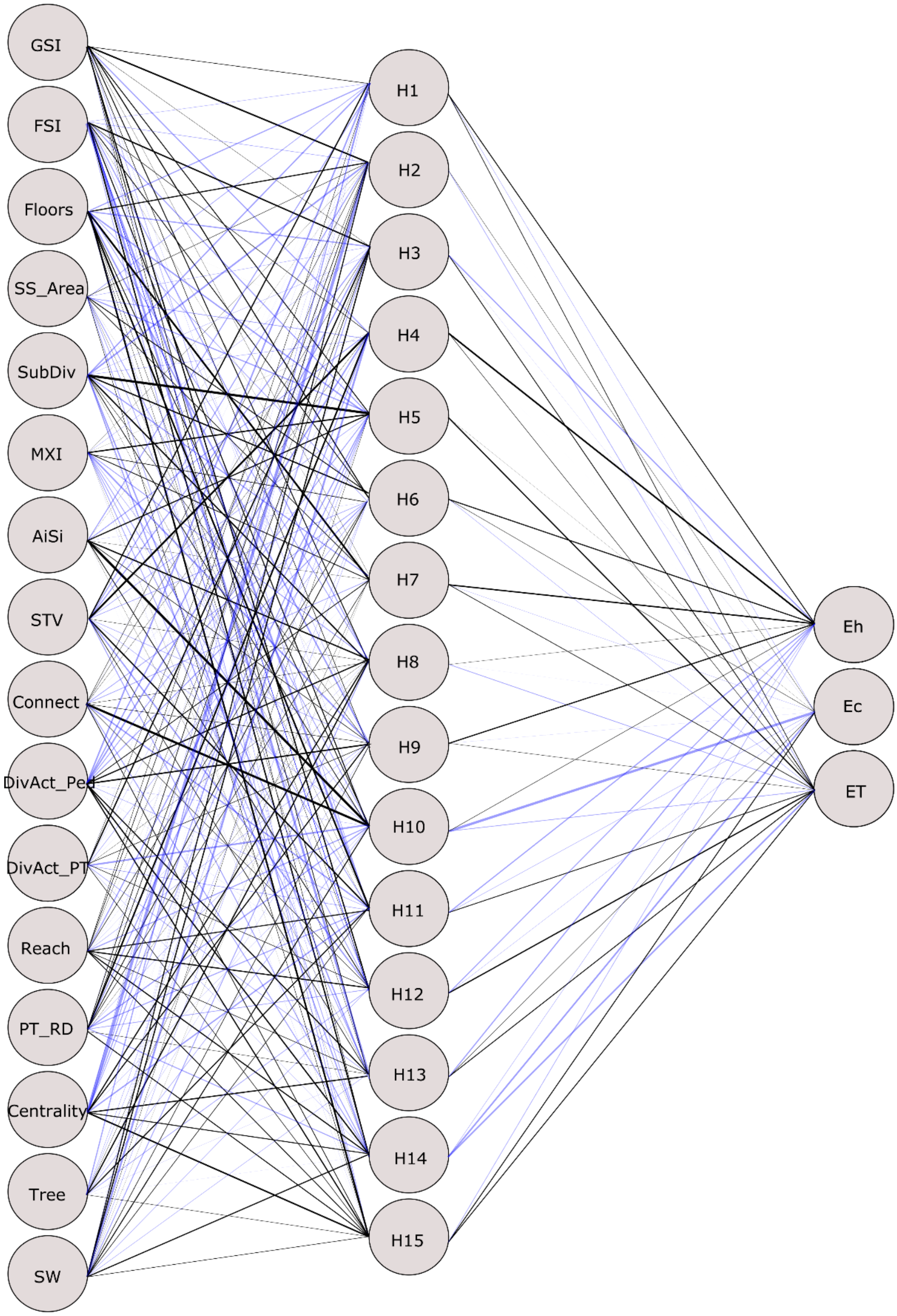

Figure 58. Neural Interpretation Diagram (NID) for the Porto model

In order to further explore the impact of each variable of urban form considered on energy demand, the Garson's algorithm was applied (Garson, 1991; Goh, 1995). It has the drawback of computing absolute connection weights to calculate the contribution of the model variables (i.e. it does not consider the direction of the input-output effects). However, it is the most straightforward method to assess the effect of each predictor on the overall model, and has delivered successful results so far (Gevrey et al., 2003; Fischer, 2015).

The method consists of splitting the hidden-output connection weights for each neuron in the hidden layer into components linked to each input. The contribution of each input for each output is computed through the normalized product of the input-hidden and the hidden-output connection matrixes (the full procedure is illustrated in Olden and Jackson, 2002).

Figure 59 shows the results of the application of the Garson's algorithm to the Porto model, depicting the relative weight of each variable in the urban form / energy demand ANN model. Individual weights roughly range from 4% to 9%. Generally speaking, the most important variables found by Garson's algorithm are in line with the ones identified in the stepwise MLR. These are mainly macro urban form variables related to density (such as GSI, FSI, F) and granularity (Subdiv and SS_Area), along with building compactness (STV) and an accessibility measure for the pedestrian mode (Divact_Ped). The ANN revealed two additional relevant factors: the MXI loses importance in the variable rank, while Centrality becomes a variable with a high explanatory power. In the case of Porto, the city center represents an important hub of urban activities, and thus this evidences that energy demand is significantly influenced by the distance to CBD. This is in line with other authors' findings (e.g. Hachem, 2016). It is also worth noting that the remaining variables account for over 40% of total variable weight. It is interesting to note that ANN was able to find significant relationships between these predictors and the response variables, while MLR and SEM performed better without them.

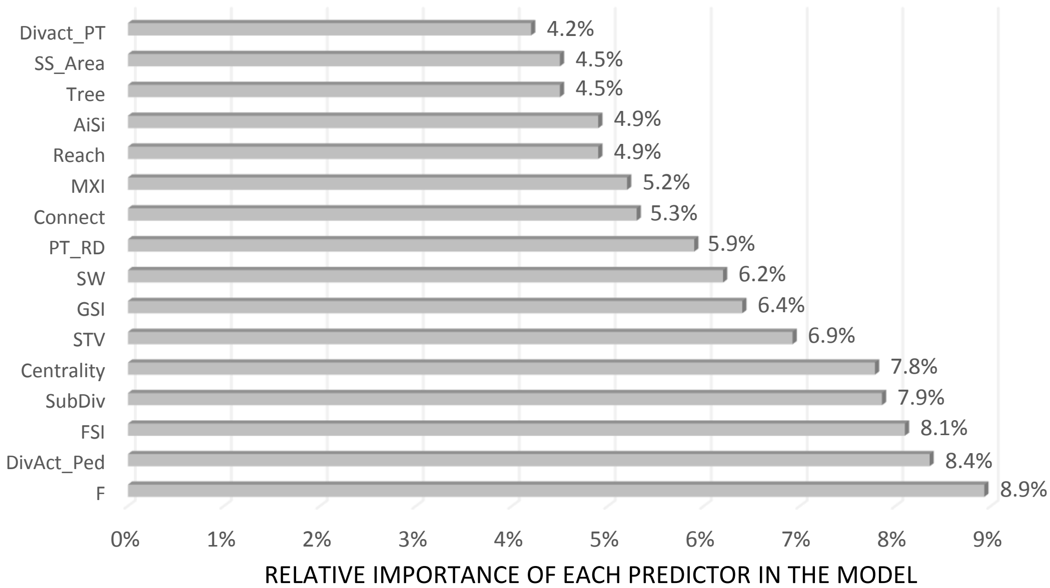

Figure 59. Weight of each predictor in the ANN model (application of Garson's algorithm). Porto.

The last method considered to explore the results from the ANN model is a sensitivity analysis. This is a widely applied method consisting of the variation of input variables in an iterative process, to check for the respective effect on the dependent variables. It has the disadvantage of being a time-consuming process (Olden and Jackson, 2002) in relation to the remaining methods. The sensitivity analysis applied in this context will not cover the full range of combinations between the independent and dependent variables (i.e. 16x15x3). Still, a few illustrative examples are presented in Figure 60, consisting of the variation of a response variable in relation to a specific predictor, for different values of a second predictor (hence, two predictors are analysed at a time). All the remaining independent variables are kept constant. The assessment of urban development alternatives (explored in Chapter 6) may also be considered as a type of sensitivity analysis.

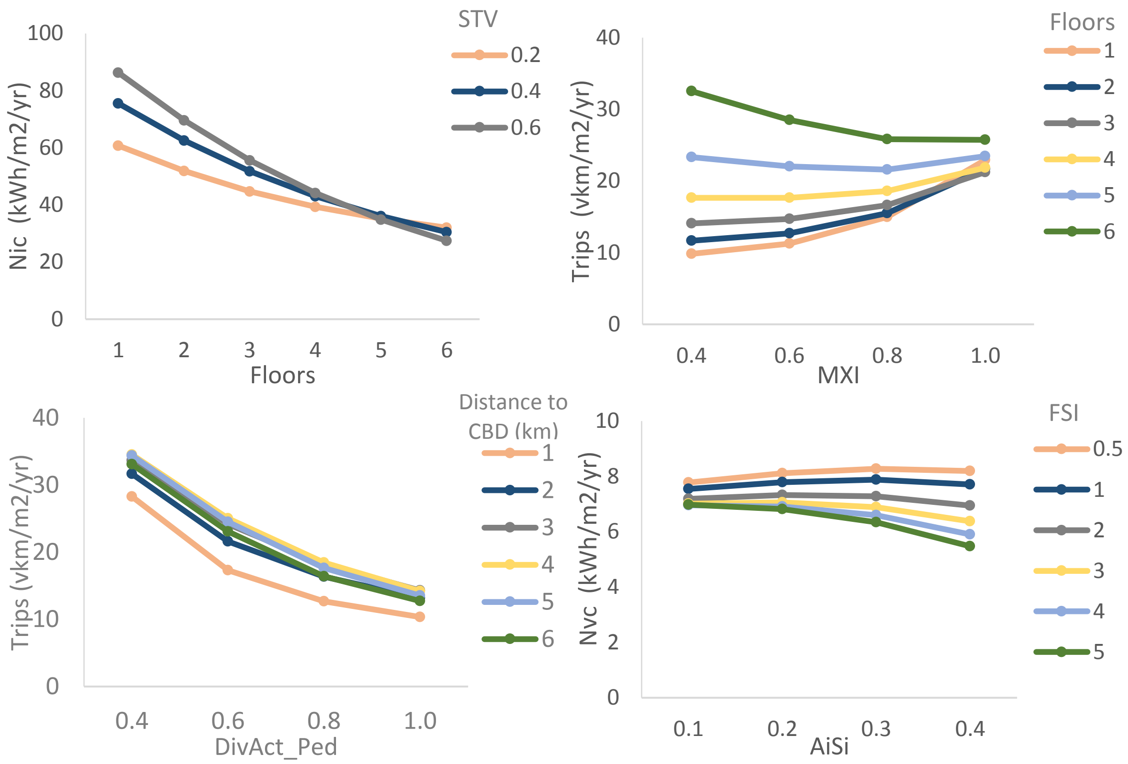

Figure 60. Sensitivity analysis for selected model variables. Porto.

Figure 60 shows that heating needs tend to decrease with higher number of building floors, and with higher compactness indices (lower STV) – the three curves representing different compactness levels seem to converge to a minimum for higher number of floors. A higher number of floors is also (surprisingly) associated with increased travel needs, while the best mix of uses seems to be located somewhere between 0.4 and 0.8, depending on the building type. Still, regarding mobility, pedestrian accessibility is consistently inversely associated to travel needs, with smaller distances to the CBD implying a decreasing energy demand. Finally, cooling needs are inversely associated to the floor space index, and to the share of green areas (although it is not evident whether the latter is captured by the certificates).

In order to take advantage of the spatially explicit approach developed, it is worthwhile to map the prediction errors of the ANN model for each output variable. This enables to compare the model accuracy throughout the territory, for each model output. As advocated by Horta and

Keirstead (2016), a good understanding of the local context is essential to interpret the results of any model, as it allows distinguishing between a poor model performance and unique local characteristics.

Whereas Figure 61 evidences a dominance of low errors related to the predicted heating needs by the ANN model, Figure 62 shows that the needs for cooling are less accurately estimated, with overall higher errors. There seems to be no specific spatial trend in both cases. However, in the urban blocks for which the model predicts heating needs less accurately, cooling needs generally present quite high prediction errors.

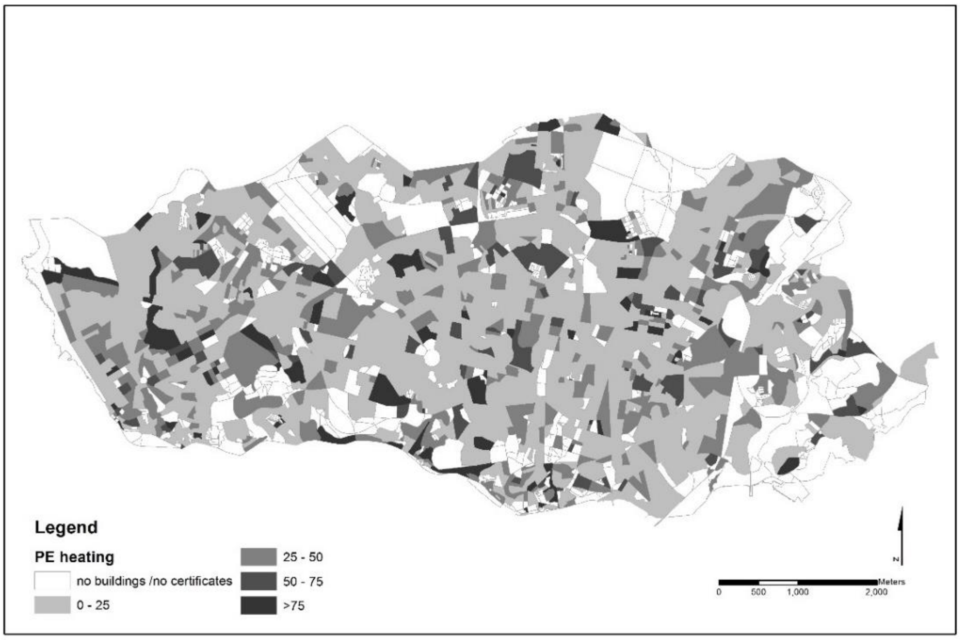

Figure 61. Percent errors of the ANN model for heating needs

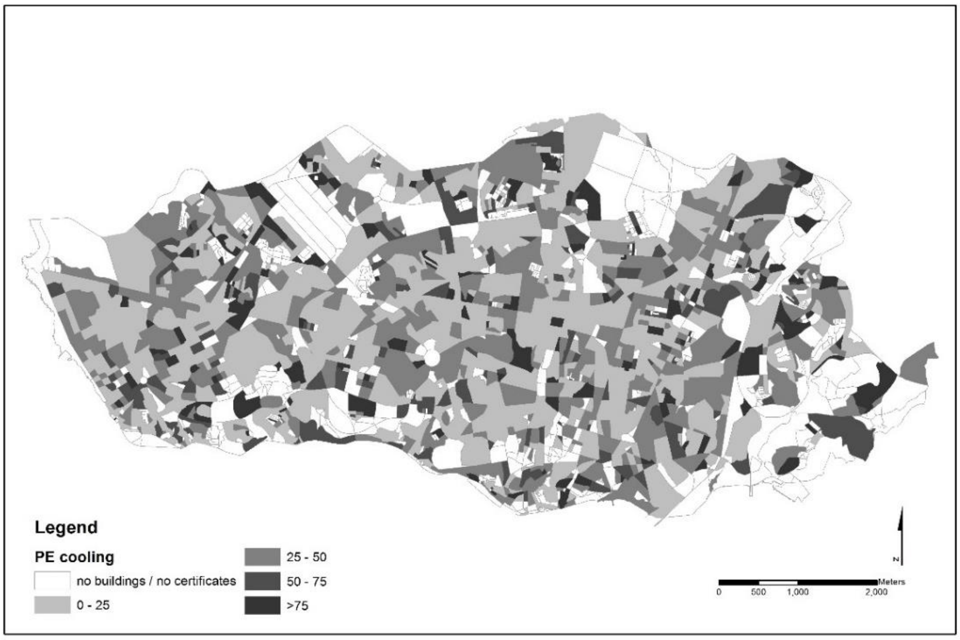

Figure 62. Percent errors of the ANN model for cooling needs

Conversely to heating and cooling, the highest prediction errors for mobility needs (Figure 63) seem to be concentrated in specific urban areas, which may hold an atypical behaviour. This happens in peripheral areas of the municipality that serve as entry/exit points to and from the city (notably in the southern border where the traffic is channelled by few bridges), also in some specific high-class neighbourhoods where people may be more prone to use private vehicles (*Avenida Marechal Gomes da Costa*), and some zones of the municipality that are clearly more segregated (like the zones around *Campanhã* and *Ramalde*). Nevertheless, low errors still predominate for the mobility output.

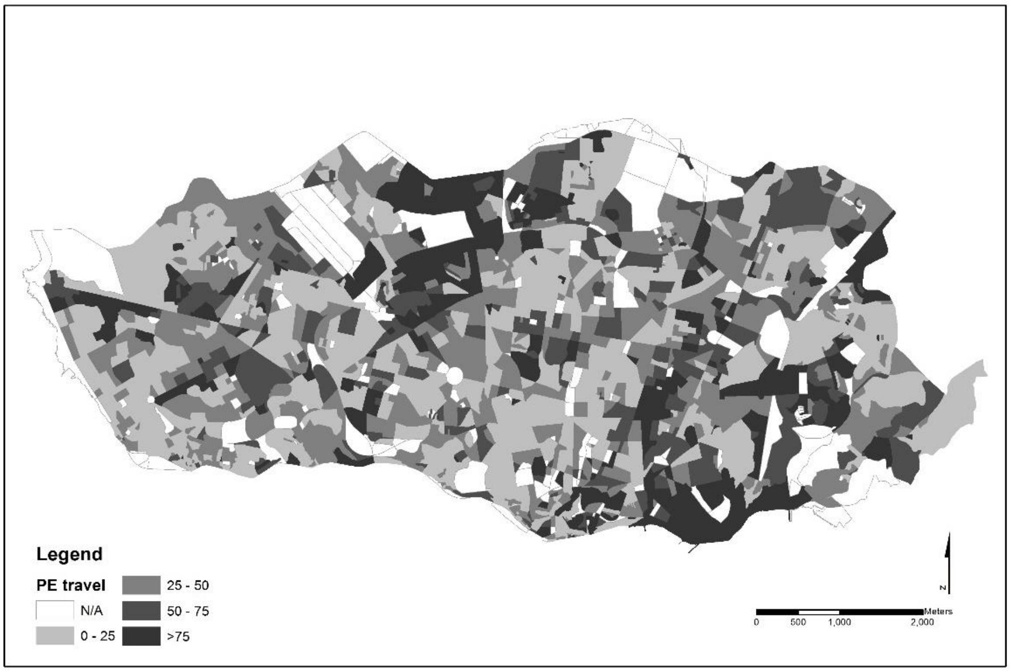

Figure 63. Percent errors of the ANN model for mobility needs

Additionally, considering the spatial distribution of the model outputs, some general trends may be found from the application of this methodology to Porto. Urban blocks in the city centre conspicuously evidence lower needs for motorized travel. The city centre of Porto is characterized by narrow mixed-use pedestrian streets, with a small blocks and high granularity, being one of the areas better served by public transports. One of the areas with highest energy demand for mobility corresponds to the surroundings of the academic campus, located in an outer part of the city, characterized by large blocks, individual buildings, and largely monofunctional areas.

Concerning thermal needs in buildings, as expected, heating and cooling typically have contrary performances. Again, the city centre presents a distinct behaviour from the remaining areas, with overall higher needs for cooling, but lower ones for heating. This largely corresponds to the areas of the city with highest building compactness. This seems the most relevant indicator for determining building’s energy balance.

4.3. Synthesis

This chapter presents an exploratory application of a new methodological framework for characterizing the influence of a set of attributes of urban form on the energy needs for the building (heating and cooling) and transport sectors together. The methodology combines the advantages of a spatially explicit high-resolution analysis, including a mapping component, with the analytical power and accuracy of neural networks (see also Silva et al. (2017b)). The ability to depict in a map the variables under analysis enables to link the data to the territory (at scales ranging from the urban block to the whole city), and helps capturing spatial trends both for the model predictors and outputs, as well as for the prediction errors.

While disaggregated and spatial data is increasingly available for measuring urban form indicators, it is still quite difficult to have access to high-resolution data on energy. In the case of buildings, the building certification schemes in the EU constitutes a major source of information. As for transports, disaggregated data is more difficult to find. A traffic assignment model or traffic surveys represent good alternatives. Although the application of the methodological framework enabled to retrieve interesting results, systematic data collection on transport patterns could enhance the results obtained.

From the three different techniques (MLR, SEM and ANN) applied to model the relationship between urban form and energy demand, ANN has proven to return better results than the remaining techniques, closer to traditional statistics. It enabled to identify relationships with higher accuracy, substantially reducing the errors of the model for all dependent variables. Although it was initially anticipated that the application of MLR and SEM would not deliver results as good as the ANN, this was deemed a useful exercise to explore how the variables relate with each other. In addition, the results evidence the relevance of addressing energy needs for buildings and mobility together.

Although the coefficient of determination (R^2) was superior to those of the remaining techniques, it is lower than one (R^2= 0.78). This was expected, as the variables of the model capturing urban form characteristics are not able to explain the full variability of the data. There are other factors that influence the response variables, such as behavioural and socio-economic factors, which if suitable data was available, could have explained the remaining variability. Still, the goal of this work is to investigate the influence of urban form on energy demand, quantifying its impact and describing the urban environment as extensively as possible.

For the case study analysed, the energy needs for cooling was the response variable least affected by urban form (R^2=0.12). Conversely, heating (R^2=0.48) and mobility (R^2=0.36) needs are subject to a higher influence from the physical structure of the city. Additionally, the most relevant variables of urban form affecting energy demand correspond to macro features, mostly related to density and land uses (the number of floors, pedestrian accessibility and floor area). This is in line with the literature, which has been dominantly focusing on macro features of the urban environment, notably density. However, the results also show that micro variables also have an important role altogether, and should not be neglected. In the case of Porto, increasing densities through higher buildings heights combined with promoting the diversity of activities within a walkable reach should constitute development priorities. In addition, planning for a higher granularity within urban blocks, as well as increasing residential densities closer to the city centre would return significant results.

The model revealed to work as a case-specific tool, enabling to predict the likely energy behaviour of a given urban area from a set of characteristics of the urban environment. The application of this approach to a testbed city confirmed the existence of significant relationships, and enabled shedding some light on the effect of each individual variable on energy demand. This may be an important step towards disentangling the patterns shaping energy demand when a comprehensive set of urban form attributes is considered together. The results from the application of the methodology to the city of Porto encourage its replication in other urban contexts. An additional case study will be explored (Chapter 5) in order to validate the applicability of the methodology in a different urban context, and to compare the results obtained for Porto with a different reality. It is expected that the overall influence of urban form may differ, for instance, due to a more prominent effect of socioeconomic factors.

CHAPTER 5. METHODOLOGICAL APPLICATION TO THE CASE STUDY OF LISBON

This chapter presents the application of the methodological framework to the city of Lisbon. The consideration of an additional case study is expected to support the feasibility of the methodology and validate its replicability in a different urban geography. The procedure adopted will reproduce, as much as possible, the one that took place for the city of Porto. Lisbon was selected as a second case study, since it meets the three criteria desired: i) there is some degree of previous knowledge on the city background, regarding its different neighbourhoods and internal dynamics, which is expected to facilitate the interpretation of the results obtained; ii) it is a medium-sized city (provided the European and world contexts), which is an adequate size for the application of the methodological framework; iii) Lisbon is an old city, which has been developing in different ways throughout the urban territory over time. This leads to a diversity of urban settings, which may be interesting for the analysis.

This Chapter is structured as follows. Section 5.1 provides a description of the case study, considering both territorial aspects and the patterns of energy use in the city. Section 5.2 presents the methodological application to the case study, whereas Section 5.3 synthesizes the results obtained.

5.1. Case study description

Lisbon is the Portuguese capital city, with over 500.000 residents. It has a prominent cultural, institutional and marketable role in the country, geographically located at the centre of the national territory. Lisbon is also the centre of its metropolitan region (with roughly 2.82 million inhabitants), creating a strong polarity effect in the neighbouring municipalities. Considering the recent demographic trends, Lisbon (similarly to what has been happening in Porto) has been suffering the loss of resident population.

Figure 64 shows the evolution of the resident population in the city of Lisbon (2002-2016), evidencing a smooth decline until 2010, after which a much steeper downward curve is visible. A possible explanation for this phenomenon might be related with the economic crisis, which may have led inhabitants to leave their properties in central Lisbon, where the floor area is typically more expensive than in the periphery. Although neighbouring municipalities have been able to attract new residents mostly due to lower housing prices, in the recent years the city seems to have been booming with tourism and foreign investment, which may be developing a gentrification process in the city centre, but rapidly expanding to the whole municipality. This may be the cause of the converse trend introduced in 2015.

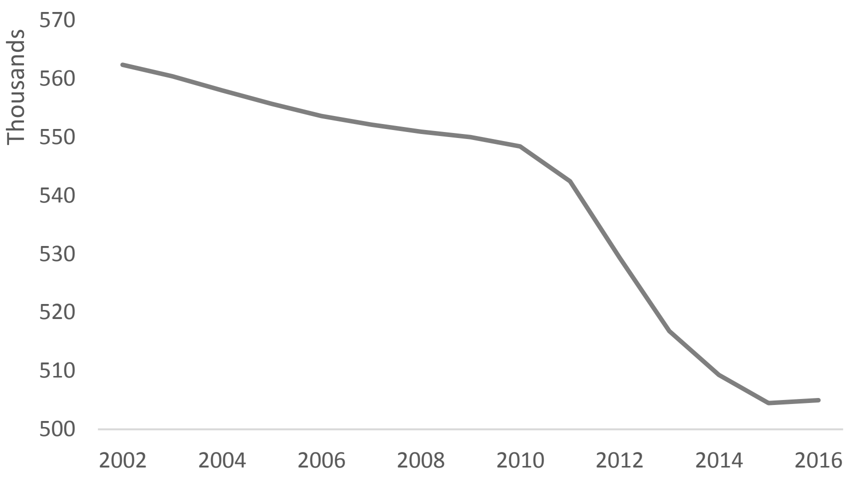

Figure 64. Evolution of the resident population 2002-2016. Lisbon.

The land uses in Lisbon are established in the so-called *Plano Director Municipal* (PDM), the municipal masterplan (Figure 65). It comprises seventeen types of land uses, divided in two main categories (consolidated urban areas and areas to be consolidated).

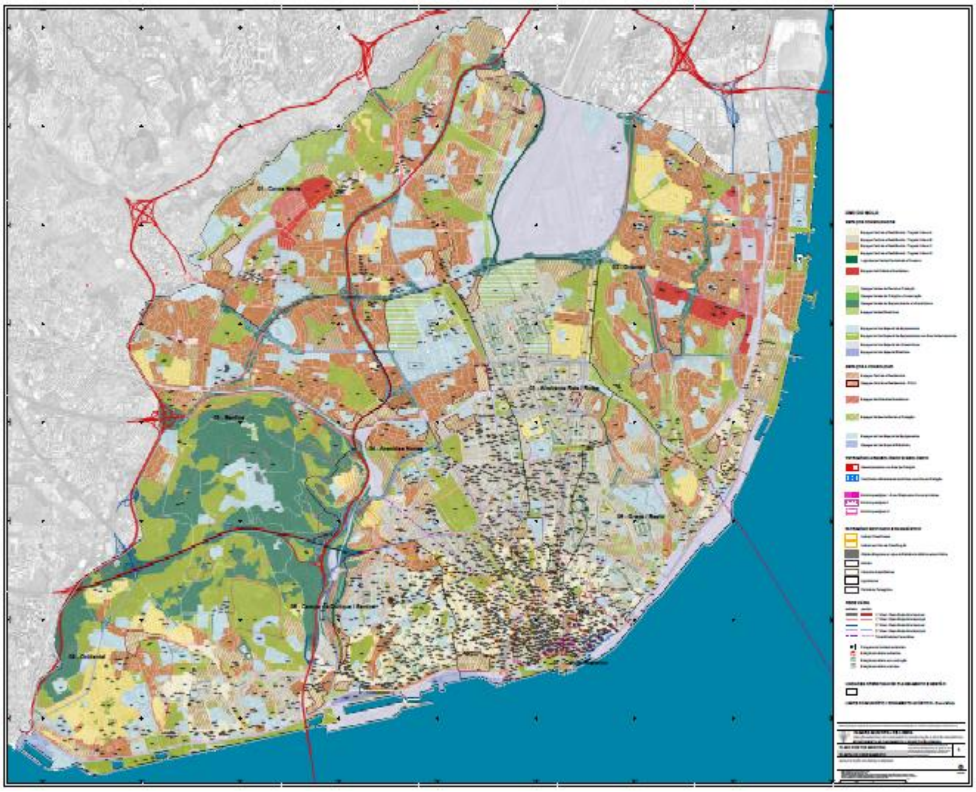

Figure 65. Lisbon Master Plan
Source: Câmara Municipal de Lisboa

The land uses types defined can be roughly matched to construction types. For instance, in consolidated areas, "Traçado A" (in beige) corresponds to older or historic areas. "Traçado B" (grey) is also a consolidated and quite stable urban tissue. "Traçado C" (brown) is a number of more recent areas that may still be subject to some restructuring. "Traçado D" (yellow) corresponds to areas of detached and semi-detached housing. Areas coloured with diagonal stripes are areas to be consolidated of different types. Economically oriented areas are depicted in red. Finally, green areas are broadly represented in several shades of green, and a light tone of grey represents special infrastructure locations (e.g. the city port). Table 24 shows the size of the areas described in the masterplan, evidencing that the city still has some margin for restructuring (given the dimension of the occupation of areas of "Traçado C" and of the areas to be consolidated).

Table 24. Land uses considered in the Lisbon Master Plan

Land Cover Types	**Area (ha)**	**Percentage (%)**
Consolidated areas – Type A	555	8
Consolidated areas – Type B	930	13
Consolidated areas – Type C	1392	20
Consolidated areas – Type D	335	5
Residential areas to be consolidated	717	10
Economic areas	153	2
Green Areas	2355	33
Special Infrastructure	695	10
Total	**7132**	**100**

Lisbon is also a signatory of the Covenant of Mayors, which has enabled the production of relevant documents for the characterization of the patterns of energy use in the city, the most recent referring to 2014 (released in 2016). This is the so-called energy matrix (Lisboa E-Nova et al., 2016). According to this source, in 2014 Lisbon used roughly 4% of the total national primary energy. Figure 66 depicts the primary energy use (tep) by sector and vector in Lisbon, with reference to the year 2014.

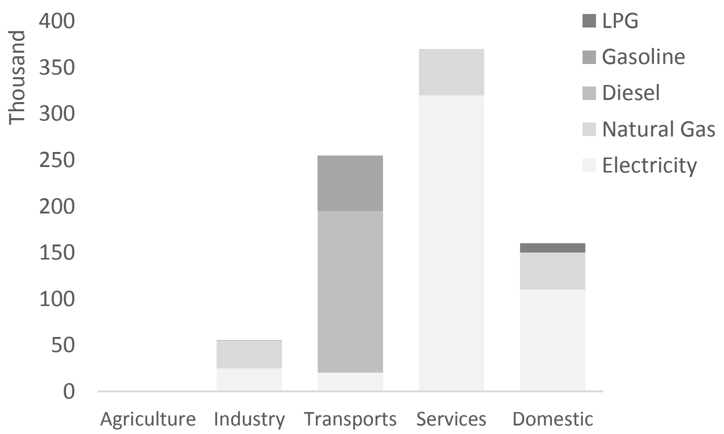

Figure 66. Primary energy use (toe) by sector and carrier in Lisbon (2014).
Source: Lisboa E-Nova et al. (2016)

Overall, the amount of primary energy for the production of electricity holds the largest share in the municipality (around 57%), followed by diesel (21%) and then natural gas (14%). Specifically considering the different urban sectors, the dominance of electricity is naturally conspicuous within the building sector, notably in the case of service buildings. Gasoline and diesel are mostly linked to the transportation sector and their share is 7% and 21%, respectively. Buildings stand out as the largest primary energy users, with the share of service buildings being 43% and domestic buildings using 19% of total primary energy for the municipality. This evidences the role of commerce and service in this particular municipality. Finally, transports used 31% of the total primary energy (Lisboa E-Nova et al., 2016). In regard to the final energy uses, in the case of the municipality of Lisbon, this document does not disclose the shares of final energy for the different end uses, such as ambient heating, cooling, or lighting in buildings; neither does it inform on the shares of the different transport subsectors, such as private transport and freight.

5.2. Data and Methods

5.2.1. Database preparation

Similarly to the case study of Porto, for the database preparation three main types of data were gathered: spatial data, statistical data, and energy data.

5.2.1.1. Spatial Data

The vector data for Lisbon was obtained from two key sources. The municipal authority provided most of the data, including: the municipal master plan – the so-called PDM – with the corresponding land uses (2012), the buildings' footprints (2007), the street network (2007), the green spaces – from the PDM (2012), the public transport stations and stops (2010), the streets with trees (2012) and the sidewalks (2006).

Additionally, the spatial units for the analysis were obtained in vector format from INE, along with the corresponding micro statistics. These geographical features are encoded, and correspond to the lowest level of disaggregation of statistical data (from the Census 2011). They have a relatively homogeneous physical structure, and are roughly equivalent to the urban block, the so-called *subsecções estatísticas*.

5.2.1.2. Statistical Data

The statistical data was obtained from INE. This allowed to keep the same rationale for calculating the indicators of urban form between the two case studies. The statistics included mainly information referring to the characteristics of the built environment and its description may be found in Table 8 in Chapter 4.

5.2.1.3. Energy Data

The search for data on energy demand followed the same reasoning as in the case of Porto. The data sought should reflect the energy demand of buildings, at least at the block scale, and be spatially explicit. In regard to transports, the data desired includes the traffic flows or the corresponding fuel/energy use at the lowest disaggregation level available.

As mentioned above, ADENE made available the building certification database for the two case studies, Porto and Lisbon. The use of this database enabled to achieve interesting results for the case of Porto, and due to comparability reasons, a similar approach will be used for Lisbon. In regard to mobility, this was also the type of data that was most difficult to get access to. As in the case of Porto, due to the lack of official "real" data, artificial mobility data was considered. This was retrieved from the best available transport model for the case study of Lisbon. A more detailed description of the data obtained for buildings and mobility is provided below.

5.2.1.3.1. Built environment

The building certification database was again made available by ADENE. Similarly to the case of Porto, the national database is split in two different datasets, following two different regulations. The first database was built under the framework of the EPBD (Directive 2002/91/EC), first published in 2002 and transposed into the national legislation in 2006 (Decree-Law 78/2006 of April, 4th, 2006 on the National Energy and Indoor Air Quality Certification System for Buildings; Decree-Law 79/2006 of April, 4th, 2006, regulating acclimatization systems in buildings; and Decree-Law 80/2006 of April, 4th, 2006, regulating the thermal behaviour of buildings). The second database follows the transposition of the EPBD-recast (EC, 2010a) to the Portuguese regulatory system (Decree-Law 118/2013 of August, 20th, 2013, updated by the Decree-Law 68A/2015 of April, 30th, 2015), and subsequently by the Decree-Law 194/2015 of September, 14th, 2015).

Pre-certificates and certificates of building projects were discarded from the database (only effectively built structures were considered). Also, only residential buildings were selected, since non-residential buildings are more complex and have a larger set of drivers influencing their energy needs (as described in Chapter 2). In addition, the coordinate system was made uniform and imported to the GIS.

More than half of the initial certificates for Lisbon were invalid. From an original sample of over 74.300 certificates, and after eliminating entries with null fields and certificates with fairly wrong coordinates located outside the boundaries of the municipality, roughly 35.500 were obtained. Further stages of analysis were developed in the GIS and correspond to the spatial analysis described in the following section.

Due to the differences in the method for calculating the energy needs between the two different regulations (in the first regulatory framework the temperature set point was 20 ºC, and in the second regulation the set point was 18ºC), it was necessary to make the two databases comparable. The database from the former regulation was converted into the new one. The sample was large enough to provide insights on the average energy needs for both datasets cases. The conversion factor considered was the ratio between the average energy needs from the later (SCE2) and the former regulation (SCE1) - SCE2/SCE1, both for heating (N_{IC}) and cooling (N_{VC}). This was performed for each construction period, in order to ensure that differences would be due to the calculation method, instead of efficiency improvements in time. The results are depicted in Figure 67 and Figure 68.

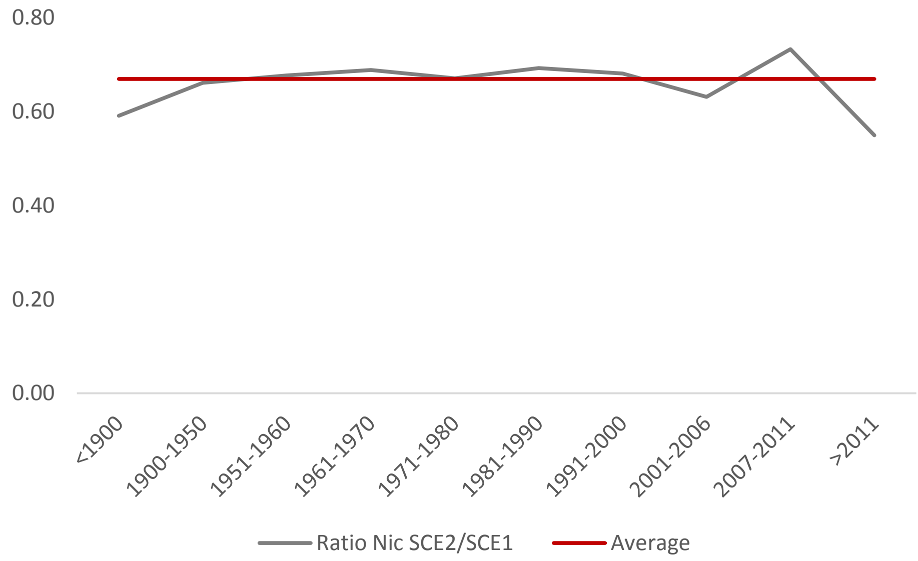

Figure 67. Ratio between the average nominal energy needs for heating of the second regulation (2013) and the first one (2006). Lisbon

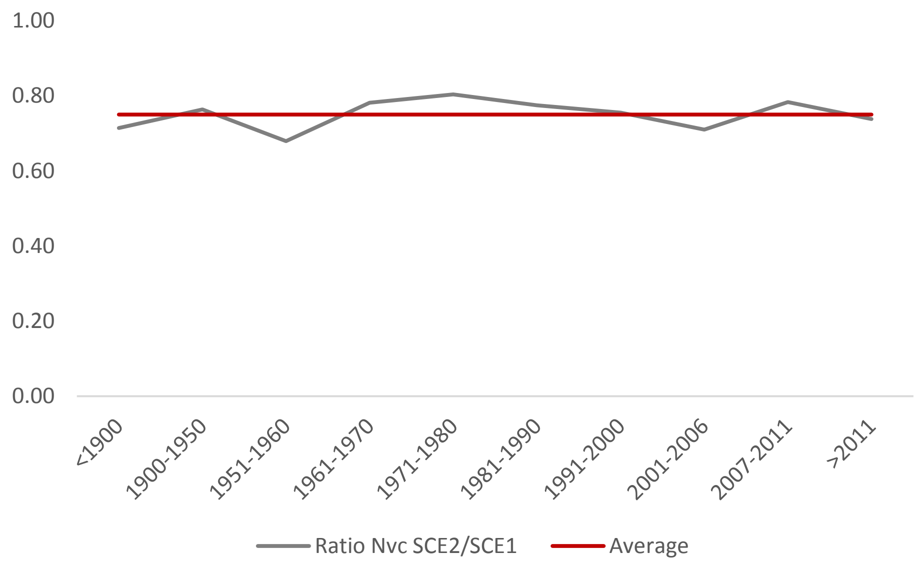

Figure 68. Ratio between the average nominal energy needs for cooling of the second regulation (2013) and the first one (2006). Lisbon.

Whereas in the case of Porto, the heating needs decreased and the cooling needs increased comparing the former and the later datasets (the set point having changed from 20ºC to 18ºC), in the case of Lisbon, both the heating and the cooling needs decreased from the first regulation to the second (although heating needs decreased more than those for cooling). It is also evident that there is much less variability in the ratio values amongst the different age periods in the case of Lisbon than in the case of Porto (especially for cooling). This may indicate that the database on building thermal needs for Lisbon presents less noise than the one from Porto.

5.2.1.3.2. Urban Networks

The existence of disaggregated data on urban mobility patterns is quite limited. There isn't much tradition of disseminating this type of information to the public, and it often happens that some institutions collecting and producing relevant data do not agree on sharing it. There may be the case that traffic studies are developed by private entities, subcontracted by local authorities, and that the original database is kept private, while the public authority gets access to a report with the characterization and to the conclusions on the state of local mobility.

Due to the lack of real data, there also was the need to resort to artificial data in Lisbon. An OD matrix as used in Garcia et al. (2016) was made available by this author[8]. The OD matrix provided is synthetic and was estimated based on a mobility survey developed in 2011, as described in Viegas and Martínez (2010) and Abreu e Silva and Garrido (2011). The estimation applied principles of fuzzy logic to produce a synthetic population of trips with a continuous representation in space and time, as well as a Monte Carlo simulation for the trip dispersion according both to the survey data and to the land uses. The resulting matrix refers to the trips in private mode, in a grid of 500x500 meters over Lisbon's territory (with a few additional zones representing entry and exit points to and from the city).

Two data versions were made available, one referring to the morning peak hour (07.00-10.00a.m.) and another concerning the annual average daily traffic (AADT). The last option was used, as it is closer to the characterization of the mobility patterns sought, thus avoiding additional estimation iterations. The estimation of the total yearly trips was obtained by multiplying the matrix values by 365 – since the value provided is a daily average, it was assumed that differences between weekly and weekend flows would have been already offset.

5.2.2. Spatial Analysis

The spatial analysis consists of measuring the indicators of urban form with energy relevance (Table 4 in Chapter 2), including those related to the built environment and to the urban networks, as well as matching the data of energy demand (for buildings and transports) to the spatial units considered, i.e. the urban block.

This stage resorts to a GIS, allowing to build a dataset of urban form indicators that is attached to the territory, i.e. a geospatial dataset. The indicators/ metrics were computed in this spatially-

[8] This was indicated as being the best available characterization of the mobility patterns in Lisbon by a mobility expert and professor in this institution.

explicit environment and saved in the attribute table of the corresponding layer. Since the data collected for Lisbon is very much aligned with the data used for case study of Porto, it enables to perform the analysis in a similar way to the one adopted before. Recall that in the case study of Porto, a few indicators were not included in the final model (discarded either in the stage of the spatial analysis or early in the modelling phase). As a result, it was decided that these indicators (UHA, passivity, orientation and cycling infrastructure) shouldn't be included in the Lisbon case study (and thus, they will not be mapped or discussed in the next subsection). The reasons for dropping the first three indicators were related to the measurement method at the block scale, which is the same for the Lisbon case study. Thus, the limitations found before are still valid. The reason for discarding the indicator on cycling lanes, had to do with the fact that cycling infrastructure is not yet significantly widespread in the city territory, which also applies in Lisbon (CML, 2017). Although it is projected the expansion of the existing infrastructure, to date it is mostly located in recreational areas (e.g. the riverside, or in green areas) and it does not have enough expression throughout the territory. For these reasons, and in order to maintain a certain degree of comparability between the two case studies, these indicators are not further explored.

In addition, the "atypical" spatial units were removed (for instance, public spaces), as they will not enter the model. A map was produced for each indicator considered, enabling to visualize the variation of the indicators in the territory. The procedure adopted to produce such maps is not described in detail, as it generally followed the same rationale as the one from the previous case study. Still, the existing differences are pointed out.

The following subsections present the maps produced for each indicator (built environment and urban networks), along with an interpretation of the results obtained. Here, some areas of the city are often pointed out, in order to illustrate specific urban form features. For further insights on the location of the areas referred to in the discussion of the maps produced, please see Annex III.

5.2.2.1. Built environment

5.2.2.1.1. Density

Recall that density is measured by three indicators, in line with Pont and Haupt (2005): the ground space index (GSI) – often called compactness of the urban fabric, the floor space index (FSI) – also called intensity and, building height – number of floors (F).

Ground Space Index (GSI)

The GSI (Figure 69) is the ratio between the building footprint and the total ground area of the urban block.

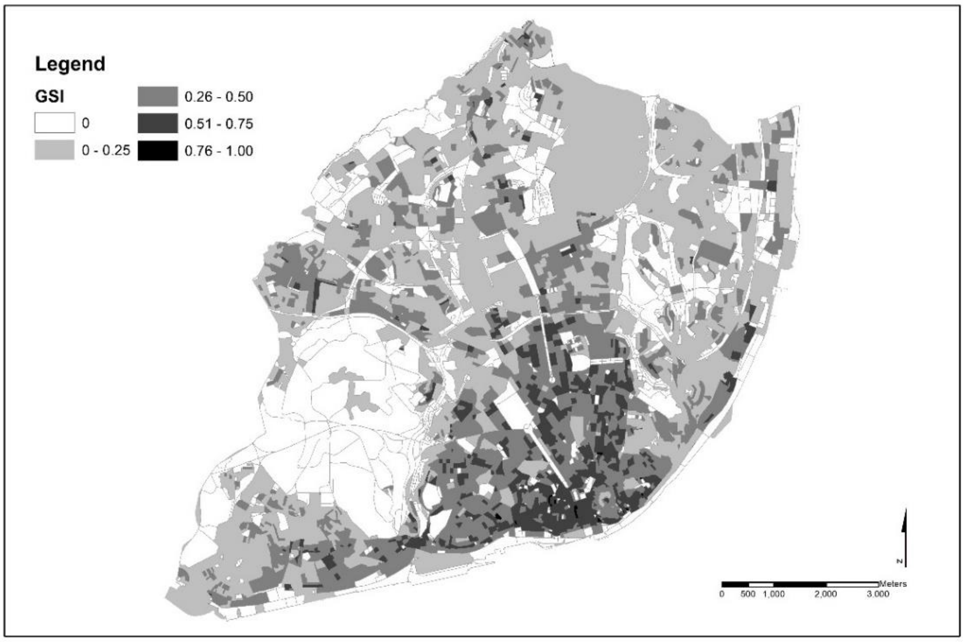

Figure 69. Density, Ground Space Index. Lisbon

Whereas the city of Lisbon has a quite dense core (mostly inwards the city ring road), it is visible that except for some specific nuclei, its periphery still has a quite low land occupation index. This is particularly visible for the GSI indicator, as the type of construction in the outer parts of the city is typically characterized by taller isolated buildings, with a relatively small footprint considering the total floor area. The higher values of GSI are located in older parts of the city, characterized by attached housing patterns.

The white areas in the map represent mostly unbuilt areas, such as parks, squares, or rotundas, which will not be considered in the analysis. In addition to the urban core, some particular areas evidencing high GSI values include small areas in *Benfica*, *Alcântara* or *Belém*.

Floor Space Index (FSI)

The FSI (Figure 70) is the ratio between the building gross floor area (GFA) and the total ground area of the urban block.

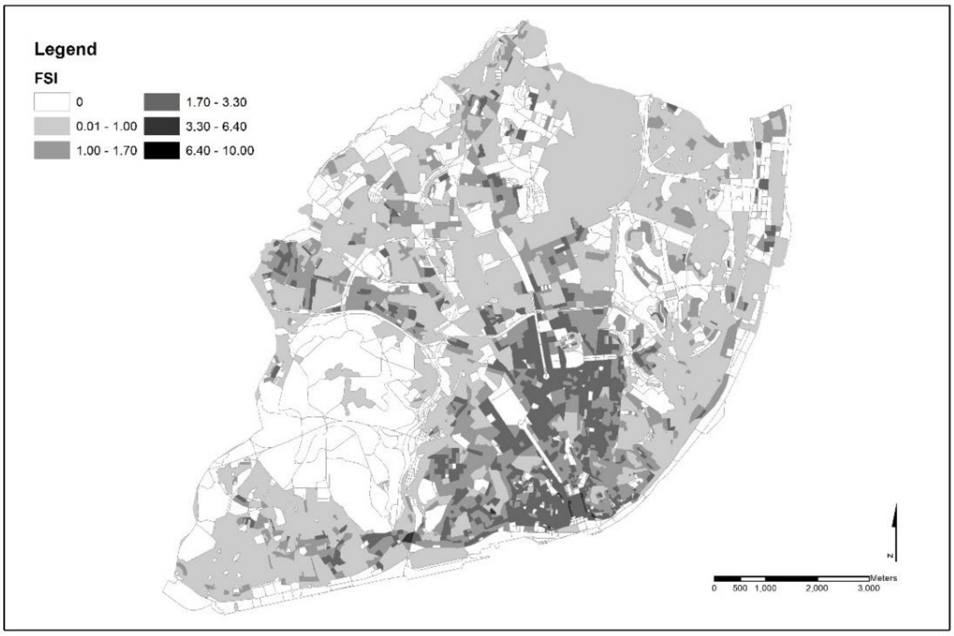

Figure 70. Density, Floor Space Index. Lisbon

The FSI map reveals quite similar trends to the one depicting the GSI, although evidencing even higher intensities in the city centre. This shows that, in the case of Lisbon (and conversely to the case study of Porto), the areas with higher ground space use typically correspond to the ones with higher total floor area.

<u>Building height (F)</u>

The average number of floors in an urban block was estimated following the same process as in the case of Porto (the data source is the same – INE).

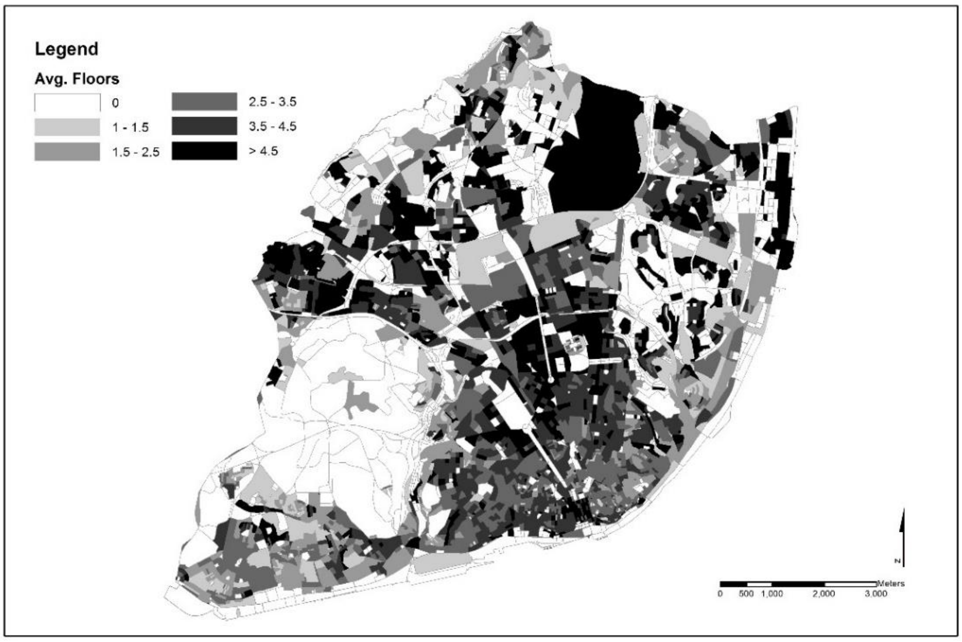

Figure 71. Density, Average building floors. Lisbon

Figure 71 makes evident that the highest buildings in the city are located just outside from where the previous two indexes have scored highest (the visible exception being the *Baixa Pombalina*). It shows that while moving towards the outer parts of the city the number of floors increases, except for the cases that are effectively unbuilt (in white) or neighbourhoods of single family housing (as in the case of *Encarnação*). Note that, although the large block (in black) in the northern part of the city is where Lisbon's airport is located, it also includes some (tall) buildings within this area.

5.2.2.1.2. Granularity

<u>Subdivision indicator</u>

The subdivision indicator (Figure 72) is given by the ratio between the number of plots and the area of the block. In order to compute it, it is assumed that a building corresponds to a plot (following Oliveira and Silva, 2013b).

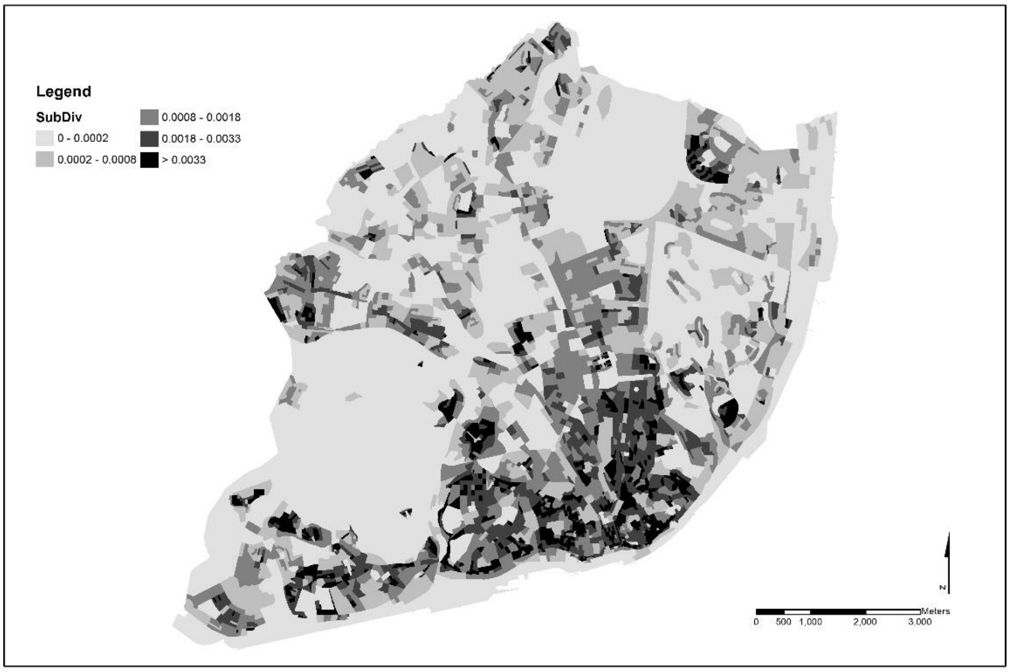

Figure 72. Granularity, Subdivision Indicator. Lisbon

It is interesting to note that the results for this indicator are quite different from those obtained in Porto. In order to facilitate comparisons, the colour coding intervals were kept. The indicator on the subdivision of blocks takes into account the area of the block. As such, it is not surprising if the effect of size is attenuated, since larger blocks have the possibility to have more plots than smaller blocks. However, in the case of Lisbon, it is clear that blocks located in the historical kernel (which are typically smaller) are much more subdivided than those in outer areas of the city (even though these are typically larger). The results of this indicator are in line with those obtained for the GSI and the FSI (meaning that here density is very much attached to granularity). Besides the city centre, the areas presenting high values for this index are again, *Benfica*, *Belém* and *Ajuda*, as well as the neighbourhood of *Encarnação*.

Size of the blocks

The size of blocks (Figure 73) is automatically given from the geometry of the spatial features.

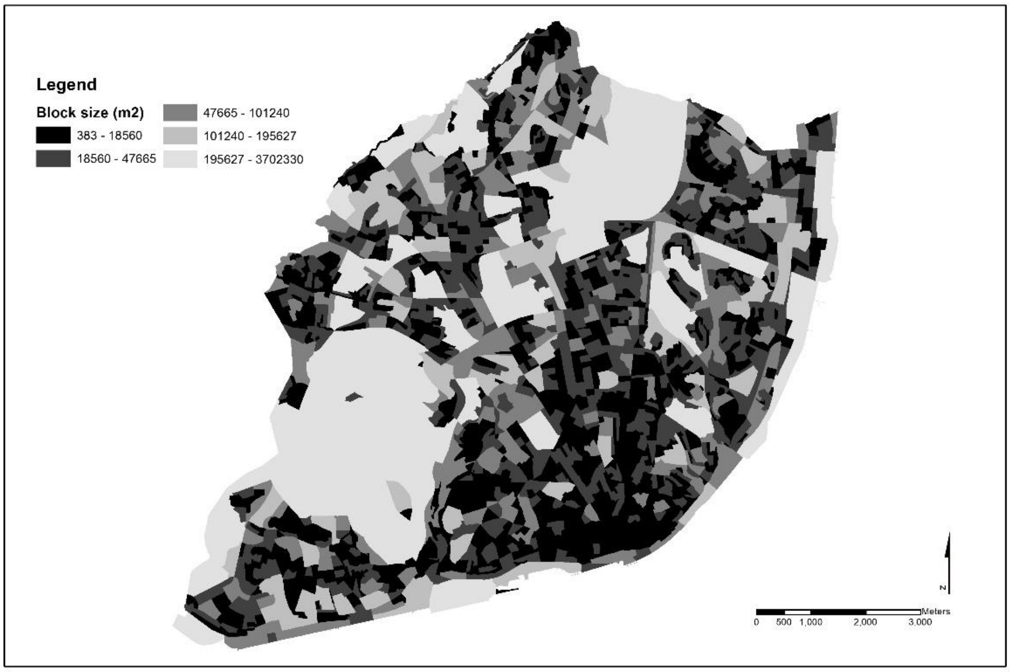

Figure 73. Granularity, Size of the Blocks. Porto

Regarding the size of the blocks, as expected, smaller blocks are mostly located in the city centre, corresponding to older areas of the city such as *Baixa*, *Chiado* and those in the surroundings of the city castle (*Castelo*). Outside the city centre, the location of small blocks is very close to those places mentioned above, with a higher subdivision index. In addition, two large patches mark this map, corresponding to very large urban blocks. In the south-west is the *Monsanto* green park and in the north-eastern part of the city is located the airport.

5.2.2.1.3. Diversity

Diversity is measured by the MXI – mixed-use index (van den Hoek, 2008) as the ratio between residential gross floor area (GFA) and the total GFA in the urban block. The method adopted to allocate gross floor areas to land uses followed the same rationale as in the case study of Porto. Figure 74 depicts the MXI in Lisbon.

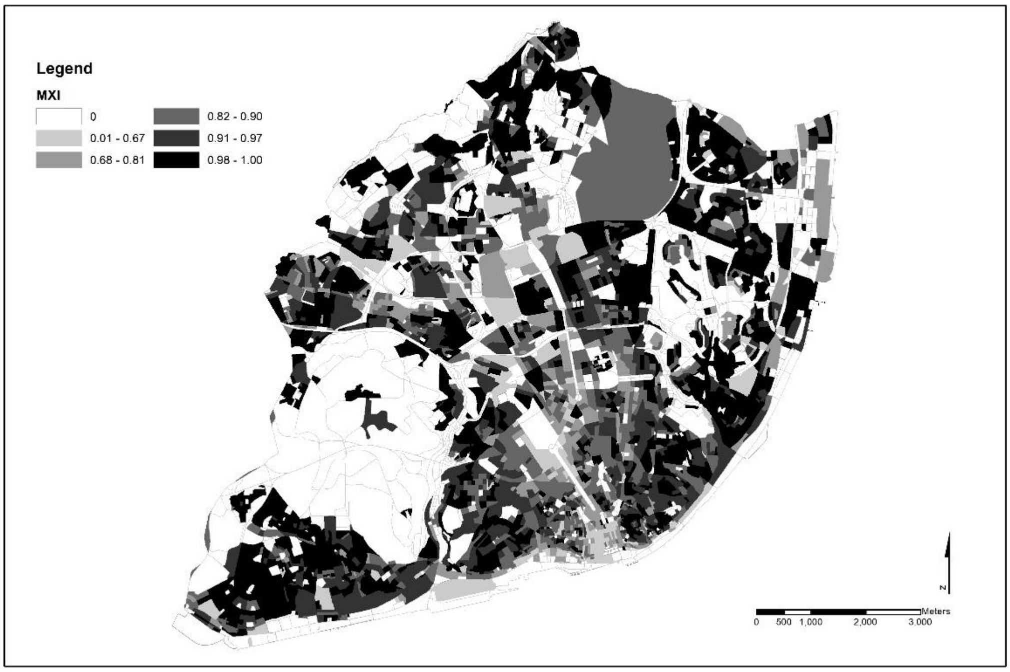

Figure 74. Diversity, MXI. Lisbon

Higher values for the MXI reveal areas that are dominantly residential (depicted in darker colours). As expected, the downtown (*Baixa*) presents lower MXI values, as well as some urban blocks that are adjacent to major street axes (for instance along *Avenida da Liberdade*, *Avenida Fontes Pereira de Melo*, *Avenida da República*, or *Avenida Almirante Reis*). Apart from these, the territory does not evidence a significant mix of uses. Blocks depicted in white are either areas without buildings (such as squares), or areas with buildings that are not accounted in the existing statistics (as described above), like an urban block occupied only by a hospital or the industrial district. Note that the airport block is depicted in grey because the airport building is not considered in the existing statistics, and this block has other buildings with residential uses (in any case, this block will not be considered for the modelling stage).

5.2.2.1.4. Green areas

The data used on the location and size of green areas was retrieved from Lisbon's Master Plan. The land use categories considered were:

- Green spaces for leisure and production;
- Green spaces to be protected and preserved;
- Green spaces on the riverside.

Again, the green spaces bordering road axes were left out of the analysis because these are not used by the people, as they are locked in the middle of large and traffic-intensive roads. Figure 75 maps the spatial distribution of green areas in the city of Lisbon.

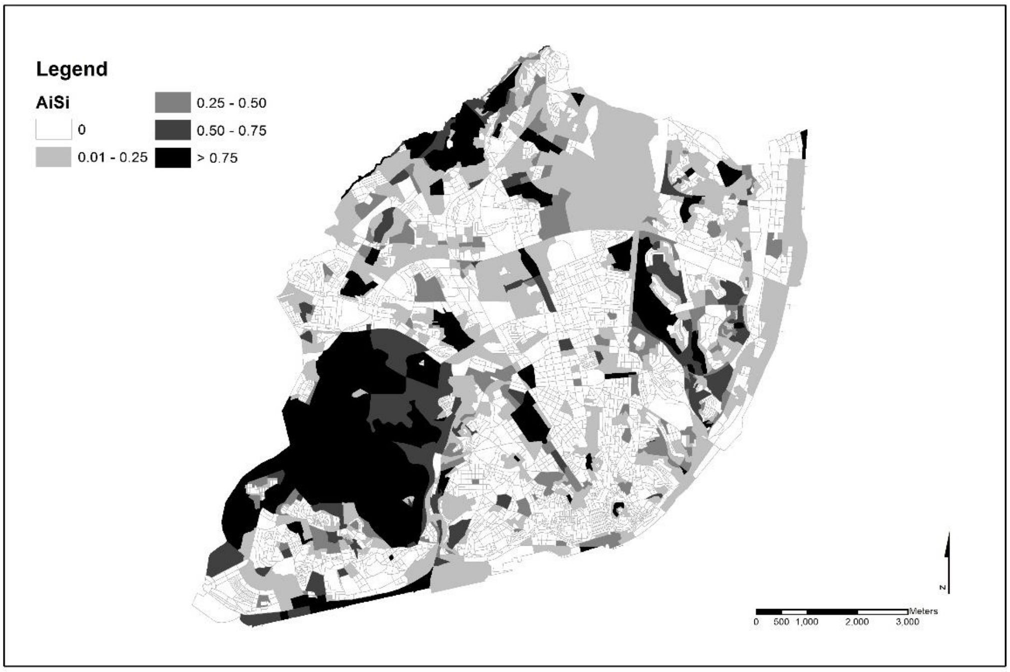

Figure 75. Spatial distribution of green areas. Lisbon

Higher values for this index, represented by darker colours, mean a higher importance of a green area in a block and in the city. From the map, it is evident the importance of Monsanto park (the large western black patch), as well as the role of green areas like *Eduardo VII* park in the city centre and *Bela Vista* in the Eastern side. This seems to be captured quite well in the map, since these are important recreational and leisure areas in the municipality.

5.2.2.1.5. Compactness

The building compactness (Figure 76) is characterized by the surface to volume ratio (Ratti et al., 2005). Only exposed façades are considered to determine the surface area (S) of each building.

The higher the STV, the lower the building compactness. Higher STV are depicted in darker colours (Figure 76). It is visible that the areas with greater compactness are located in the city centre, but these do not necessarily correspond to the historic areas (as in the case of Porto), see for instance the case of *Castelo* or *Belém* presenting high STV. It is interesting to note that the zones of the city with greater building compactness seem to coincide with those where the price of the floor area is higher. This is the case of *Baixa*, but also *Roma-Areeiro*, and *Avenidas Novas*.

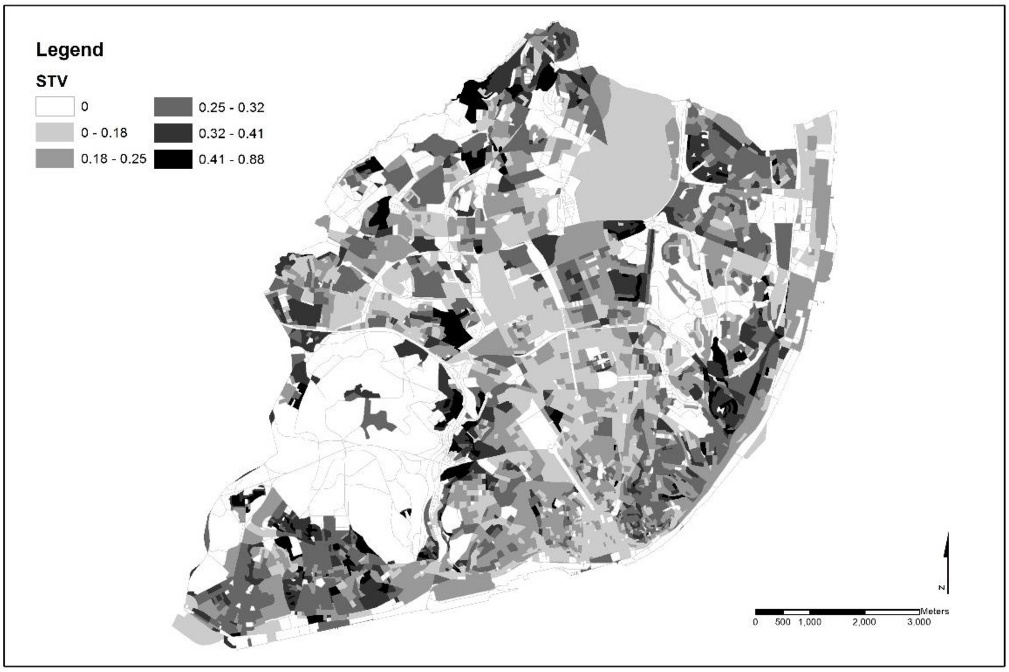

Figure 76. Compactness. Surface to Volume ratio. Lisbon

5.2.2.2. Urban Networks

In order to measure the indicators of urban networks, some preliminary operations were performed. The ID code of the adjacent blocks for left- and right-hand sides of a street were attributed to each street edge, which enables to import data to the block layer through a table join. Additionally, since the computation of some indicators needs to run the street network as a network dataset, it was important to check for and to fix network connectivity problems.

5.2.2.2.1. Connectivity

Connectivity is measured through the Beta index (β), which gives the average number of edges (e) per node (n) in a given network. In this case, the beta index of an urban block is determined as the average connectivity value of the streets delimiting its boundaries.

Figure 77 evidences that the blocks in the city centre are typically better connected. However, the most conspicuous area with better connectivity is not located in the downtown. Instead, it corresponds to the zone of *Saldanha* (extending south-west towards *Marquês do Pombal* and north towards *Campo Grande)*, which has been developing as a trendy business area, expanding from Lisbon´s CBD. In addition, larger connectivity indexes are obtained in the recently developed area of Parque das Nações (north-east, by the river), which is possibly a result of the street network design, typically with gridded patters in this area. Lower beta values are obtained for the urban blocks surrounding *Monsanto* park, and *Xabregas*, largely corresponding to areas of the city that are commonly thought of as segregated, as well as those close to the airport, as a consequence of its size.

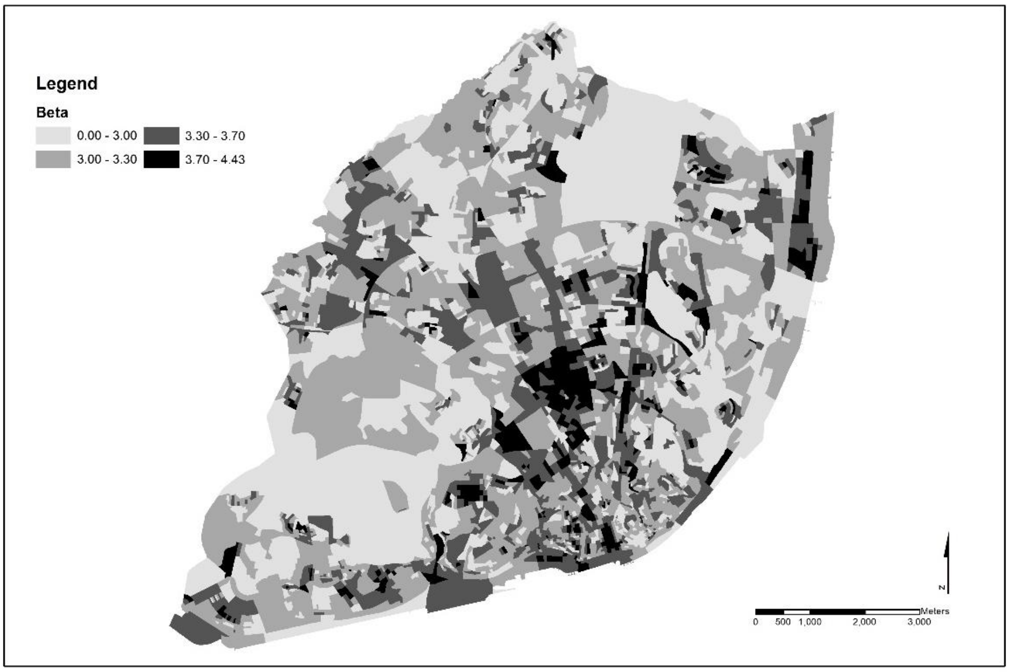

Figure 77. Connectivity. Beta Index. Lisbon

5.2.2.2.2. Accessibility

Two indicators are considered for measuring accessibility: the *DivAct* and *Reach*.

DivAct

Similarly to what happened in the Porto case study (Silva, 2013), there was a previous application of the Divact index to the city of Lisbon, under the scope of the research project EVIDENCE – Reinventing analysis, design and decision support systems for planning – funded by the Portuguese government (the candidate was part of the project team). As such, the data for this indicator was again made available by C. Silva, and thus there was no need to compute it from scratch. In any case, this could have been done resorting to information on the location of activities and housing in the city, and the existing transport networks for each travel mode (car, public transport and walking).

The DivAct index for private vehicles is not very useful in the case of Lisbon, since all of the city's territory is accessible by car (with DivAct_car values very close to 1). The DivAct for public transport (DivAct_PT), presents a more interesting spatial differentiation (the time impedance for the DivAct_PT is twenty minutes), but it is visible that most of the municipality has a high accessibility by public transport (Figure 78). There is a couple of quite centrally located exceptions: *Olaias* and *Penha de França,* which present lower accessibility values, and denote some segregation patterns. Finally, the pedestrian DivAct (DivAct_Ped) provides a better differentiation of the existing local accessibility. The time impedance for calculating the pedestrian index is a ten-minute walking reach. The pedestrian DivAct is expected to be inversely related to the need of using private motorized vehicles (PMV). Areas with lower values for this index are expected to have higher PMV trips, representing places where walking becomes unfeasible to reach a certain number of activities.

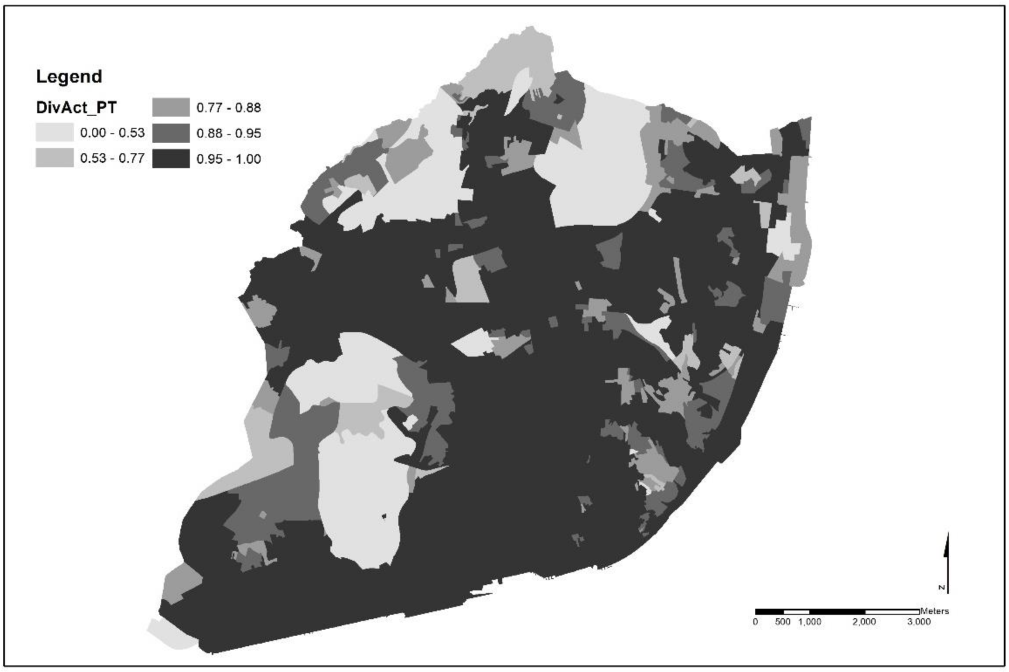

Figure 78. Accessibility. Public Transport DivAct. Lisbon

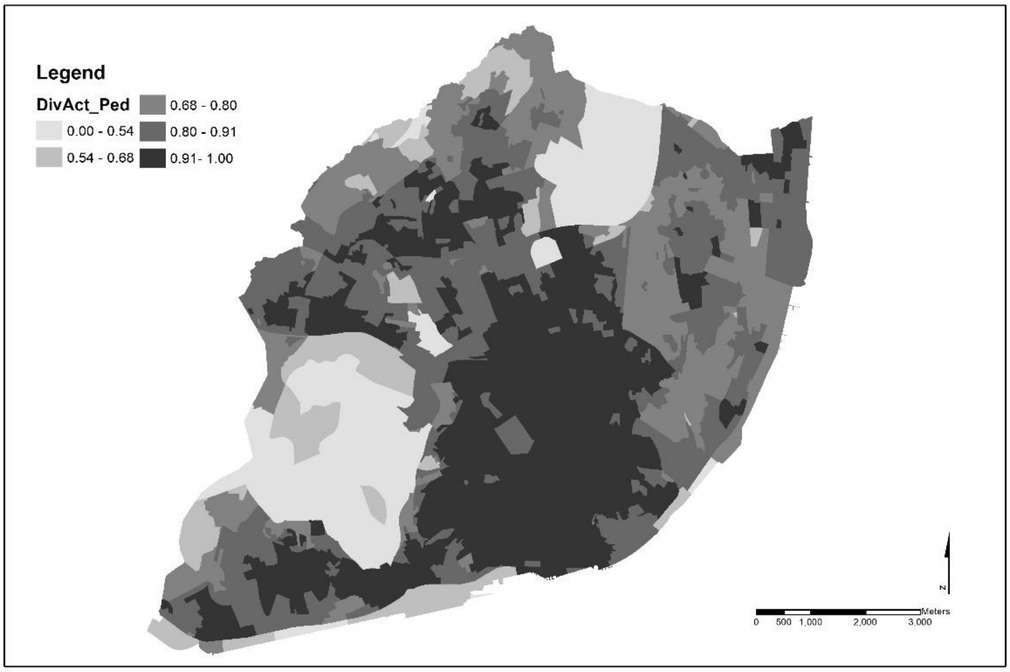

Figure 79. Accessibility. Pedestrian DivAct. Lisbon

Figure 79 depicts the pedestrian DivAct. Darker colours represent areas where walking enables reaching a larger number of urban activities within a ten-minute time budget. It is evident the strong accessibility of the urban core, together with other areas presenting a good provision of commerce and services, mostly corresponding to older and more traditional areas of the city, notably *Belém*, *Ajuda, Alcântara*, *Benfica*, *Alvalade* and *Lumiar*. Of course, the lowest values of DivAct_Ped are obtained for the surroundings of *Monsanto* park and the airport. Again, it is conspicuous the segregation of the eastern side of Lisbon. It is also worth noting the relatively lower values obtained for *Baixa*. This may be related to the fact that this area has whole buildings and blocks occupied by governmental bodies, or eventually to a significant number of vacant buildings nearby.

Reach

The *Reach* index (Figure 80) was measured by resorting to the urban network analysis toolbox (Sevtsuk and Mekonnen, 2012a). The parameters considered to compute this index include a radius on the network of 500 meters, and a weighting field referring to the built volume.

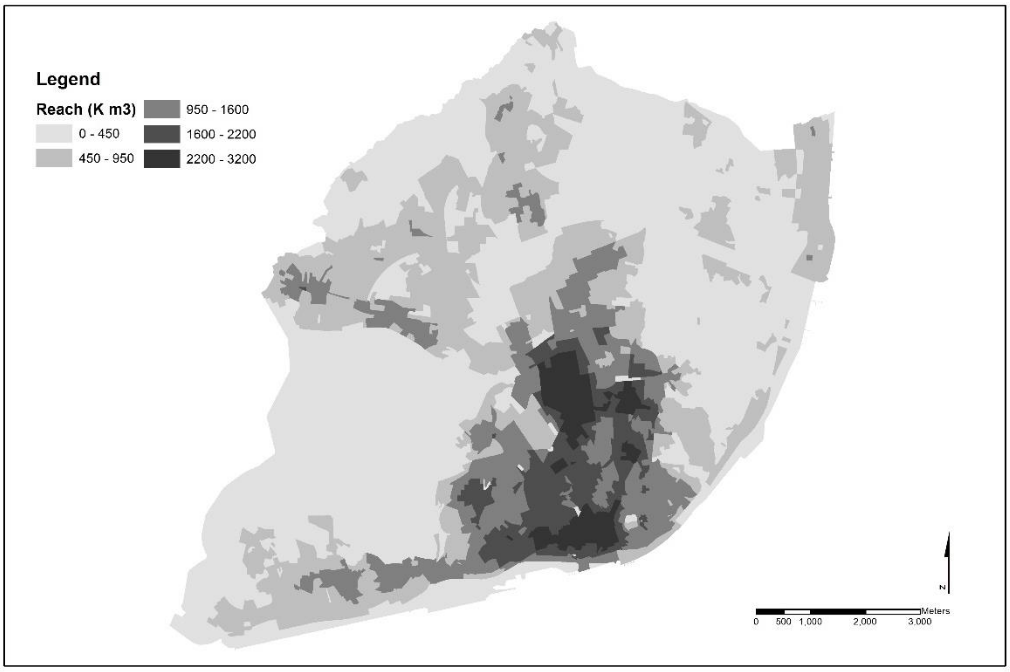

Figure 80. Accessibility. Reach. Lisbon

The map depicts the amount of built volume reachable within a 500 meter radius on the network. The *Reach* indicator reinforces the importance of specific areas in the city, in line with some indicators previously considered (notably the FSI for density and the Pedestrian DivAct for accessibility). The areas of Lisbon where it is possible to reach a larger amount of built volume is the downtown (*Baixa*) and *Saldanha*. Despite *Reach* does not reflect the location of urban activities, it is very interesting to observe that the areas with a higher *Reach* correspond to those with a significantly high share of non-residential uses (thus representing busy and lively city areas), which has happened already in the case of Porto.

5.2.2.2.3. Public transport route density

In order to compute the public transport route density, two types of public transport were considered: public buses and the metro system. This choice was made in order to keep the results obtained comparable with those from the case of Porto, although it is acknowledged that the rail and private road operators have a significant role in this case. The process adopted was similar to the case of Porto, resorting to a buffer of the stop layer (with 10 meters) so that a stop located in the border of two different blocks could be accounted for in both cases.

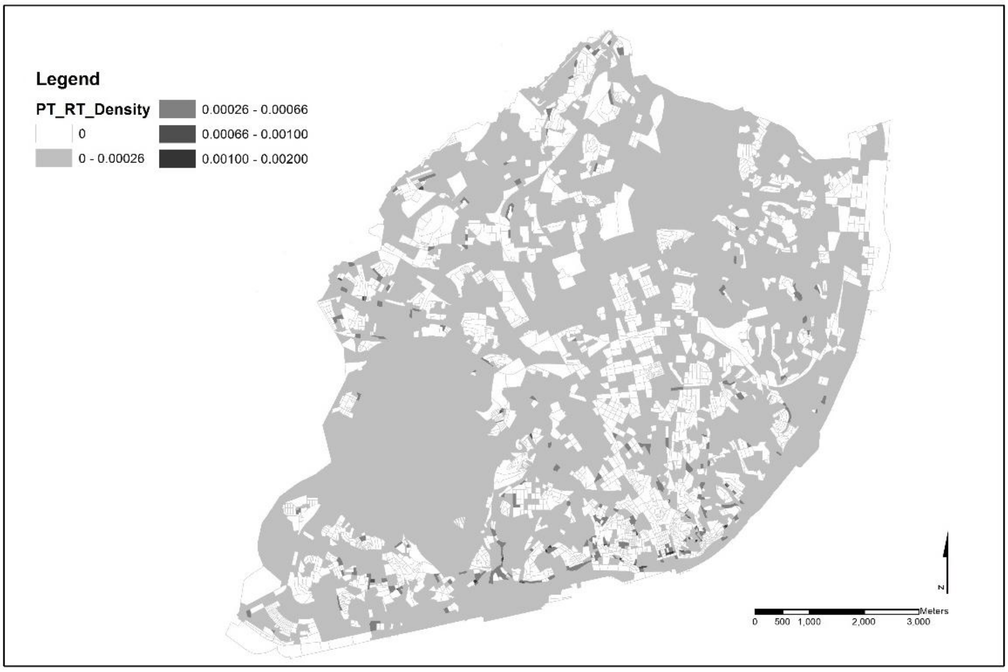

Figure 81. Public Transport Route Density. Lisbon.

Figure 81 shows that most of the municipality is served by public transports, however, it is surprising to see that important central areas are lacking public transport infrastructure (conversely to the case of Porto). It seems that the location of stops and stations is quite "diluted" within the city, as it isn't evident the location of key hubs with significantly high public transport densities (at least for these two types of public transport). It is possible that some of these results may derive from not considering the urban rail and private operators, or eventually from the use of some outdated information.

5.2.2.2.4. Centrality

The centrality indicator (Figure 82) reflects the distance (in the network) of each block to the CBD. It is measured by using the network analyst toolbox. In this case, the *Praça Marquês do Pombal* was considered as the city CBD. It is a key point in Lisbon, hosting the headquarters of several important companies.

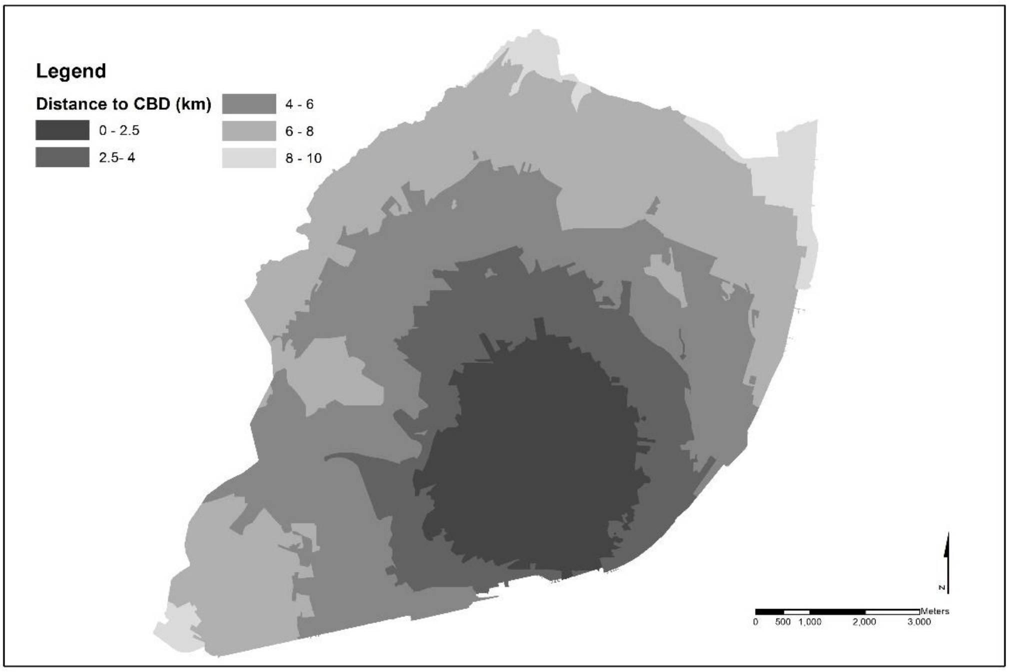

Figure 82. Centrality. Distance to CBD. Lisbon.

The centrality map reflects the distance to the CBD (*Praça Marquês do Pombal)*. Figure 82 displays distance clusters, with darker colours meaning shorter distances to the CBD. These areas are expected to unveil lower energy needs for travel, since they have a greater proximity to a likely (work) destination in the city.

5.2.2.2.5. Design

The design attribute originally entails four different indicators (referring to sidewalks, trees, cycling lanes and parking). However, the latter two indicators are not included in this analysis for the same reasons as they weren't included in the Porto case study, i.e. cycling infrastructure does not yet have a significant expression in the city of Lisbon, and as for parking, it was not possible to get suitable data for computing this indicator.

Sidewalks

This indicator is targeted at assessing the quality of the sidewalks, and is given by the ratio between the area of the sidewalk and the area of the block (Figure 83). The data on the characteristics of the sidewalks was local obtained from the local authority (*Câmara Municipal de Lisboa*) in vector format (polylines). Although the data made available was not complete, it covered a large proportion of the municipality and was considered sufficient to establish conclusions on this indicator. The process for calculating the sidewalk area was slightly different from the one of Porto, as it was necessary to adapt it to the existing information.

The distance from the nearest sidewalk to each building was computed, in order to obtain an average sidewalk width for the urban block. Then, since the sidewalk length surrounding each urban block had already been computed (from preliminary operations in the street layer), it becomes straightforward to compute the ratio between the area of the sidewalk and the area of the block.

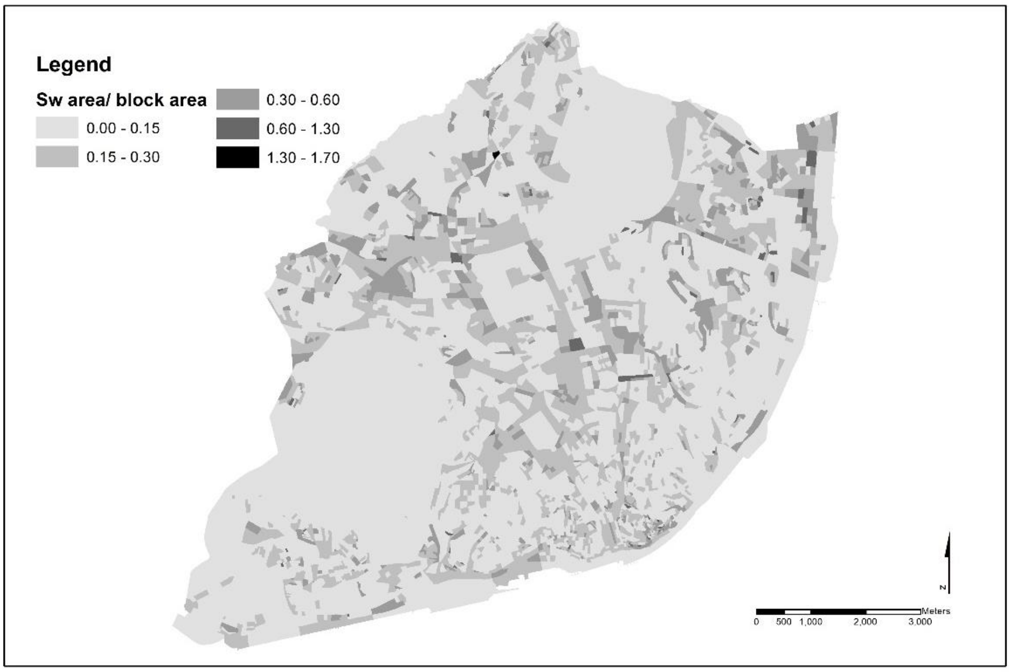

Figure 83. Design. Sidewalk area / block area ratio. Lisbon.

The purpose of this map is to allow for the analysis of whether the areas with larger sidewalk infrastructure correspond to pedestrian-friendly zones. There is some degree of overlap between these two (visible, for instance, in *Baixa*), but it is generally visible that larger sidewalks are typically located in wider streets (*Avenidas*), with quite high traffic volumes. This is the case of *Avenida Almirante Reis* and *Avenida da República*. It is also visible a slight trend showing that outer (and more recently developed) areas of the municipality typically have larger sidewalks, as it is the case of *Parque das Nações*. Larger sidewalks may also be found in some leisure-oriented areas, like the ones on the riverside, as well as around key urban squares like *Parque Eduardo VII*.

Provision of trees

The presence of trees is measured as the proportion of street length with provision of trees. The data used for this indicator was also made available through the local authority (*Câmara Municipal de Lisboa*). Departing from a layer considering the streets with trees, this information was transferred to the layer with the complete street network, where the presence of trees was signalled. Having calculated the overall street length, it was possible to compute the indicator as the ratio between the length of street with trees and the total street length. Again, this information was overlaid with the block layer in order to get an average value for the spatial unit considered.

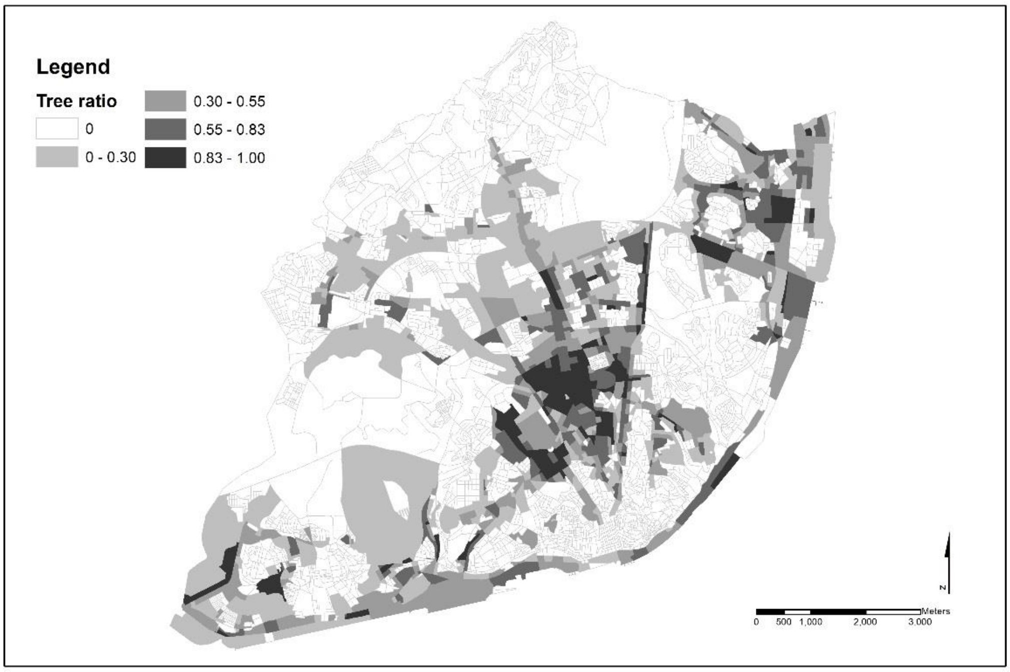

Figure 84. Design. Proportion of street length with trees. Lisbon.

Figure 84 depicts the proportion of street length with trees facing each urban block. There is a large share of the territory without trees in the street. It is visible that trees are located mostly in leisure-oriented areas (for instance, considering the continuous corridor alongside the river), and facing the most important road arteries in the city, which coincide with relatively traffic intensive streets. This is visible in the surroundings of *Avenida da Liberdade*, *Avenida Almirante Reis*, and *Avenida da República*, as well as in the surroundings of urban speed roads (e.g. *Segunda Circular*), most likely as a traffic mitigation effort.

5.2.2.3. Energy

5.2.2.3.1. Built environment

The characterization of the energy needs of the built environment (for heating and cooling), was made resorting to the national building certification database, for the city of Lisbon. This database was imported to the GIS by using to spatial coordinates. About 35.500 were used in the spatial analysis, after eliminating null and invalid certificates.

Figure 85 shows the spatial distribution of the existing certificates. The lines correspond to the boundaries of the urban blocks, the grey polygons correspond to existing buildings, and each orange dot corresponds to a building certificate. Most of the city territory is characterized by the existing database. Although there are urban blocks without certificates emitted, these areas are mostly occupied by non-residential buildings (as it is the case of the football stadiums, or the *Parque das Nações* blocks for public services and offices), or they may also correspond to areas of abandoned built structures (as in the zone of *Xabregas* and *Beato*).

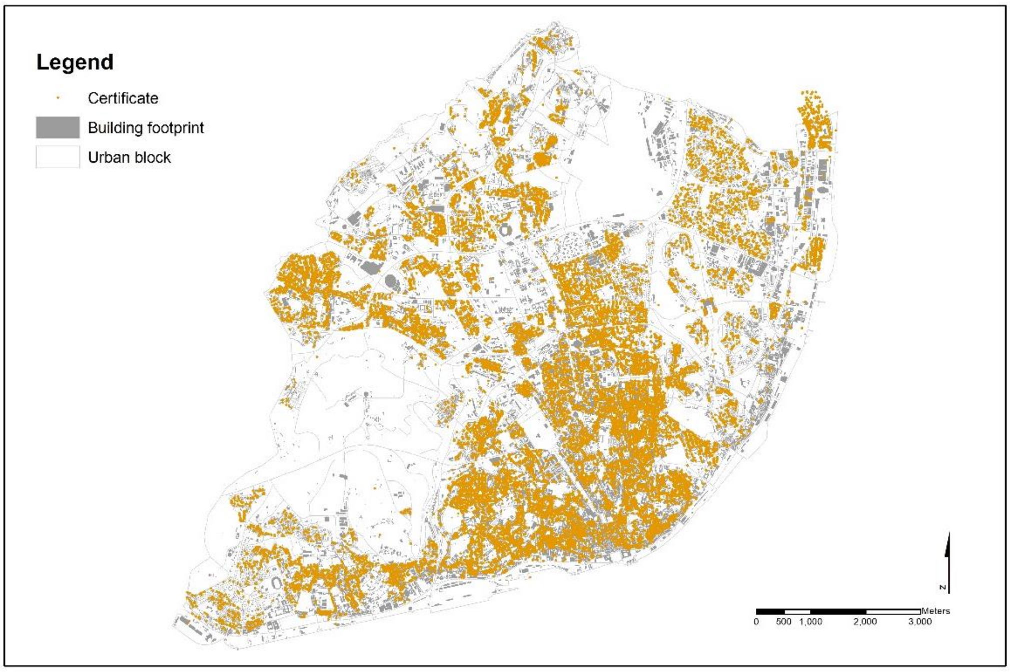

Figure 85. Spatial Coverage of the buildings certification system database for the Lisbon case study.

After matching the energy needs of the former regulation (2006) to those of the second regulation (2013), both databases were merged into one single GIS layer. This was overlaid with the layer of the urban blocks, which enabled to determine the average nominal useful energy needs for heating – Nic (Figure 86) and, the average nominal useful energy needs for cooling – Nvc (Figure 87). These have been converted into final energy in the modelling stage. Once the conversion factor of useful to final energy (for heating and cooling, respectively) for the municipality of Lisbon was not available, the ones from the Porto energy matrix were adopted. In the case of cooling, the conversion factor is expected to be equivalent for the two case studies, as cooling equipment is dominantly electric, and one can assume that the efficiencies do not differ significantly between the two cities. For heating, it is anticipated a greater difference in the conversion factor between the two case studies, as this entails a larger diversity of technologies. It is expected a greater use of electricity for heating in Porto, than in Lisbon. However, since the same average conversion factor is applied to the whole municipality, this only affects the total estimation of energy use in the city (which gets diluted), whereas the variability among the different urban blocks should not be affected.

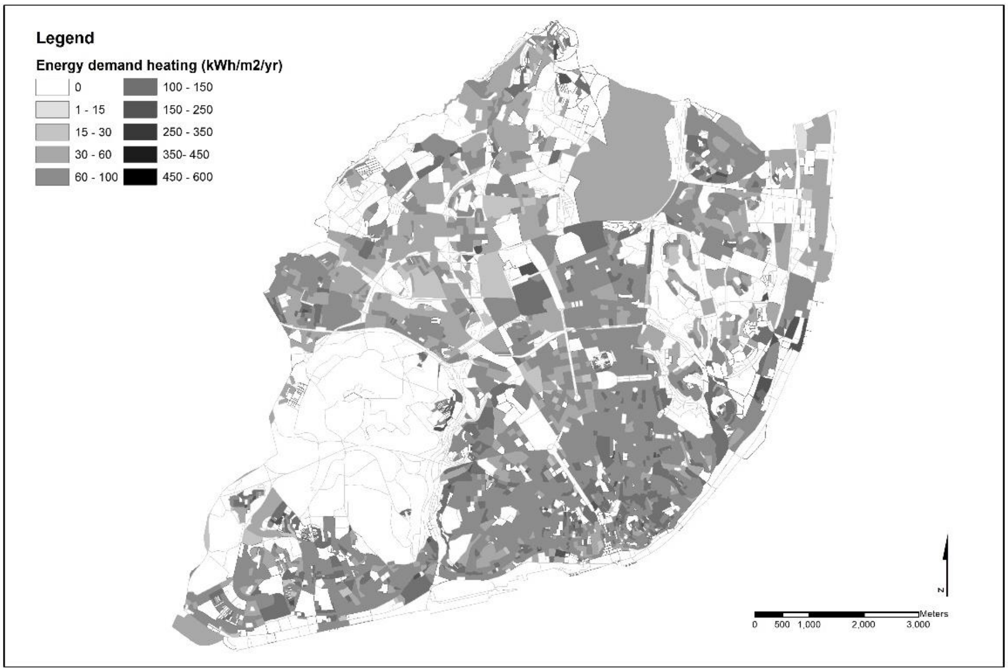

Figure 86. Average nominal energy demand for residential heating (kWh/m²/yr). Lisbon.

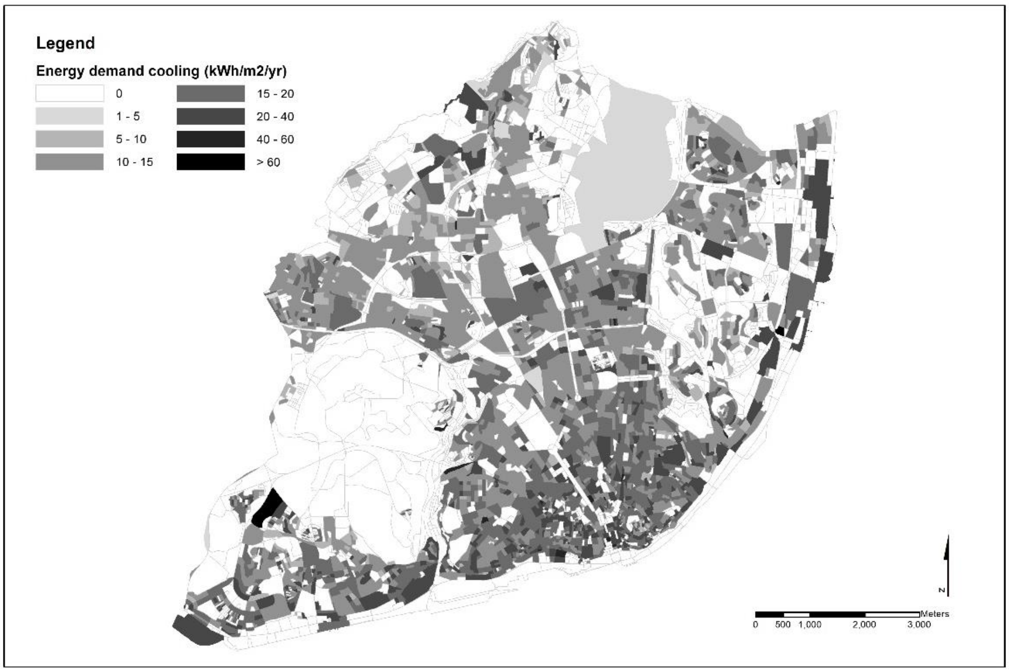

Figure 87. Average nominal energy demand for residential cooling (kWh/m²/yr). Lisbon.

Regarding energy demand in buildings, there is a significant difference between the case of Porto and Lisbon. Although the energy needs for heating are generally, higher than those for cooling in both cases (Figure 86 and Figure 87), most of Lisbon's territory has heating needs below 100 kWh/m2/yr, whereas in Porto, there is a large share of the territory with a heating demand higher than this threshold. Table 25 compares the average needs for heating and cooling in the two cases.

Table 25. Comparison of the average heating and cooling needs of the two case studies

	Porto	**Lisbon**
Avg. heating demand (kWh/m2/yr)	80	70
Avg. cooling demand (kWh/m2/yr)	8	15

Conversely, the cooling needs in Lisbon are much higher. The average value for cooling in Lisbon is almost the double of the average cooling needs of Porto. It is also visible a larger variability for cooling (Figure 87) than for heating (Figure 86), with the largest values mostly located in the city core, associated to more compact built structures.

5.2.2.3.2. Urban Networks

The mobility data used for the case study of Lisbon consisted of a synthetic OD matrix estimated from a mobility survey (2011). The matrix made available includes the trips in private mode, in a grid of 500x500 meters over Lisbon's territory (with a few additional zones representing entry and exit points to and from the city), referring to the annual average daily traffic (AADT). The estimation of the total yearly trips was obtained by multiplying the daily trips by 365. Since the values provided are a daily average, it was assumed that the differences between weekly and weekend flows would have already been offset.

The O/D matrix was imported to the GIS, and the estimation of the mobility needs of Lisbon followed a similar process to the one from Porto, in order to allocate the trips (O/D) to the territory. The centroids of the traffic zones were computed, in order to allow for the following steps. Since mobility, and thus, energy needs, depend not only on the trip frequency, but also on the distances travelled, the later were estimated. For this, the reference distance between each O/D pair was calculated as the shortest path, on the network, between the centroids of the corresponding (O/D) zones. For each traffic zone, the number of trips was multiplied by the corresponding trip length (in km), which resulted in the indicator for characterizing the private car mobility (vehicle kilometre travelled).

Whereas in the case of Porto the boundaries of the traffic zones coincided with specific spatial features, such as street axis, and also with the boundaries of the spatial units considered; in the case of Lisbon, the OD matrix has a gridded configuration, and hence its boundaries seldom match the ones from the spatial units. This makes the downscaling of the data from the traffic zones into the spatial units considered more challenging. The downscaling process used a ratio-based normalization (following Horta and Keirstead, 2016) based on the built-up area. A normalization based on the resident population was also tested, but the model fit obtained in the next methodological step was worse, given this disaggregation option. This may be explained by the fact that Lisbon's matrix refers to daily trips (in opposition to the morning peak hour), and thus a significant share of travel would be made by non-residents, and would be a result of the built-environment.

The AADT is represented per square meter of floor area, in order to produce a relative measure (rather than an absolute one), similarly to the ones used for characterizing the thermal needs of the built environment. Figure 88 depicts the results obtained.

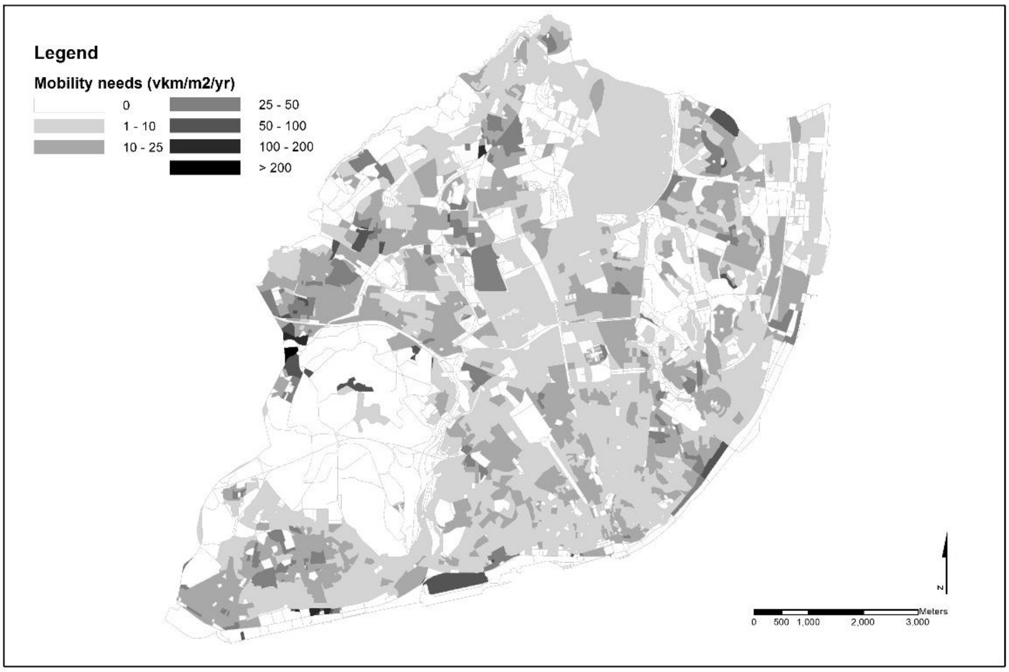

Figure 88. Average demand for motorized mobility (vehicle.km/m2/yr). Lisbon

Although it is visible that the city centre generally has lower energy needs than more peripheral blocks (in the northwest and eastern part of the city), it is visible that the downtown (*Baixa*) area and the urban blocks adjacent to *Avenida da Liberdade*, *Marquês*, as well as *Saldanha* show higher values. These areas likely correspond to stronger trip attractors, as it is where commerce and service areas are concentrated in the city.

5.2.3. Extraction of Metrics

Following the measurement and mapping of the indicators of urban form and energy, the extraction of the metrics corresponds to gathering and merging all the data produced into a suitable format for modelling.

Before doing so, it was deemed suitable to remove the information of urban blocks without buildings (e.g. public spaces, green areas…) and other blocks considered “atypical”. This was considered important either because these areas do not have an associated energy consumption figure, and/or because it would only make sense to model comparable areas, in terms of the expected influence of urban form on energy. Although green and public areas are expected to influence energy demand, depending on their proximity to built-up structures, they should not be included in the analysis as independent units.

For each map that was created for the representation of the indicators (.mxd files), the relevant fields of the attribute table were extracted in .dbf format. The relevant fields are the ID code of the spatial units analysed and the field containing the indicator depicted in the map. This was performed for all the indicators of urban form, as well as for the energy indicators referring to the built environment and to mobility patterns.

The .dbf file exported from the ArcGIS is compatible with MS Excel. The several .dbf files should be merged into a single spreadsheet for modelling (the merging can also be done in the GIS by “joining tables” – either way, this a time-consuming process). A key aspect is to ensure that the data entries match the corresponding ID of the urban block when merging tables. The interim structured spreadsheet (e.g. from excel) is, in its turn, compatible with most of the suitable modelling software for addressing this research problem, notably with those used and described in the following section.

5.2.4. Modelling

Before reproducing the modelling process to the case study of Lisbon, it was tested the extent to which the Porto model could be applied to a different urban context. As such, the ANN model developed before was applied to the data of Lisbon, and the prediction accuracy was analysed.

It was acknowledged that different cities represent different realities, and that the patterns that the model was able to identify in the previous case may differ. The existing differences may be either due to a diverse overall influence of urban form in relation to the remaining drivers of energy demand, and to a varying weight of each urban form variable. Nevertheless, it was felt the need to confirm whether the model developed is case-specific, or whether it can be extended to different urban contexts.

The results obtained confirm the first hypothesis, i.e. that the ANN model developed is case-specific. The high prediction errors revealed that the Porto model is not suitable to predict the energy demand in Lisbon, and that the local patterns of urban form that shape energy demand are unique and non-generalizable.

Nevertheless, the methodological framework proposed in this work can still be used to identify the existing relationships between the variables considered (i.e. to determine the right weights for Lisbon case study), and therefore to build a functional model for a different geography. The modelling process for Lisbon will be described in the following paragraphs.

Given the review of modelling approaches (Chapter 3), and the results of the application of the methodological framework to the case study of Porto, which confirmed the suitability of Artificial Neural Networks (ANN) to model the research problem, it is expected that ANN perform better than the remaining techniques for the case study of Lisbon, as well. Nevertheless, similarly to what happened previously, two more techniques will be tested and compared to the results obtained for ANN: Multiple Linear Regression (MLR) and Structural Equation Models (SEM). Recall that the model is formulated considering energy demand for heating, cooling and travel as a function of a set of urban form variables (*Equation 1* in Chapter 3).

The preliminary statistical analysis aims at providing an additional sensitivity on the relative explanatory power and significance of the predictors, as well as having a basis for comparing the ANN results. ANN are expected to capture nonlinear relationships, conversely to MLR, as well as providing the analysis with a prediction dimension that lacks in SEM.

After the modelling process, the different modelling techniques will be compared considering their coefficients of determination (R^2) and selected fit measures. The application of these three techniques is expected to enable selecting the best modelling option(s) for this problem, as well as to conclude on the influence of each of the attributes of urban form on energy demand. The final model selected will be used for the subsequent stages of research, on the consideration of alternative urban environments for improved energy performance.

Table 26 presents the summary statistics of the independent and dependent variables considered for the case study of Lisbon (*Equation 1*).

Table 26. Descriptive Statistics of the variables considered

Code	Variable description	N	Minimum	Maximum	Mean	Std. Deviation
E_h	Final energy needs for heating (kwh/m²/yr)	2775	6.2	300.8	105.3	38.9
E_c	Final energy needs for cooling (kwh/m²/yr)	2775	.33	29.7	5.2	2.1
ET	Final energy needs for travel (kwh/m²/yr)	3293	0	474.3	11.9	13.8
GSI	Ground Space Index	3534	0	.93	.34	.18
FSI	Floor Space Index	3534	0	4.18	1.15	.78
F	Number of Floors	3534	0	5.00	3.24	1.46
SS_Area	Size of block	3534	384	1643100	19367	48049
SubDiv	Subdivision Indicator	3534	.00001	.02047	.00226	.00237
MXI	Mixed-use Index	3534	0	1.00	.85	.25
AiSi	Spatial Distribution of green areas	3534	0	1.00	.05	.15
STV	Surface-to-Volume Ratio	3534	.03	.88	.24	.10
Connect	Beta index	3534	0	4.42	3.23	.44
DivAct_PT	Divact Public transport	3534	0	1.00	.94	.18
DivAct_Ped	DivAct Pedestrian	3534	.43	1.00	.90	.10
Reach	Reach (within 500m radius)	3534	0	3149591	990187	732023
PT_RD	Public transport route density	3534	0	.001862	.000063	.000137
Centrality	Linear distance to CBD	3534	101	9546	4237	2223
Tree	Proportion of street length with trees	3534	0	1.00	.12	.25
SW	Sidewalk area / block area	3534	0	1.00	.19	.14

A total of 3534 urban blocks were modelled. The variables of urban form evidence a significant variability, given the standard deviation values. Nevertheless, they seem to present an overall lower variability than those from Porto, notably the variables related to density. With regard to energy, again the energy needs for travel (ET) show the highest variability among the dependent variables, whereas the variation of energy demand for heating (E_h) is significantly lower than in the case of Porto. The building sector is not as well characterized as the transport sector, due to missing values (see the sample size, 2775 values, in Table 26). The following sections describe the rationale for the application of the modelling techniques considered (MLR, SEM, and ANN), followed by the results obtained.

5.2.4.1. Multiple Linear Regression (MLR)

Three MLR models, one for each dependent variable in relation to relevant urban form variables, are considered, followed by a forward stepwise analysis. This consists of adding independent variables, step by step, in order to improve the quality of the model. The analysis was performed in IBM SPSS Statistics 23. The three regression models tested are described in *Equation 7* to *Equation 9*.

The transport model includes more variables because the number of attributes of urban form influencing mobility identified in literature is also higher, in relation to the ones affecting the built environment. For evaluating the models built, two criteria will be considered. The first is the explanatory power, which is given by the coefficient of determination (R^2). It may be defined as the proportion of variance of the dependent variable(s) associated with the predictor(s), with values closer to one indicating a larger explanatory power of the model. In addition, using goodness-of-fit measures allows for the evaluation of model quality/ fit. For the MLR, the standard error (SE) is the error involved in the prediction. The model significance (Sig.) is also an important measure to account for. It refers to the probability of rejecting the null hypothesis (where the predictors do not influence the response variables), with values closer to zero indicating a better fit. In order allow for comparisons between the results obtained for the MLR and the results from ANN, some additional accuracy metrics are considered: the mean absolute percentage error – MAPE *(Equation 11*) and the root mean square percentage error – RMSPE *(Equation 12)*.

5.2.4.2. Structural Equation Models (SEM)

The SEM were built in the software Amos 23, with the previously created SPSS database working as an interface for storing the data. The specification and mapping of the relationships between the variables was made following two modelling options: one considering all the initial variables *(Equation 1*), and another based on the MLR stepwise models (similarly to what happened in Chapter 4).

The two accuracy measures to infer on the overall model suitability and to compare the two SEM versions are: the RMSEA – Root Mean Square Error of Approximation *(Equation 14*) and the CFI – Comparative Fit Index *(Equation 15*). RMSEA is an absolute fit index based on the chi-square, with values closer to 0 being better. CFI compares the developed model with the null model. CFI is normalized and ranges between 0 and 1, with higher values indicating a better fit.

5.2.4.3. Artificial Neural Networks (ANN)

The ANN model designed includes urban form variables as model inputs (predictors), while the outputs are energy demand for heating in buildings (E_h) and cooling (E_c) and mobility (ET), according to *Equation 1*. It was modelled in MATLAB R2015a, resorting to the neural network toolbox. The data was normalized within the range of -1 and 1, in order to meet the requirements of the hyperbolic tangent sigmoid transfer function (Figure 51). In addition, a log normal transformation was applied to the target variables, leading to an improved model performance.

Different network architectures were tested, following the same rationale as in the case of Porto, i.e. the number of hidden neurons was increased from 10, to 13, and to 15. Considering the training process, only the Levenberg-Marquardt (LM) backpropagation algorithm was applied, due to two fundamental reasons. The first, is that the LM provided significantly better results than the remaining algorithms in the previous case study. The second reason being that it was intended to keep a certain degree of comparability between the ANN models of the two case studies, so that the differences obtained wouldn't be attributed to differences in the method applied, but instead to the existing differences between the two cities.

The data sample for training, validating and testing the model was randomly split, within a proportion of 80%, 10% and 10%, respectively. The training phase is used for computing the gradient and updating the weights and the biases of the net. The validation phase is targeted at avoiding overfitting. The validation errors are monitored during the training process, in order to be kept at a minimum (before the point where they begin to rise again due to overfitting). Finally, the testing dataset, works as a reference for the validation one. If the error of the test phase reaches a minimum at a very different iteration, it may evidence a poor division of the data. The same script developed to run a pre-specified number of trainings (e.g. 100, 200, 1000,…) and select the net with the lowest MSE *(Equation 5*) was used.

The net with 15 neurons in the hidden layer and with a Levenberg-Marquardt (LM) training algorithm also delivered the best results. Thus, the architecture of the selected ANN model for Lisbon is the same as in Figure 52. The results obtained for the different networks were compared along with key evaluation criteria, similar to the one from MLR. The coefficient of determination (R^2) enables to infer on the explanatory power of the model, while the prediction errors enable to evaluate the prediction power. The MAPE and the RMSPE were calculated using the testing dataset and for each of the dependent variables considered (*Equation 11* and *Equation 12*, respectively).

The mean squared error – MSE *(Equation 5*) was determined considering all variables together, both for the global model and for the testing dataset.

5.2.4.4. Results and discussion

In order to conclude on the suitability of the modelling techniques, the following subsections present and interpret the accuracy metrics obtained. The explanatory power is given by the R^2 and the prediction power is evaluated resorting to the accuracy metrics selected (in relation to a specific response variable (E_h, E_c, ET) or to the whole model, i.e. E_h, E_c, and ET modelled together).

5.2.4.4.1. Multiple Linear Regression (MLR)

Three MLR models were built considering each of the response variables individually, as a function of the corresponding urban form variables. The results obtained are presented below.

$$Eh = f\ (GSI, FSI, F, SS\_Area, SubDiv, AiSi, STV, and\ Tree) \qquad (Equation\ 7)$$

Table 27. Multiple Linear Regression. E_h as dependent variable. Model Summary

Model	R^2	SE	MAPE	RMSPE	F	Sig.
E_h	.313	23.9	28.2%	55.4%	157.5	.000

Table 28. Multiple Linear Regression. E_h as dependent variable. Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics
	B	Std. Error	Beta			VIF
(Constant)	63.814	4.468		14.284	.000	
GSI	29.530	9.552	.174	3.091	.002	12.763
FSI	-.163	2.291	-.004	-.071	.943	13.915
Floors	-5.429	.829	-.232	-6.549	.000	5.060
SS_Area	-2.651E-5	.000	-.044	-2.490	.013	1.231
SubDiv	2929.955	286.322	.242	10.233	.000	2.248
AiSi	7.799	4.240	.033	1.839	.066	1.287
STV	70.162	7.295	.211	9.617	.000	1.943
Tree	-1.347	1.897	-.012	-.710	.478	1.108

The heating model (E_h) is significant at a probability level of .05 (Table 27), and presents quite acceptable prediction errors. It evidences the strongest relationship of the three response variables, with an R^2 of 0.313. This is in line with the previous case study, suggesting that heating needs, of all end-uses are the most affected by urban form (although this field of research derived from the transportation field). It is expected that the use of a more flexible modelling technique may uncover even stronger relationships.

The variables of urban form with the highest explanatory power (Table 28) are the subdivision index and the number of floors, followed by the STV. While higher granularities suggest the existence of inefficiencies associated to the existence of more independent urban parcels, a higher number of floors leads to lower energy needs for heating. Also, building compactness is again a relevant indicator, with a higher STV, and thus less compact built structures, implying higher needs for heating.

$$Ec = f\ (GSI, FSI, F, SS\_Area, SubDiv, AiSi, STV, and\ Tree) \qquad (Equation\ 8)$$

Table 29. Multiple Linear Regression. E_c as dependent variable. Model Summary

Model	R^2	SE	MAPE	RMSPE	F	Sig.
E_c	.105	5.85	30.6%	71.5%	40.8	.000

Table 30. Multiple Linear Regression. E_c as dependent variable. Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics
	B	Std. Error	Beta			VIF
(Constant)	18.680	1.091		17.129	.000	
GSI	-.430	2.332	-.012	-.184	.854	12.763
FSI	2.524	.559	.303	4.513	.000	13.915
F	-1.760	.202	-.352	-8.696	.000	5.060
SS_Area	-2.604E-6	.000	-.020	-1.002	.316	1.231
SubDiv	88.940	69.892	.034	1.273	.203	2.248
AiSi	3.708	1.035	.073	3.583	.000	1.287
STV	-1.760	1.781	-.025	-.989	.323	1.943
Tree	.637	.463	.026	1.375	.169	1.108

Although the cooling model (E_c) consistently evidenced the weakest relationship of the three response variables (as anticipated), there seems to be a more prominent influence of urban form on cooling needs in the case of Lisbon. It is possible that cooling gains an increased importance due to the climatic conditions of this case study. It may also be that the cooling database is less noisy for Lisbon, given the analysis of Figure 67 and Figure 68 (Chapter 5), although the value obtained for the RMSPE is still significantly high.

It is visible that for the MLR cooling model (E_c) the indicators of density are the ones with the highest explanatory power, notably the floor space index and the number of floors.

$$ET = f\ (GSI, FSI, F, SS\_Area, SubDiv, MXI, AiSi, Tree, Connect, DivAct\_PT, DivAct\_Ped, Reach, PT\_RD, Centrality, SW) \qquad (Equation\ 9)$$

Table 31. Multiple Linear Regression. ET as dependent variable. Model Summary

Model	R^2	SE	MAPE	RMSPE	F	Sig.
ET	.140	12.80	97.6%	483.2%	35.4	.000

Table 32. Multiple Linear Regression. ET as dependent variable. Coefficients

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics
	B	Std. Error	Beta			VIF
(Constant)	27.121	4.312		6.290	.000	
GSI	-26.804	4.817	-.335	-5.564	.000	13.825
FSI	4.591	1.251	.250	3.671	.000	17.621
Floors	-4.990	.404	-.447	-12.365	.000	4.973
SS_Area	7.898E-7	.000	.003	.153	.879	1.248
SubDiv	-71.851	140.343	-.012	-.512	.609	2.225
MXI	-5.242	1.983	-.049	-2.644	.008	1.297
AiSi	-2.206	1.839	-.022	-1.199	.230	1.301
Connect	-.404	.576	-.012	-.701	.483	1.209
DivAct_PT	3.366	1.368	.042	2.461	.014	1.119
DivAct_Ped	6.075	3.350	.042	1.814	.070	2.019
Reach	-1.079E-7	.000	-.006	-.177	.860	4.013
PT_RD	-1482.872	1669.195	-.015	-.888	.374	1.015
Centrality	.001	.000	.082	3.232	.001	2.430
Tree	.278	1.015	.005	.274	.784	1.217
Sidewalks	7.777	1.658	.080	4.691	.000	1.114

The R^2 for the travel model (ET) is still lower than expected, roughly 0.14 (Table 31), but is higher than the one found in the MLR for the case of Porto. Here, the influence of density is most prominent (Table 32) whereas the effect of the remaining variables seems to be almost negligible. The following section describes a MLR modelling process, including a stepwise approach. The models are built in a similar way, but only the significant variables in each model are selected.

5.2.4.4.2. Stepwise Multiple Linear Regression (MLR)

A stepwise approach was tested for the same MLR models described earlier, in order to investigate which variables do not add significant explanatory power to the model (under a linear environment). This method enables to identify model terms that may be removed from the original model formulation.

Table 33. Stepwise Linear Regression. E_h as dependent variable. Model Summary

Model	R Square	SE
a	.193	25.97
b	.285	24.45
c	.299	24.22
d	.311	24.01
e	.312	23.99

a. Predictors: (Constant), SubDiv
b. Predictors: (Constant), SubDiv, F
c. Predictors: (Constant), SubDiv, F, STV
d. Predictors: (Constant), SubDiv, F, STV, GSI
e. Predictors: (Constant), SubDiv, F, STV, GSI, SS_Area

The stepwise approach for E_h (Table 33) evidences that five of eight urban form variables enable to achieve an R^2 close to the initial model formulation (with a difference of only .01). Still, the effect of the three remaining variables (FSI, AiSi and Tree) will be further explored by the additional modelling techniques to check if they are able to identify more relevant links.

Table 34. Stepwise Linear Regression. E_c as dependent variable. Model Summary

Model	R Square	SE
a	.052	6.02
b	.092	5.90
c	.100	5.87
d	.100	5.87
e	.104	5.86

a. Predictors: (Constant), GSI
b. Predictors: (Constant), GSI, F
b. Predictors: (Constant), GSI, F, FSI
b. Predictors: (Constant), F, FSI
b. Predictors: (Constant), F, FSI, AiSi

The stepwise approach for the E_c model selected only three urban form variables (Table 34). It is worth noting that while several urban form variables were not included here, they had been selected for the heating model (E_h). This suggests that in the model with all the three energy end uses, a larger set of variables should be considered.

Table 35. Stepwise Linear Regression. ET as dependent variable. Model Summary

Model	R Square	SE
a	.100	13.07
b	.122	12.91
c	.127	12.87
d	.132	12.84
e	.133	12.83
f	.136	12.82
G	.138	12.80
h	.139	12.79

a. Predictors: (Constant), F
b. Predictors: (Constant), F, GSI
c. Predictors: (Constant), F, GSI, SW
d. Predictors: (Constant), F, GSI, SW, FSI
e. Predictors: (Constant), F, GSI, SW, FSI, Centrality
f. Predictors: (Constant), F, GSI, SW, FSI, Centrality DivAct_PT
g. Predictors: (Constant), F, GSI, SW, FSI, Centrality DivAct_PT, MXI
h. Predictors: (Constant), F, GSI, SW, FSI, Centrality, DivAct_PT, MXI, DivAct_Ped

Mobility is consistently the energy use that is influenced by a larger set of variables. Still, the overall coefficient of determination is quite low. A possible explanation, given the application of the methodology to the case study of Porto, may be that mobility needs may be dominantly influenced in a nonlinear way. Overall, the stepwise MLR (Table 35) presented very close results to the ones from the simple MLR. Under a linear environment, a smaller set of predictors than those included in the model evidence a significant explanatory power for energy demand, with density, centrality and accessibility being the most prominent. This justifies the dominance of existing research in these topics.

5.2.4.4.3. Structural Equation Models (SEM)

Structural Equation Models (SEM) are the second modelling technique applied to the research problem. These have the advantage of being more flexible than MLR, allowing to model the three response variables together. The results obtained for the two modelling options are presented below.

SEM1) including the full set of variables:

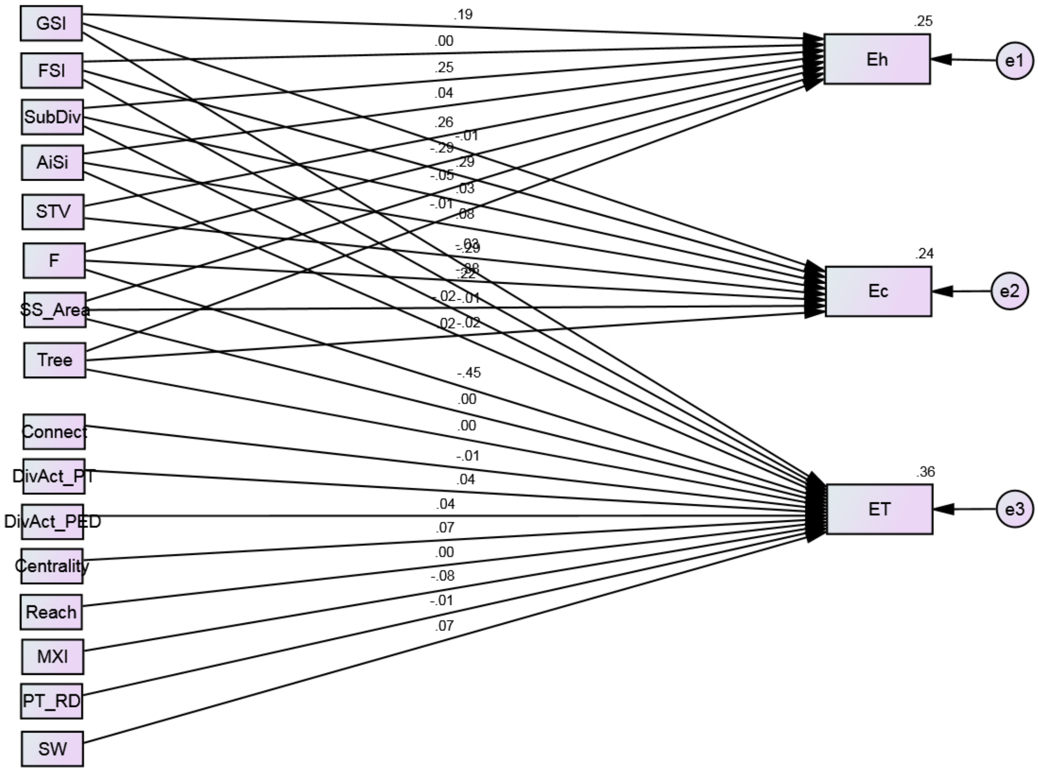

Figure 89. SEM considering all variables under an input-output framework

Table 36. Fit Metrics for SEM 1. Lisbon.

SEM1	RMSEA	CFI
	0.226	0.066

SEM2) considering covariations derived from the stepwise approach:

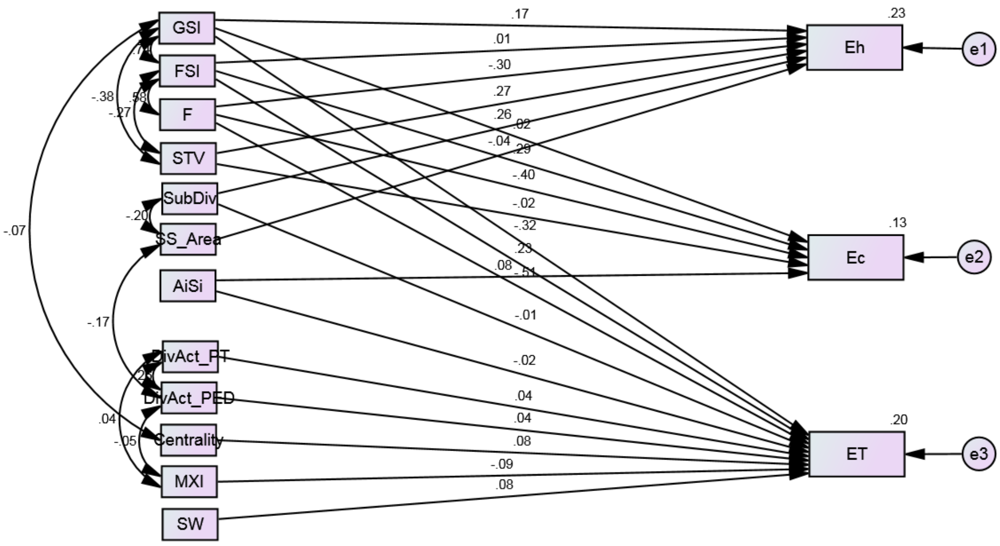

Figure 90. SEM with fewer variables, grounded on the stepwise MLR

Table 37. Fit Metrics for SEM 2. Lisbon.

SEM2	RMSEA	CFI
	0.196	0.326

The SEM model depicted in Figure 89 entails the same individual relationships as the Multiple Linear Regression models built earlier, but it considers at the same time E_h, E_c and ET as outputs. While the coefficients of determination of E_c and ET significantly increase, the one for E_h is considerably lower. This suggests that SEM was able to identify links that the MLR didn't find (for E_c and ET), but for that it may have compromised the analysis of E_h. Although the graphic representation of the SEM does not enable to perceive the individual regression weights due to the high number of variables involved, it is important to refer that the contribution of the independent variables on explaining the variation of the depend ones is very much in line with the ones obtained in the univariate multiple linear regression (MLR). SEM2 (Figure 90) shows a model based on the MLR stepwise approach.

The two models tested were both significant at the level 0.01. Although SEM1 retrieved a relatively better coefficient of determination for all the response variables, the performance (model fit) of SEM2 is better, both considering the RMESEA and the CFI (Table 36 and Table 37). This reinforces that removing variables *per se*, is not an adequate solution for improving the model accuracy. SEM2 accounts for links between the covariates, whereas SEM1 provides a more comprehensive and expectedly realistic picture of the relationship between urban form and energy. In either case, the model fit is not satisfactory. A possible interpretation may be that SEM is still not flexible enough to fully address the relationships between urban form and energy demand in cities.

The application of SEM provided additional insights on the existing links between the variables considered. It confirmed that (still under a linear environment) despite density-related form factors are more prominent for determining the overall energy demand, the contribution of other factors should not be neglected (evidenced by the increase in the coefficients of determination). The next subsection presents the results obtained from ANN.

5.2.4.4.4. Artificial Neural Networks (ANN)

Given the review of modelling techniques performed in Chapter 3 and the successful results from the application to the case study of Porto (Chapter 4), ANN emerge as a suitable modelling tool for the research problem at hand. The modelling options tested are:

- A univariate ANN analysis, built in a similar way to the individual MLR models for each of the three response variables. This enables to compare the accuracy of ANN with MLR without changing the model structure.
- Different network architectures were tested by considering a different number of neurons in the hidden layer, in order to select the best network architecture.
- Finally, further variables were added to the base model (which includes only variables of urban form). This aimed at assessing if the addition of alternative variables, not related to urban form, would increase the model quality.

Table 38 compares the coefficients of determination for each response variable, obtained from the previous techniques (MLR and SEM), and those from the univariate ANN models. It is interesting to note that SEM was able to identify a stronger coefficient of determination for cooling than MLR. This is aligned with the results from Porto, suggesting that cooling patterns may be more accurately modelled along with heating. Nevertheless, while SEM found a larger coefficient of determination for travel than MLR, it performed worse for heating. It seems that the multivariate analysis from SEM, implies a compromise between increasing the R^2 for cooling and mobility and decreasing the one for heating.

Conversely, the univariate ANN models returned significantly higher determination coefficients for all the three variables when comparing to the MLR, whereas it only performed worse than SEM regarding the coefficient of determination for mobility. The results suggest that there may be trade-offs between the effect of urban form on buildings and on mobility, since the multivariate analysis returns a higher R^2 for travel. In addition, the higher coefficients of determination for heating (and cooling) suggest the existence of stronger (nonlinear) relationships that the techniques based on linear models couldn’t identify. This supports the application of ANN for modelling the three energy end-uses together.

Table 38. Comparison between the different R^2 obtained from each of the modelling techniques applied.

Variable	MLR	SEM	ANN univ.
E_h	0.31	0.25	0.40
E_c	0.10	0.24	0.24
ET	0.14	0.36	0.29

As a result, the analysis moved towards considering a comprehensive model, including all the predictors from Table 26, as well as the three response variables at the same time (E_h, E_c, ET).

In order to avoid unnecessary modelling complexity, the analysis began by considering a default number of 10 hidden neurons, which was increased up to 15. Since the number of inputs (blocks) in Lisbon is significantly higher than in Porto, it was expected that more neurons may deliver better accuracies, as well as higher coefficients of determination.

The fact that the results obtained with 15 hidden neurons were satisfactory enabled to keep a similar network architecture to that considered in the previous case study. This enables to assume that possible differences in the model results between Porto and Lisbon are due to the existing differences between the two case studies, instead of differences in the method employed. Table 39 presents the accuracy metrics and the coefficients of determination for the best LM-ANN models obtained with, with 10, 13 and 15 hidden neurons.

Table 39. Accuracy metrics of different LM-ANN for each response variable

# Neurons	Variable	**R^2 test**	**MAPE**	**RMSPE**	**R^2 global test**	**MSE test**
10 neurons	**E_h**	0.32	25.1%	37.3%	0.52	0.024
	E_c	0.20	25.8%	41.6%		
	ET	0.64	59.8%	94.0%		
13 neurons	**E_h**	0.34	25.4%	40.5%	0.60	0.026
	E_c	0.22	28.8%	59.1%		
	ET	0.41	56.6%	133.6%		
15 neurons	**E_h**	0.46	24.8%	41.9%	0.56	0.024
	E_c	0.21	27.9%	50.1%		
	ET	0.48	51.8%	83.9%		

All the three ANN models evidenced better results than those obtained above with the MLR and with SEM. This proves that ANN are, indeed, a suitable modelling technique for dealing with complex problems and with a large number of variables. Overall, a larger number of neurons in the hidden layer enables to obtain greater accuracies (i.e. lower errors), not only considering each of the individual variables, but also the whole model (Table 39). The exception is the MSE test error for the ANN model with 13 neurons (larger than the one for 10 neurons). The criteria for the selection of the best model included a good global model performance (given by the MSE), while privileging better accuracies for heating and mobility. This is due to the fact that these two energy end uses are the most important in determining the overall urban energy demand (the needs for cooling have a significantly lower share of final energy use). As such, the ANN with 15 hidden neurons was considered the best model, not only because it presents a low MSE for the global model, but also because it was able to find individual relationships of higher magnitudes for heating and mobility without losing the respective accuracy (Table 39).

The results reinforce that urban form mainly influences the energy demand for heating (R^2 = 0.46) in buildings and mobility (R^2 = 0.48). Cooling is again the response variable evidencing the lowest coefficient of determination (R^2 = 0.21). Yet, the R^2 for cooling is considerably higher than the one obtained for the Porto case study, evidencing that urban form may play a more prominent role in determining the cooling needs in Lisbon.

With regard to the prediction power of the model, the energy needs for heating (E_h) are consistently those presenting better accuracies. Conversely, the travel variable presents the largest prediction errors. Although the R^2 obtained for ET is quite high, evidencing a significant influence exerted by the predictors, the prediction errors are quite high as well (for instance, comparing to those obtained for Porto). This has two possible explanations. The first has to do with the nature of the data. The travel matrix of Lisbon had a spatial zoning less compatible with this approach (a reticulate matrix *in lieu* of traffic zones coinciding with specific streets and/or real urban boundaries). Also, it is suspected that the overall number of trips may be underestimated (taking the case study of Porto as reference) – the original version of the dataset wasn't accounting for intra-zone trips (meanwhile this was corrected by the source, but it may be possible that some small errors may still exist).

The second possible explanation is the specificity of the case study. Lisbon may have different intrinsic dynamics in relation to Porto. The fact that Lisbon is the national capital city may imply a more intricate set of factors and drivers (notably behavioural and economic ones) in determining the mobility patterns. This makes it more difficult to predict ET with a better accuracy based on urban form indicators only. It is also expected that the strong interdependency of this municipality in relation to the remaining metropolitan region, in terms of travel, may partially explain these results.

In addition to the accuracy metrics from Table 39, the selection of the ANN model took into account other modelling aspects. The normality of the errors was verified (Figure 91), the minimum MSE for the validation and testing datasets was obtained at close iterations (Figure 92), and similar coefficients of determination for each of the modelling phases – training, validation and testing (Figure 93) was also ensured.

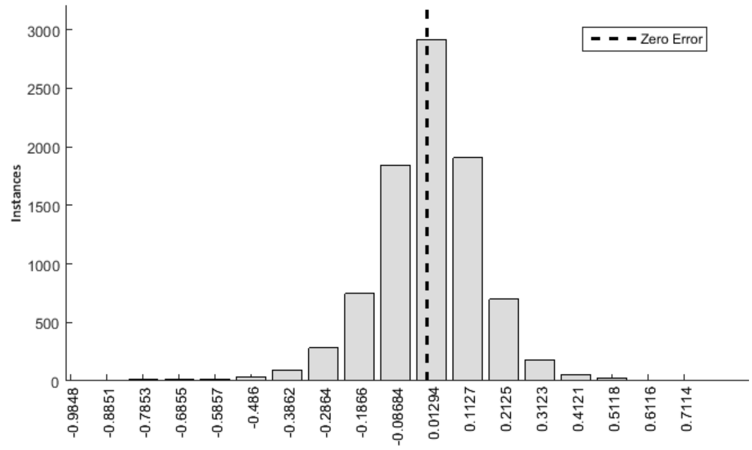

Figure 91. Error histogram of the ANN model. Lisbon.

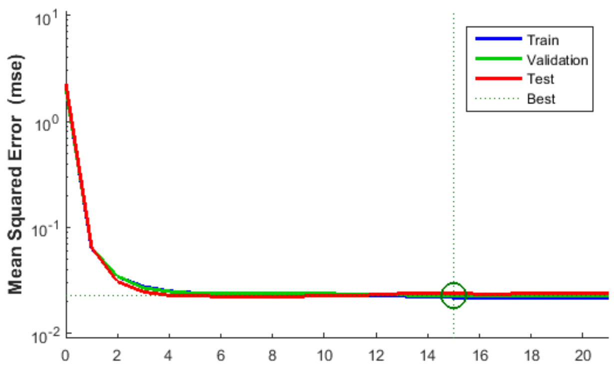

Figure 92. Mean Squared Error of the three datasets at different iterations. Lisbon.

The minimum MSE values obtained in close epochs for the test and validation datasets (Figure 92), suggests a good split of data samples.

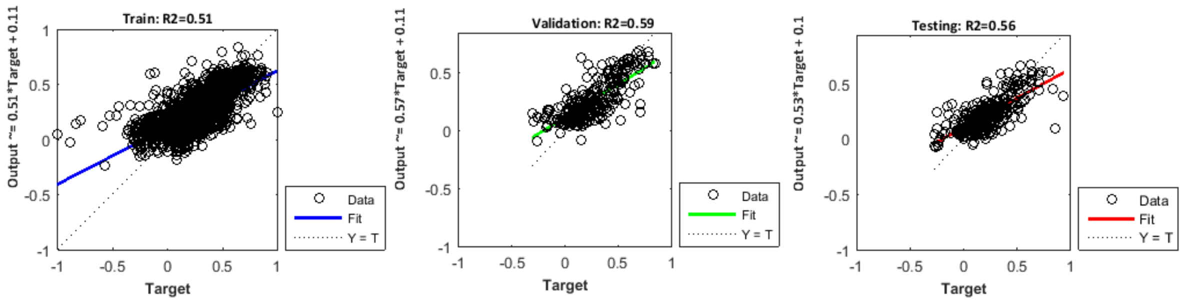

Figure 93. Relationship between the real values (targets) and the modelled values (outputs) of the global model. Lisbon.

The coefficients of determination for each of the different modelling phases (Figure 93) are not significantly different, indicating that the model has enough generalization capacity, i.e. it is not overfit.

The application of ANN to the case study of Lisbon aimed at supporting the feasibility of the methodology and validating its replicability in a different urban geography, as well as providing a basis for comparing the results obtained in the previous case study. It is considered that the methodological framework was successfully applied, and that ANN constitute a suitable technique to model thermal energy needs in buildings and mobility altogether. The results corroborate the existence of significant relationships between the variables of urban form (predictors) and energy needs (response variables), with the coefficients of determination presenting a significantly higher magnitude than those obtained from the previous methods.

In addition to the values obtained regarding each of the three predictors, the global ANN model fit is quite good, as well. It showed that a model relying only on variables of urban form enables to estimate with enough accuracy the energy demand for the urban area at stake, at a high resolution level. This is especially true for two specific end-uses (heating and travel). Although the accuracy in estimating travel patterns is not as good as in the previous case study, it is considered that the prediction errors are still within an acceptable range, and that this does not eliminate the usefulness of the methodology itself. It is not evident whether such errors derive from a lack of adaptation of this methodology to the characteristics of the case study, or from the quality of the data available. The results are likely a combination of both factors.

The R^2 of the global model supports the literature that claims that the combined effect of urban form may be quite significant (Ewing and Cervero, 2010). In the case of Lisbon, urban form may explain about 56% of the variation of the overall energy needs for the building and transport sectors together. Although the R^2 obtained for this case study is lower than the one obtained for the case of Porto (0.78), this may still be considered a significant influence worth controlling for (especially bearing in mind that urban form is not the only driver of energy demand). This supports the adoption of urban planning and urban form-oriented policies targeted at energy conservation.

It is acknowledged that there are other variables influencing energy demand (e.g. behavioural/ social and economic factors) not included in this model. This is the reason why the coefficient of determination is considerably lower than 1. The goal of this work was to focus on the contribution of the variables of urban form, and to check for their combined influence on specific urban energy uses. The results obtained from the application of this methodology to two case studies confirmed the relevance of urban form attributes for urban energy performance. Such model may work as a case-specific tool, with relevance for local early stage decision-support in urban and energy planning.

Similarly to what happened in the previous case study, it was considered an additional modelling iteration, which consisted of adding socio-economic variables to the ANN model selected. Such variables were:

- Resident population;
- Average construction period of buildings;
- Percentage of active population;
- Purchase power (PP) or Gross domestic product (GDP)

Since the last item of this list is not available at the level of detail of this analysis, the variables that were effectively included in the model were: the resident population; the average construction period of buildings; and the percentage of active population (as proxy of the occupancy of dwellings and mobility patterns of active *vs.* non-active population, i.e. employed *vs*. children, unemployed and retired people).

Again, this last modelling option was dropped because it didn't return significantly improved results (higher determination coefficients or lower prediction errors), comparing to the base model including only the variables of urban form. Table 40 presents the results for the best ANN model with the social indicators. Although the coefficient of determination of the global model increased, the global model accuracy is kept the same. In addition, the individual relationships are lower and the prediction errors are less interesting (except for heating, which has slightly lower errors). This slight improvement for heating is expected to be related to the variable characterizing the construction period of the buildings, since the building certification system reflects the characteristics of the building itself, instead of real occupancy patterns (given by the resident population and the percentage of active population).

Table 40. Accuracy metrics for each response variable of the model with social indicators

Model	Variable	R^2 test	MAPE	RMSPE	R^2 global test	MSE test
Base model + social vars.	E_h	0.42	24.1%	43.7%	0.60	0.024
	E_c	0.22	29.2%	63.3%		
	T	0.34	56.6%	86.9%		

In order to understand the extent of the contribution of each predictor to explain the variability observed in the dependent variables, three methods are applied in order to extract information from the best ANN model. The following section illustrates this process and the respective results.

5.2.5. Knowledge Discovery

Notwithstanding the ANN model fit, another relevant aspect is the ability to explore the links between the different variables of urban form (predictors) and energy demand (response variables). As mentioned, ANN are often criticized for behaving like a black box. There are several methods for extracting information from ANN, regarding the relative contribution of the different model variables. However, there is no consensus on the best approach to do so.

The ones adopted in the case follow Olden and Jackson (2002), who refer to three methods for understanding the effects of the predictors in ANN model: i) the Neural Interpretation Diagram (NID), ii) Garson's algorithm, and iii) sensitivity analysis.

Figure 94 depicts the NID for the case study of Lisbon, with positive weights represented in blue and negative weights in black. However, due to the large number of model variables and neurons, and the need to follow the weights in two steps (due to the hidden layer), this method offers little insight on the existing relationships between the model variables.

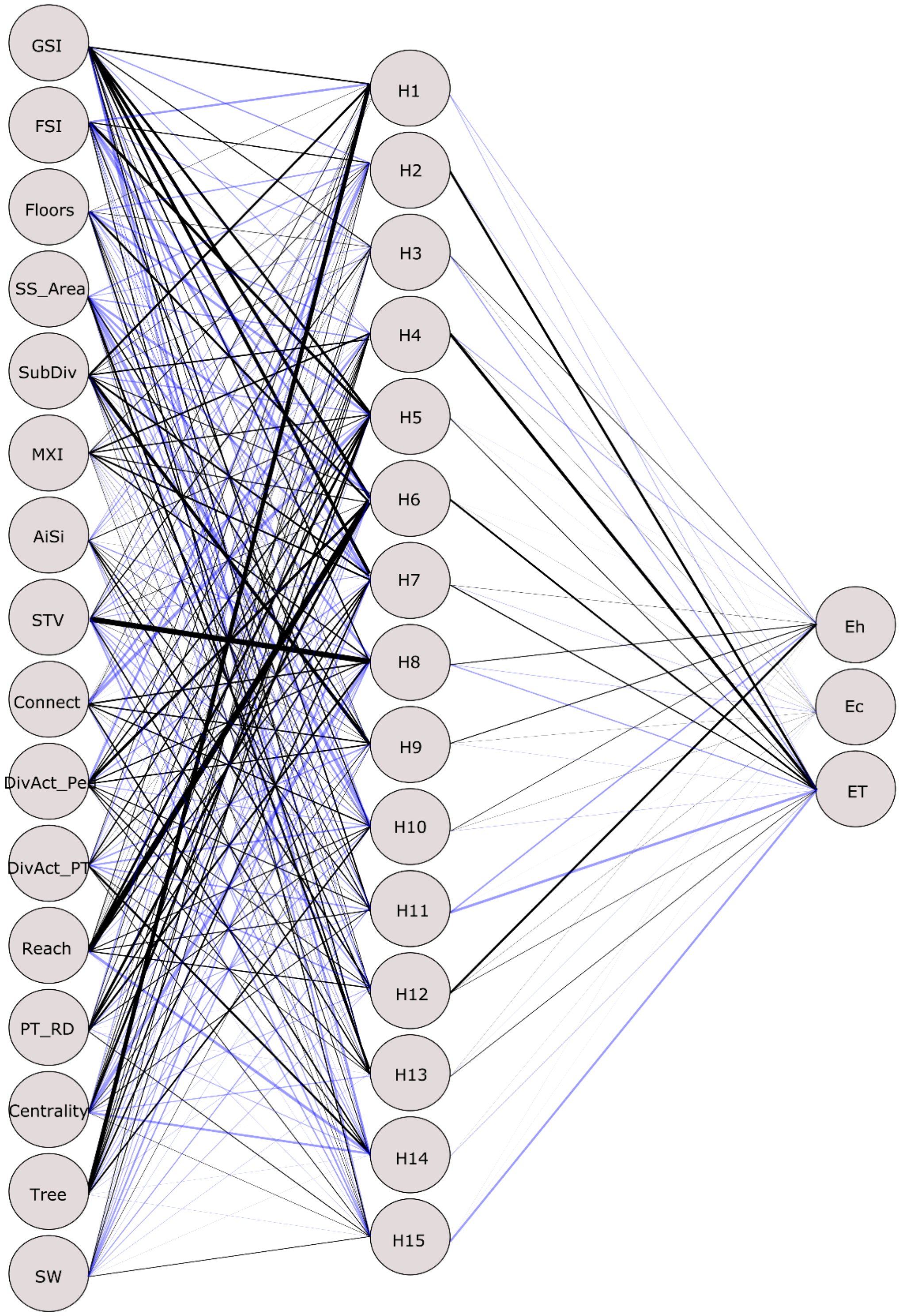

Figure 94. Neural Interpretation Diagram (NID) for the Lisbon model

Alternatively, the Garson's algorithm (Garson, 1991; Goh, 1995) enables to further explore the impact of each variable of urban form on energy demand. It has the drawback of computing absolute connection weights to calculate the contribution of the model variables (i.e. it does not consider the direction of the input-output effects). However, it is the most straightforward method to assess the effect of each predictor on the overall model, and has delivered good results (Gevrey et al., 2003). The method consists of splitting the hidden-output connection weights for each neuron in the hidden layer into components linked to each input. The contribution of each input for each output is computed through the normalized product of the input-hidden and the hidden-output connection matrixes (the full procedure is illustrated in Olden and Jackson (2002)).

Figure 95 shows the results of the application of the Garson's algorithm to the connection weights of the ANN model for Lisbon. It depicts the relative weight of each variable in the ANN model. The individual weights range from 4% to roughly 10%.

Overall, the most important variables found by the Garson's algorithm correspond to the ones identified in the stepwise MLR. These are mainly macro variables of urban form related to density (notably the GSI, FSI) and granularity (Subdiv and SS_Area), along with building compactness (STV), centrality and the accessibility measures (DivAct_PT and DivAct_Ped). This is consistent with the literature, which has mainly focused on macro variables of urban form, and also with the results from the case study of Porto. The most striking differences between the stepwise analysis and the Garson's algorithm correspond to the weight of the F variable (number of floors) and Reach. Although F was selected in all the three individual stepwise models, in the Garson's algorithm is not ranked as one of the most relevant variables. Conversely, Reach gains importance in the variable rank. In addition, the Sw, the MXI and the AiSi were selected by the stepwise approach, but their weights are now lower than variables like Connect and Tree, which were not included in the stepwise selection (Figure 95). The remaining variables (not included in the stepwise models) account for roughly 22% of the total variable weight. The ANN was able to find quite significant relationships between these predictors and the response variables, while the other techniques performed better without them.

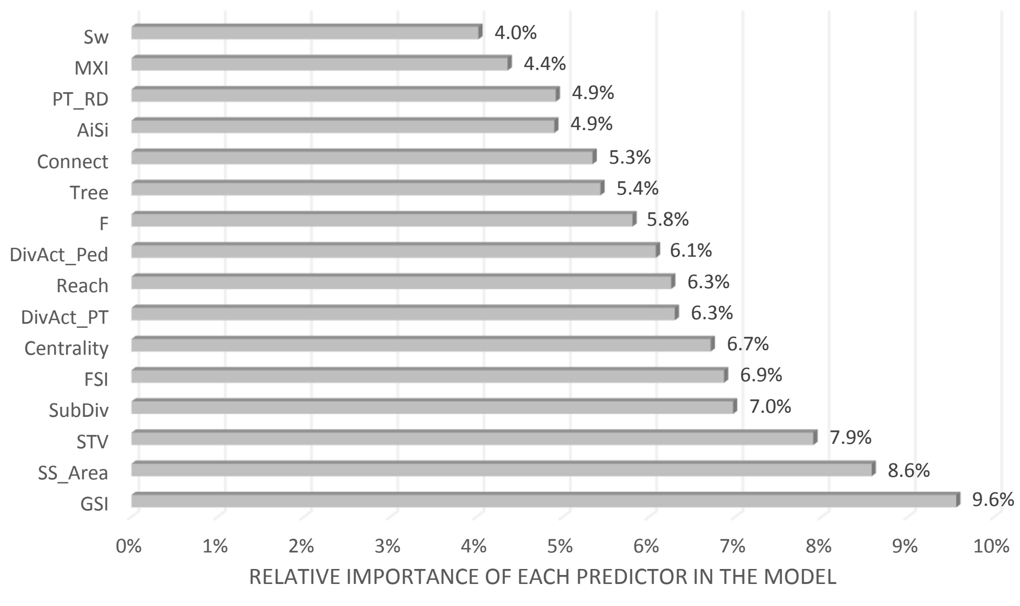

Figure 95. Weight of each predictor in the ANN model (application of Garson's algorithm). Lisbon.

The last method used to extract information from the ANN model is a sensitivity analysis. It consists of the variation of the input variables in an iterative process, to check for the corresponding effect on the dependent variables. Its application will be done in a similar way to the case study of Porto, for a few selected examples. Figure 96 presents the examples considered. Note that each graph depicts the variation of a response variable according to changes in a model predictor (in the *yy* axis), for different values of a third variable (predictor).

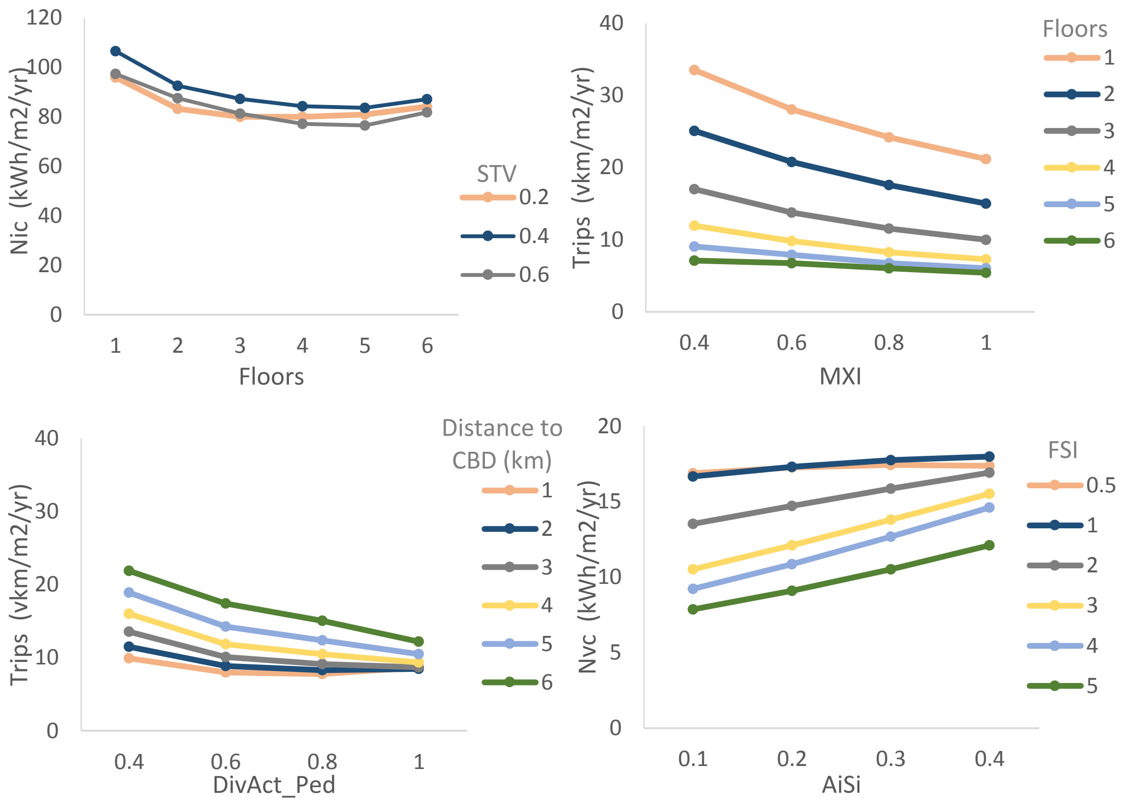

Figure 96. Sensitivity analysis for selected model variables. Lisbon.

Figure 96 shows that heating needs tend to decrease with higher number of building floors (although a slight increase is visible from 5 to 6 floors). Higher compactness indices (lower STV) are also associated with lower needs for heating (except for the curve STV = 0.6). A higher number of floors is associated with fewer needs for motorized travel, whereas the best mix of uses seems now to be located somewhere between 0.8 and 1, depending on the building type. In addition, typically pedestrian accessibility is inversely associated to travel needs, with smaller distances to the CBD implying a decreasing energy demand for mobility. Finally, cooling needs are inversely associated with the floor space index, while larger shares of green areas are now associated with higher cooling needs (although it is not evident whether this latter effect is captured by the certificates).

A last type of insight that can be obtained from this spatially-explicit approach is the mapping of the prediction errors of the ANN model for each output variable, according to Horta and Keirstead (2016). As advocated by these authors, a good understanding of the local context allows distinguishing between a poor model performance and unique local characteristics.

Both Figure 97 and Figure 98 evidence a predominance of small errors regarding the predicted heating and cooling needs by the ANN model, respectively. There isn't a conspicuous spatial trend on the location of the errors, however many of the blocks with greater errors and located in peripheral areas of the city. Also, there seems to be some correspondence on the blocks with greater errors for the heating and cooling end uses.

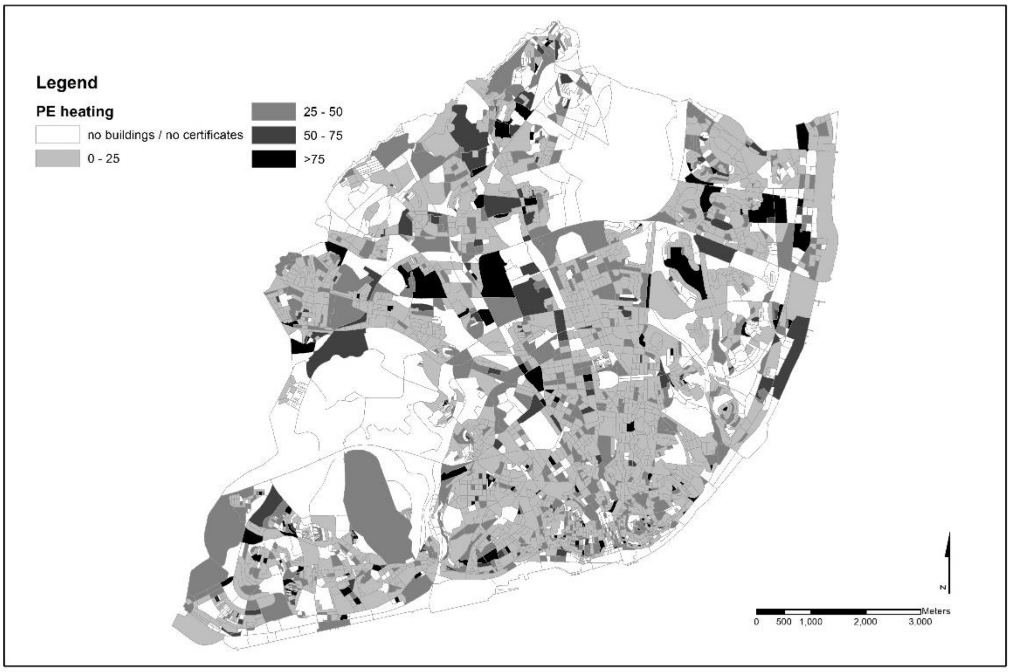

Figure 97. Percent errors of the ANN model for heating needs

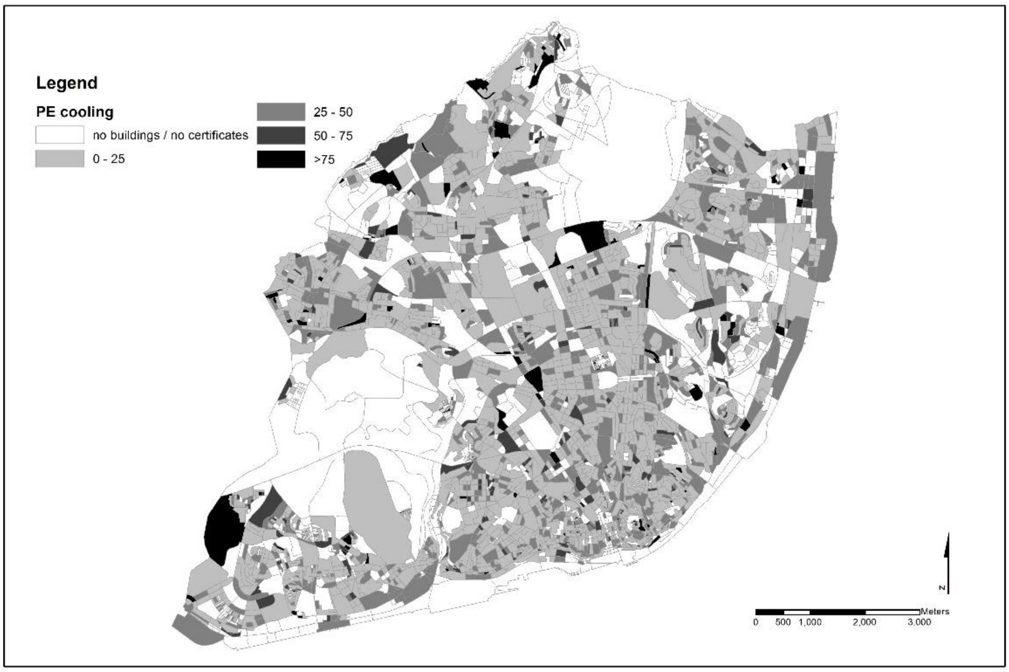

Figure 98. Percent errors of the ANN model for cooling needs

In regard to mobility, although there is a predominance of smaller prediction errors, there is also a considerable number of errors with higher magnitudes (Figure 99). As noted earlier, mobility is the energy end-use that is being predicted with lower accuracy in the city of Lisbon.

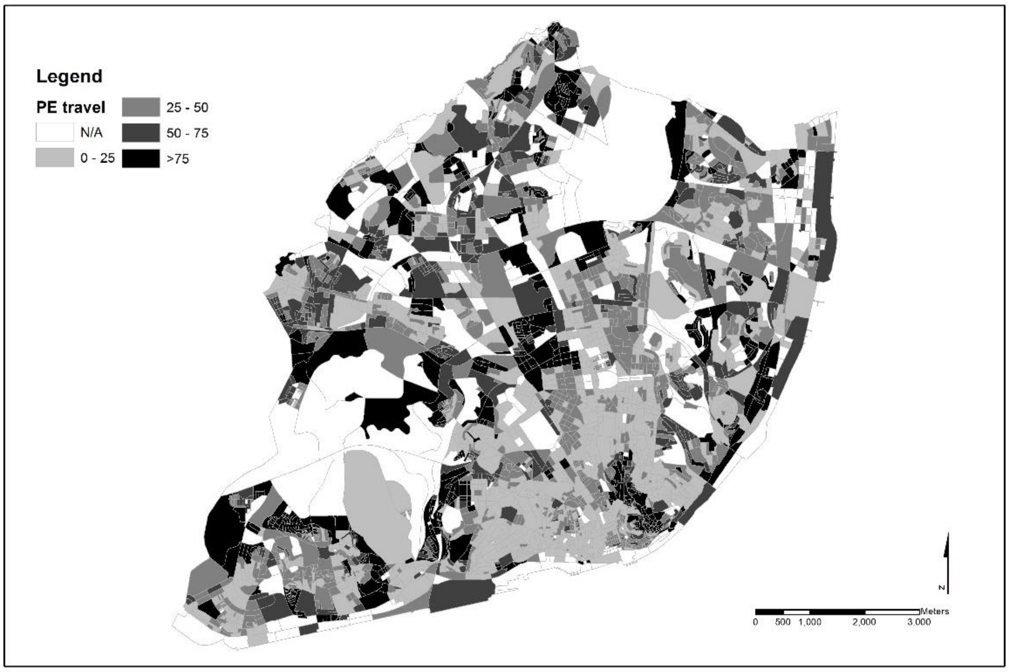

Figure 99. Percent errors of the ANN model for mobility needs

Interestingly, some spatial trends are visible in the map depicting the prediction errors of the ANN model. It is possible to identify some sort of clusters with higher errors. Similarly to the case of Porto, the higher errors seem to be located in areas that are adjacent to urban freeways that cross the municipality, particularly the *Segunda Circular* and *Eixo Norte-Sul*. These areas serve as entry/exit points to and from the city, and it is possible that the higher concentration of vehicular influxes in these areas may be significantly different from those from the remaining parts of the city (also note that the polarisation effect in Lisbon is stronger than in the case of Porto). Also, there is a peculiar area with higher errors, in an older part of the city, around Castelo, in which the model is not working properly. In fact this area has some specificities regarding the characteristics of urban form. It has narrow streets, it is very much densely built and has a high granularity, but there isn't much people actually living there. Conversely, it attracts large amounts of tourism and sightseeing trips. This may be the cause of such results.

Finally, considering the spatial distribution of the three response variables, some general trends may be found from the application of this methodology to Lisbon. The urban blocks located in the city centre are consistently the ones evidencing lower needs for motorized travel. The core areas of the city are well served by public transports and are where walking and reaching a larger number of activities is most feasible. It is characterized by smaller blocks and a high granularity. Conversely, the areas on the riverside evidence a larger demand for motorized travel, which may related to the location of specific urban activities, as well as key entry points in the city (via the two different bridges, as well as the different boat terminals).

Concerning thermal needs in buildings, the old urban core, with higher compactness, does not present one of the best performances in terms of heating needs. In addition, it evidences one of the highest cooling needs. While the high cooling needs may be due to the existing compact patterns and the lack of building ventilation, the fact that the heating needs are not lower here may be explained by the construction materials (typically with relatively low thermal inertia). One of the areas with lower energy demand for heating are those immediately following the urban core, which are also compact and dense, but which have a different construction type, and thus performing better (with lower heating needs). Still, apart from the non-urban form factors, building compactness seems to be one of the most relevant indicators of urban form in determining building's energy balance.

5.3. Synthesis

This chapter presents the application of the methodological framework proposed in this work to an additional case study, the city of Lisbon. This aimed at further exploring the feasibility of the methodology and validating its replicability in a different urban geography, as well as providing a basis for comparing the results previously obtained for the case study of Porto.

The spatially-explicit approach proposed has proven its usefulness, both in capturing spatial trends for the model predictors and outputs, as well as in the interpretation of the prediction errors of the model developed. ANN emerge as a suitable technique to model the research problem, returning better results than the remaining techniques, which are closer to traditional statistics (MLR and SEM). It enabled to identify relationships of higher magnitudes, while delivering a higher accuracy.

The results confirm the existence of significant links between urban form and energy demand. In addition, they support the relevance of addressing energy needs for buildings and mobility together. Although the coefficient of determination (R^2) for the city of Lisbon is not as high as the one for the previous case study, it still has a significant magnitude (R^2= 0.56). This suggests that the role of urban form in determining urban energy needs varies from city to city. In Lisbon, it is not as prominent as in Porto. Here, the other drivers of energy demand may play a more significant role, notably behavioural and socio-economic factors. Of course, the coefficient of determination could never be close to 1, because urban form alone could not explain the full variability of the data. Given the case studies analysed, one can say that the contribution of urban form to the energy demand of the three key urban end uses may range from 55% to 80%.

The energy needs for cooling are consistently those least influenced by urban form (R^2=0.21). Conversely, heating (R^2=0.46) and mobility (R^2=0.48) needs are subject to a higher influence from the physical structure of the city. While the ANN model consistently presents high accuracies for the heating demand, in the case of Lisbon, mobility has the highest prediction errors. Two possible explanations arise. The first refers to nature of the mobility database. The OD trip matrix for Lisbon was a gridded matrix instead of having the traffic zones coinciding with specific streets or other urban boundaries. This makes the capturing of the existing spatial patterns of the city less feasible, and makes more difficult to disaggregate the data into the spatial units considered. Also, it is possible that the overall number of trips may be underestimated (taking the case study of Porto as reference). The second possible explanation is the specificity of the case study. Lisbon may have different intrinsic dynamics in relation to Porto. The national capital city may entail a more intricate set of factors and drivers (notably economic and behavioural ones) determining mobility patterns, making the prediction of ET more difficult. It is also expected that the strong (travel) interdependency of this municipality in relation to the remaining metropolitan region may be originating some of the errors. Both explanations may coexist.

Nonetheless, it is considered that these higher prediction errors for travel purposes, do not compromise the feasibility or usefulness of this approach. The errors are still within an acceptable range, given the complexity of the object under analysis, and yet, the methodology enabled to identify significant relationships between the different variables. As such, the application of this methodological framework to the city of Lisbon validates its replicability in an additional urban geography.

In the case of Lisbon, the most relevant urban form variables are, again, macro features of the urban environment, mostly related to density and granularity (in fact, granularity may be as important as density), as well as centrality and accessibility. This is in line with the literature, which has been dominantly focusing on macro features of the urban environment, notably density. Although micro features of the urban environment are not as prominent, their combined effect is also worth controlling for. Here, increasing residential densities seem to be key for energy conservation, whether considering the building or the transport sector. In buildings, building compactness and attached housing patterns should also be accounted for in new urban developments. Also, a good accessibility and a high granularity are key factors for reducing motorized travel needs.

Overall, there is some degree of similarity between the relative weights of the model predictors (Figure 100), although some differences may be found between the two cities (e.g. the relative importance of the three density indicators is not the same). The complexity of the phenomena inherent to energy use in cities does not allow for the generalization of the contribution of the variables from one urban context to another. Still, the model works as a case-specific tool, it can be used to determine the right weights in different cities, and therefore to build a functional model in diverse geographies.

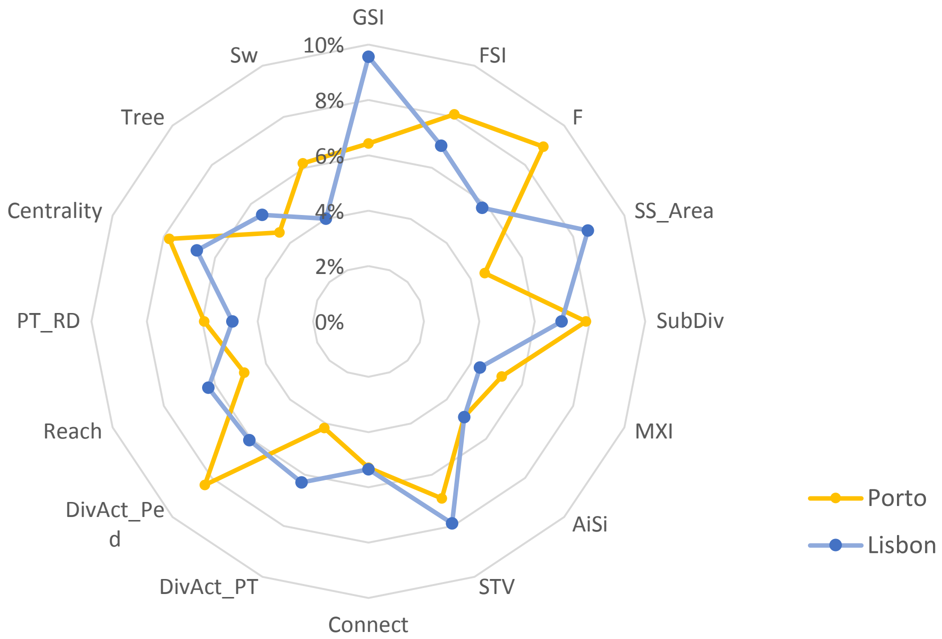

Figure 100. Comparison of the weights of each model variable between the two case studies

The application of this approach to the two case studies confirmed the existence of significant relationships between urban form and energy demand. It addition, it enabled shedding some light on the effect of each individual variable. This is expected to contribute to improve the existing knowledge on the combined effect of a comprehensive set of urban form attributes in determining the energy demand (for three end uses) in cities. In the future, it would be interesting to explore the application of the methodology to additional urban contexts. This would possibly allow finding patterns on the influence of urban form by city type (for instance, depending on city size or on economic structure).

Chapter 6 will investigate the potential of this methodological framework to work as a decision-support tool, considering both case studies (Porto and Lisbon). Different urban development alternatives will be analysed and compared in relation to their impact on the demand for the three energy end-uses (heating, cooling and mobility). This is expected to enable concluding on efficient urban development pathways in both case studies.

CHAPTER 6. PERFORMANCE ASSESSMENT OF URBAN DEVELOPMENT ALTERNATIVES

As Handy (1996b) noted, "*finding a strong relationship between urban form and (travel) patterns is not the same as showing that a change in urban form will lead to a change (…), and finding a strong relationship is not the same as understanding that relationship*". The methodological framework proposed (in Chapter 3) and applied earlier (in Chapters 4 and 5) is a novel approach for analysing the links between urban form and energy demand, combining two key urban sectors and a comprehensive set of urban form indicators. In addition to having confirmed the existence of important relationships, the methodology allows predicting the energy demand for three important end uses in cities. This predictive character is expected to allow addressing the point made by Handy, through the quantification of the change in energy needs resulting from changes in urban form. It is this ability that provides the methodology with a potential for working as a decision-support tool, offering insights in the design of more efficient urban areas, as well as informing future urban planning and development policies. The models built are expected to allow for an *ex ante* evaluation of the impact of urban development choices.

Under this perspective, the applicability of the two ANN models (Porto and Lisbon) for evaluating the energy impact of different urban development pathways will be evaluated. This is done by departing from the current urban background, in both cities, and by considering possible futures for the two urban contexts. The possible futures envisioned correspond to different development strategies, each privileging specific urban configurations and development locations throughout the city. The changes in the urban forms are expected to translate into different energy needs for each of the three end uses considered (heating, cooling and mobility).

In a sense, the consideration of the different urban development alternatives can be seen as a type of sensitivity analysis, by estimating the effect of the variation of urban form parameters on the response variables. As a result, this part of the work (Stage 4 of the research) draws on the results from the two previous chapters (Stage 3) and is expected to provide further insights on the links between the variables, by extending the results obtained from the NID and the Garson's algorithm.

Section 6.1 presents the rationale for the urban development alternatives considered, Section 6.2 presents the urban development alternatives considered, and Section 6.3 illustrates its materialization in the two case studies (Porto and Lisbon). Section 6.4 presents and discusses the results obtained from the application of the ANN models to the urban alternatives. Finally, Section 6.5 wraps up the insights from this Chapter.

6.1. The rationale for defining the urban development alternatives

The models built for Porto and Lisbon (in Chapters 4 and 5) enabled to estimate the combined influence of the variables of urban form on energy demand, as well as quantifying the relative importance of each predictor. Now, such models will be used for the analysis of different urban development pathways. The quantification of the effect of changes in the predictors is expected to provide additional insights on the connections between the model variables (i.e. shedding light into the black box). It seeks to explore which are the most efficient urban development choices for each case study, thus providing support for decision-making in urban planning. The consideration of urban scenarios is useful to illustrate the implications of different policies (Shearer, 2005), providing a basis to discuss different planning options. For the remainder of the thesis, urban scenarios and urban alternatives will be used with different meanings. Scenarios refer to a possible future that is not under the decision scope. Conversely, the term alternative will concern a possible future that can be influenced by decision-making, i.e. by the development strategies adopted.

Distinct planning options will be assed under the form of urban development alternatives. Those with a better energy performance will be considered as suitable development pathways. Both the urban development scenarios and alternatives will ground on the existing built environment and will consider possible evolution pathways from there. Future changes are constrained by the existing built structures, notably in historical areas (where the conservation of the built heritage is a real concern). Hence, development options completely breaking with the current reality are not considered (for instance, building part of the city in a Manhattan-style).

One key concern was to make the development alternatives comparable. The way to do so was to fix an amount of new gross floor area – GFA (as proxy of the resident population) and the ratio between residential and non-residential areas (as proxy of the level of economic activity) across all the development alternatives. This aimed at ensuring that the changes in the energy intensities predicted by the model wouldn't result from a change in the overall intensity in the use of the territory, but instead, from the alternative urban configurations (i.e. the choices to accommodate a certain demographic and economic change). The alternatives also aim at being non-overlapping, allowing to check for the effects of specific strategies before considering cumulative effects.

The differences between the development costs of the alternatives are expected to be reduced, once the urban alternatives are designed in order to be of comparable intensities. The construction costs are not expected to differ significantly among the different scenarios, the only difference being the price of land between the different urban areas, which can be neglected.

Two types of approaches for scenario planning can be considered: normative (identifying preferable futures) and descriptive (describing different possible futures without specifying preferences) (Shearer, 2005). Zapata and Kaza (2015) claim that time horizons are largely unimportant when building urban planning scenarios and argue that planning for a single preferred scenario (i.e. with a view to achieving specific goals) is unfeasible, as it does not address future uncertainty. In line with the above, instead of focusing on a single normative scenario, different urban development possibilities are considered in light of various planning strategies. Also, the changes do not refer to a specific time horizon, but instead to an arbitrary point in time where the conditions considered could take place, from the adoption of specific development policies.

Two magnitudes of urban growth are considered. One, entails small changes, thus corresponding to a nearer future, and another entailing larger scale changes, thus corresponding to a more distant future. These two different magnitudes are considered in order to show the corresponding size effect in energy demand. It also enables to consider the effect of scenarios that have a limited potential to be implemented at a larger territorial scale (e.g. infill development). Nevertheless, in spite of the current trend of decreasing population in the two case studies, the scenarios considered are scenarios of growth. This is due to the fact that the existing built environment is very unlikely to change in a significant way. Most of the changes come from new additions to the existing built structures and seldom from large-scale demolitions that significantly modify the existing built environment. Hence, the alternative is to consider scenarios of growth.

Furthermore, two scenario lines are analysed: line A considers that all the new development is residential, whereas line B considers that 80% of the new development is residential and thus, 20% is non-residential. Although a scenario of growth that is 100% residential may seldom be found at a large scale for all urban tissues, it is frequently found at smaller development scales, and it may take place at a larger scale in urban tissues where non-residential uses are typically discouraged. Hence, considering these two scenario lines allows to cover a broader range of development options. Figure 101 represents the four scenarios considered (two scenario lines (A and B) referring to the share of residential land uses, and the two development magnitudes referring to the magnitude of urban growth).

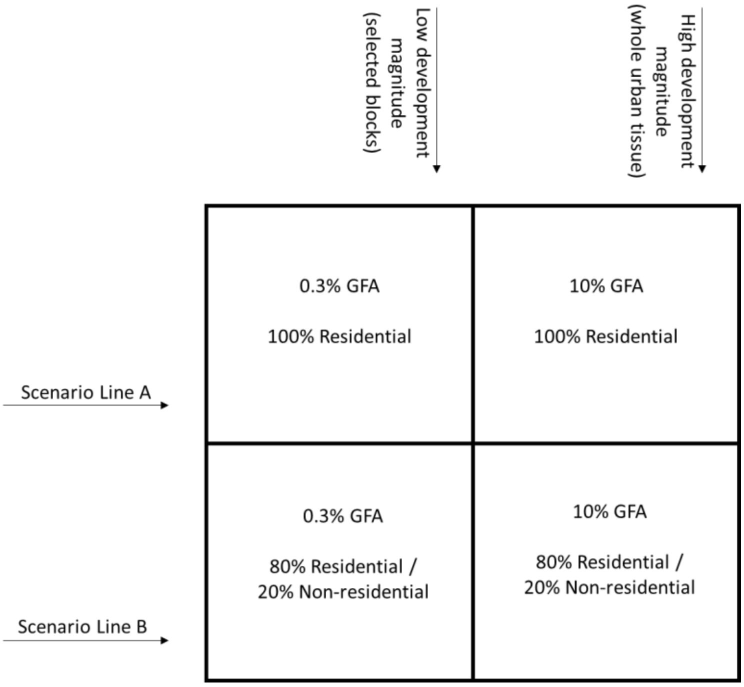

Figure 101. Urban development scenarios considered
Several alternatives will be considered within each scenario.

The development strategies (i.e. the urban alternatives) considered differ foremost in terms of their formal attributes (notably the development location, land use intensities, the diversity of activities, accessibility and presence of green spaces). For a given development magnitude, the alternatives analysed within each of the two scenario lines are similar. However, since the two lines have different land use "intensities" they are not compared with each other. Figure 102 illustrates the rationale adopted, where the two horizontal boxes represent the scenario lines upon which the urban alternatives are envisioned (A is 100% residential, and B is 80% residential and 20% non-residential). The vertical boxes correspond to the urban development alternatives, which will be detailed in the following section. This rationale was replicated for the two development magnitudes, comprising smaller- and larger-scale changes.

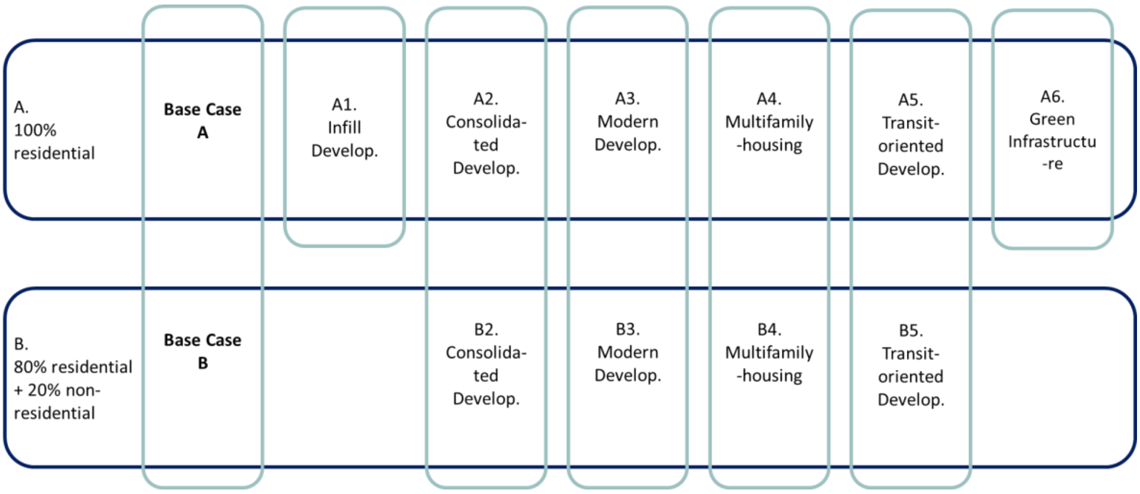

Figure 102. Rationale for building the urban development alternatives

It has been advocated that individual measures of urban form return relatively small effects, becoming more effective when combined (Grubler et al., 2012). Also, it has been questioned whether density is the driver of lower energy intensities or if it works as proxy for other variables often found in dense urban settings, such as proximity to public transport and accessibility to activities. This reinforces the relevance of considering different manifestations of density and the effect of different urban attributes (such as diversity) in separate, as well as analysing their combined effect. While line A plays with different facets of density, and considers the effect of other indicators at a time (e.g. building compactness, green infrastructure and proximity to public transport), line B allows evaluating the incremental impact of changing the mix of land uses.

In both cases, the urban alternatives are compared with a reference or base case. The base case refers to an extension of the current development patterns, where no specific strategy is followed, and which could also be called a “current policies” future. The remaining alternatives are built in the light of development strategies reinforcing energy conservation in cities, which are largely present in the literature and in existing action plans across different governance levels (international, national, regional and urban). Such strategies can, thus, be translated into quantifiable changes in the indicators of urban form considered in this study, specifically those that were consistently found to be more influential of energy demand. The changes in the indicators will not take place equally throughout the whole city, but instead at selected locations belonging to a specific urban tissue, producing different and non-overlapping urban configurations.

The alternatives will be compared in terms of their total yearly energy demand (disaggregated for the three end uses – thermal uses in buildings and mobility), resorting to the ANN models created. In order to convert the energy needs of buildings (given by the building certificates) into an estimation of real energy use, it was assumed that the useful energy use would represent 0.4 of the energy needs for heating (following Magalhães (2016) findings) and 0.2 for cooling. Given the local knowledge of building typologies, it was assumed that useful built-up areas is 60% of the GFA. Also, the conversion factors of useful to final and final to primary energy are presented in Table 68 (Annex IV).

6.2. Conceptual description of the urban development alternatives

The definition of the alternative urban development patterns was based on some renowned development approaches that are often found in the literature. These are: the infill development, urban consolidation, modern development, multi-family housing, transit-oriented development, and green infrastructure. The following paragraphs conceptually describe each of the alternatives considered (a quantitative characterization of their implementation for the case studies is given in Section 6.3).

1. **Infill development (IN)** – Consists of promoting the use of vacant lots in central locations of the city (EPA, 2014). It may be defined as a type of development that takes place in urban settings that are already built-up, with a good provision of transport and utility infrastructure. It may be located in undeveloped lots, but also in sites like parking lots and other impervious grey areas. Infill development is highly encouraged in the planning literature, as it represents a strategy to curb urban sprawl and promoting urban regeneration (Seto et al., 2014). Brownfield redevelopment may also be seen as a type of infill, given the fact that many former industrial abandoned sites are located in quite central areas.

2. **Consolidated development (CD)** – Consists of increasing urban densities in central locations of the city that are not yet consolidated. Urban consolidation involves a process of intensification either referring to the built forms or activities (Buxton and Tieman, 2005). Although consolidated development is also targeted at preventing scattered development patterns, it is distinguished from the infill development, as in this case, densification may take place by intensifying development in lots that are already built-up, instead of filling vacant lots. A frequent way to do so is by increasing the height of existing buildings. Buxton and Tieman (2005) claim that this process may take place in three ways: One, local governments identify suitable places for consolidation, and plan for it in strategic locations. Second, it can take place in an incremental and dispersed way, mostly naturally driven by the market, consisting of the redevelopment of housing lots and building conversions. The third, is to require increased densities for the issuance of building permits.

3. **Modern development (MD)** – Modernist planning has been subject to some criticism from the literature (see, for example, the critique to the contemporary city in the seminal book by Jacobs, 1961). However, because it refers to a type of development that has been taking place in cities in the last decades, not only in Europe, but worldwide, it was deemed important to consider this as a real urban development pathway, whose implications in energy should be accounted for. It is characterized by areas of isolated buildings, typically medium- to high rise, adding open space in between the building sites (i.e. detached-housing).

4. **Multi-family housing (MFH)** – Multi-family housing, in opposition to single-family housing patterns, has been widely advocated in the literature. This alternative is a type of densification, targeted at a specific urban tissue that typically leaves little room for the diversity of urban functions and, because the urban space is used less efficiently, it typically implies larger distances to be travelled. Single-family housing is often associated to

sprawled land use patterns. As a result, this alternative is targeted at assessing the impact of converting this urban typology into multi-family housing.

5. **Transit-oriented development (TOD) –** Consists of the promotion of land development (mainly residential) close to important public transport nodes (Boarnet and Crane, 1997). This type of development is based on the premise that the proximity to public transport infrastructure (notably the metro and rail services) promotes the adoption of this transport mode. It is also advocated to promote mixed-use activities (Jabareen, 2006).

6. **Green Infrastructure (GI)** – The potential benefits of green infrastructure have been discussed in Chapter 2. Overall, green infrastructure is argued to affect urban energy demand in two ways. It contributes to creating more pleasant urban settings, fostering the adoption of walking and other soft modes for travel. Moreover, they provide shade in summer and help regulate urban air temperatures, with effects on buildings thermal needs. This alternative aims at assessing the effect of adding green infrastructure to the urban matrix (notably trees and green spaces), without changing additional urban elements.

Although some urban development alternatives may be simply described as adding an average floor to a specific urban tissue, in practice this means changing several indicators of urban form that are automatically affected by changing the number of floors. The indicators that were changed in each urban development alternative are identified in Table 41.

Table 41. Indicators subject to change in each urban development alternative

Alternative	IN	CD	MD	MFH	TOD	GI
Relevant Indicators	GSI, FSI, SubDiv, STV, Reach	FSI, F, MXI, Divact_PT, Divact_Ped, Reach	FSI, F, MXI, Divact_PT, Divact_Ped, Reach	FSI, F, MXI, Divact_PT, Divact_Ped, Reach	FSI, F, MXI, Divact_PT, Divact_Ped, Reach	GA, Tree

6.3. The alternatives in the territory

Given the six development patterns described above under a conceptual level, this section specifies how they were applied in the territory of the two case-study cities (Porto and Lisbon). This approach translates into changes in a specific set of urban form indicators (Table 41). Although the overall development magnitude is kept the same among the urban alternatives, the intensity of the changes in each urban block varies, depending on the urban tissue at stake. Each development strategy privileges specific urban configurations in particular areas within the city.

Recall that two magnitudes of development are considered. One, has a smaller expression in the territory and entails the transformation of a specific set of blocks in a given urban tissue. The other, has a larger expression, entailing a more generalized transformation of an urban tissue as a whole. Figure 103 presents an overview of the urban development scenarios and alternatives under analysis in the following subsections. The reasons for considering a different number of alternatives in each case is detailed below within the corresponding topic.

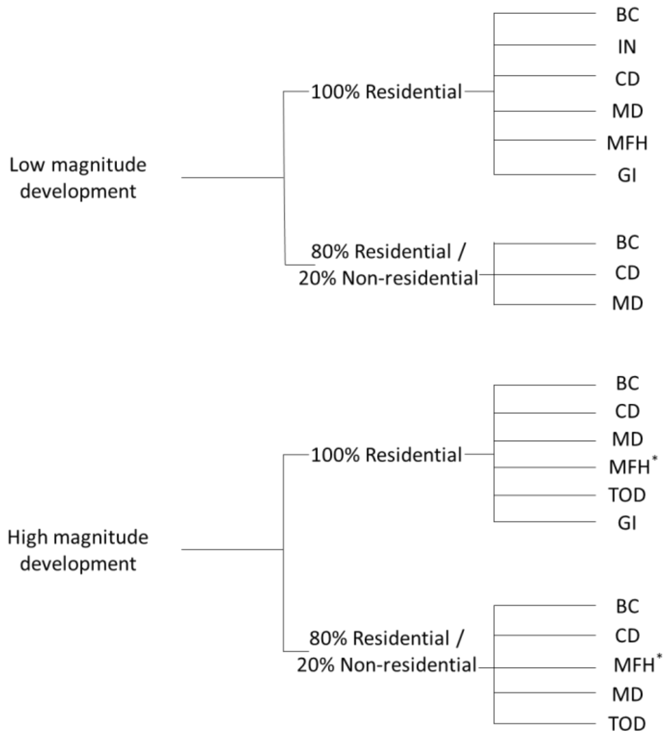

Figure 103. Overview of the development scenarios and alternatives under analysis
* Not applied in the case of Lisbon (detailed in Section 6.4.2).

The following subsections describe and map the urban development alternatives for the two case studies, illustrating the location of the urban blocks where the changes have been applied.

6.3.1. Porto

For the interpretation of the different urban alternatives, including the location of the urban blocks intervened, it is important to bear in mind the classification of the land uses, as described in the Porto masterplan (Figure 23, Chapter 4). Figure 104 provides an additional insight on the typical structure of the main urban tissues described in this masterplan. It highlights the compact configurations of historical areas in relation to other areas of the city, such as the areas of single-family housing or the areas of isolated buildings.

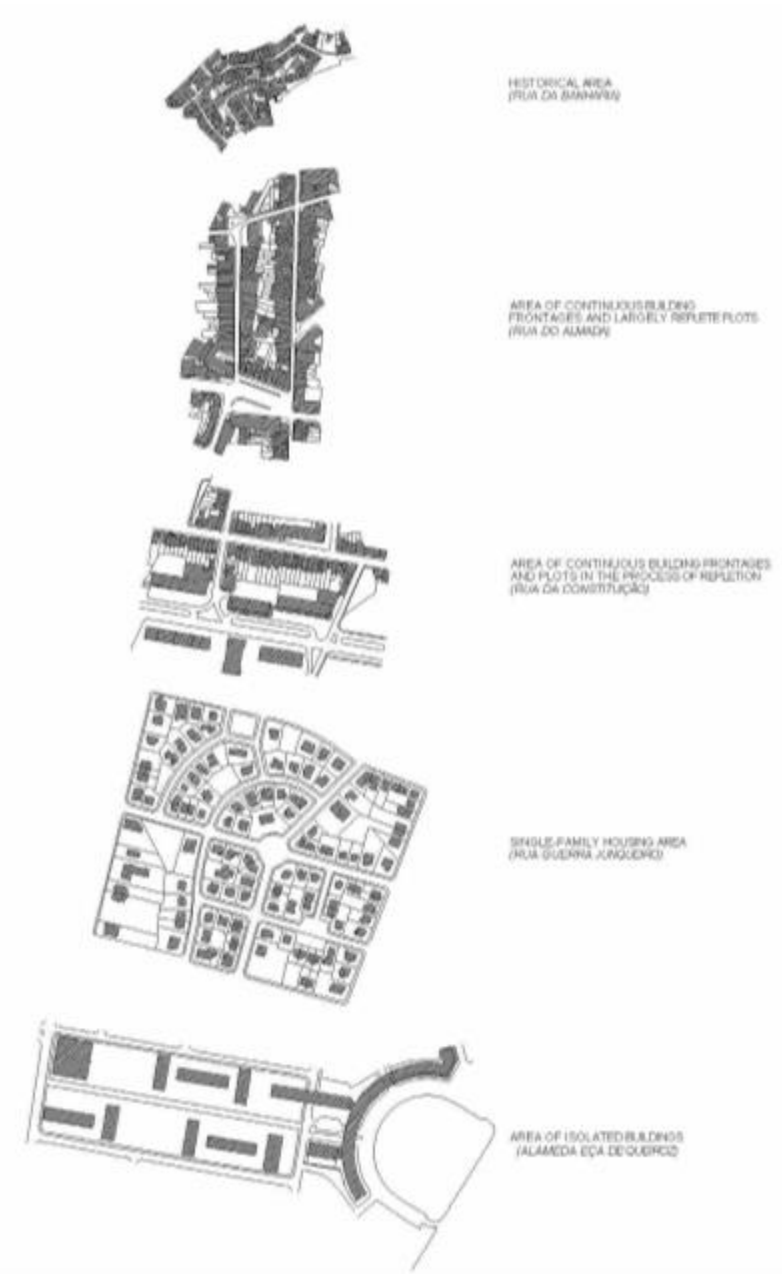

Figure 104. Typical configuration of the different urban tissues of Porto (relation between buildings and plots)
Source: (Oliveira et al., 2014)

6.3.1.1. Acting upon a specific set of blocks in a given urban tissue

This subsection refers to a small scale development magnitude, taking place in the short term (estimated to be about 1 to 1.5 years, according to new construction data from INE). In this case, the increase in the GFA is fixed to *ca.* 0.3% of the existing GFA, corresponding to about 75.500 m^2 of newly built space. In order to keep all the alternatives equivalent in terms of new GFA, this was set by the infill development alternative, which is the one with largest implementation constraints.

The alternatives are analysed under the two scenario lines: A – 100% residential and B – 80% residential and 20% non-residential. Table 42 and Table 43 summarize the changes considered for each urban development alternative (columns) within each urban tissue (rows), for scenario line A and B, respectively.

Table 42. Description of the development alternatives for a set of blocks in specific urban tissues (line A). 0.3% GFA. Porto.

Urban tissue	**Alternative**						
	Base case	**A1**	**A2.1**	**A2.2**	**A3**	**A4**	**A6**
	Current policies	**Infill develop.**	**Consolidat. develop. (concentrated)**	**Consolidat. develop. (random)**	**Modern develop.**	**Multi-family housing**	**Green infrastructure**
Historic or Consolidated areas	-	New buildings with same # floors	-	-	-	-	-
Areas in process of consolidation	+ 1 floor	-	+ 1 floor	+ 1 floor	-	-	+ 1 floor + GI
Isolated buildings	+ 2 floors	-	-	-	+2 floors	-	+ 2 floors + GI
Detached housing	+ 0.5 floors	-	-	-	-	+0.5 floors	+ 0.5 floors + GI

Table 43. Description of the development alternatives for a set of blocks in specific urban tissues (line B). 0.3% GFA. Porto.

Urban tissue	**Alternative**			
	Base case	**B2.1**	**B2.2**	**B3**
	Current policies	**Consolidated development (concentrated)**	**Consolidated development (random)**	**Modern develop.**
Areas in process of consolidation	+ 1 floor	+ 1 floor	+ 1 floor	-
Isolated buildings	+2 floors	-	-	+2 floors
Detached housing	+0.5 floors	-	-	-

As it is visible from Table 42 and Table 43, the number of alternatives explored under scenario line B is reduced. The reasons are as follows. The infill development (A1) takes place in the historical and consolidated areas of the city. Both the historical and consolidated areas of Porto are those typically evidencing the largest mix of urban functions. As a result, it was considered that there is little need of considering additional non-residential uses in these areas. Also, according to the PDM, historical areas should be kept predominantly residential. The promotion of multi-family housing (A4), at a smaller scale, is also expected to be unfeasible. These areas correspond to residential neighbourhoods, in which the masterplan would hardly enable different land uses. It would only make sense, under a scenario of a significant change, where the addition of non-residential uses should be accompanied by higher densities. Finally, the effects of green infrastructure (A6) are not expected to be influenced by the existing urban functions. The consideration of this alternative under scenario line B (80% residential and 20% non-residential) would most likely be redundant in respect to the results obtained in scenario line A (100% residential). The following topics illustrate the implementation of the alternatives in the territory, including the base case.

Base Case

The base case represents a random development pattern, without strategic development areas in the city, and without the promotion of specific urban configurations. This alternative is a mix of three of the remaining ones (i.e. alternatives 2, 3 and 4), merging different urban tissues and development intensities, depending on the tissue at stake. Figure 105 depicts the location of the urban blocks subject to changes.

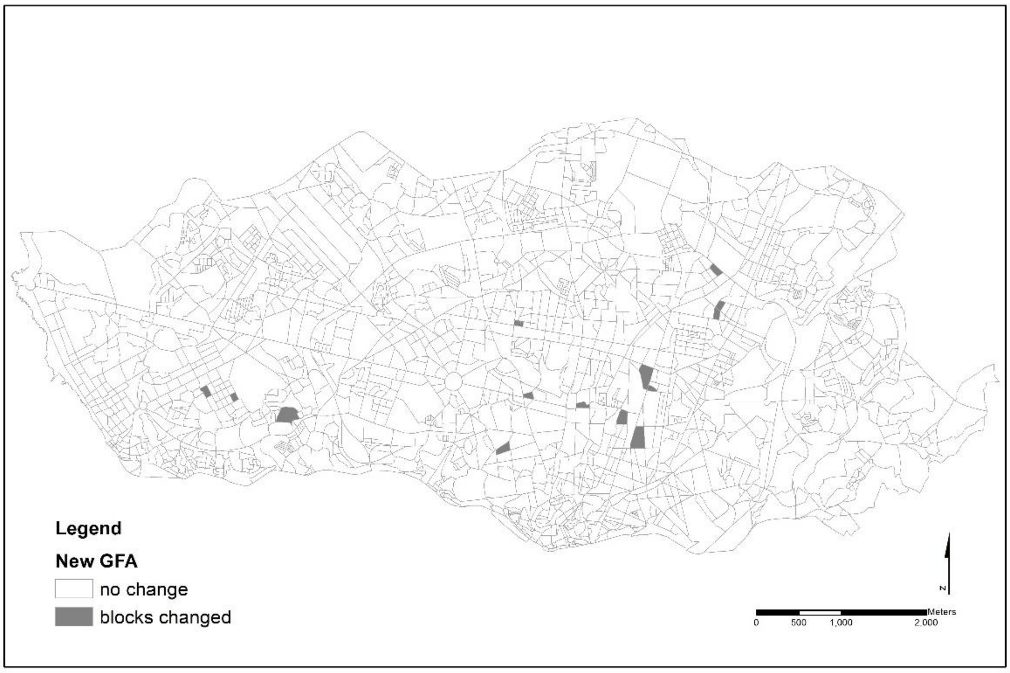

Figure 105. Base Case: 0.3% GFA. Porto.

Alternative 1 – Infill development

Infill development is widely disseminated as a good practice of urban development, expected to shorten trip distances and increase urban compactness, thus yielding reductions on the energy demand both for transport and buildings. However, it has a limited application in the territory, as it is constrained by the existence of vacant sites in the urban cores.

The potential for the implementation of infill development to the Porto case study was considered within the historical and consolidated tissues, according to Porto masterplan. The identification of vacant lots in the city centre was made resorting to a visual inspection of satellite images. In these locations, new buildings were added to the corresponding layer in the GIS (Figure 106).

Some cities have a larger potential for the implementation of infill on the ground than others. In the case of Porto, the city centre is already quite compact and occupied, which limits the implementation of this alternative at a larger scale (for instance, considering the vacant lots identified, and in order to reach a 10% increase in the existing GFA, the number of floors required would be of about 85 floors in average). As a result, the infill development alternative will only be considered under the scope of a smaller development magnitude.

In historic centres, the protection of the built heritage is an actual concern. According to the Porto masterplan, historical areas are designated as areas of mixed land uses, although they should be predominantly residential. For this reason, regarding the infill development alternative, only the scenario line A is analysed.

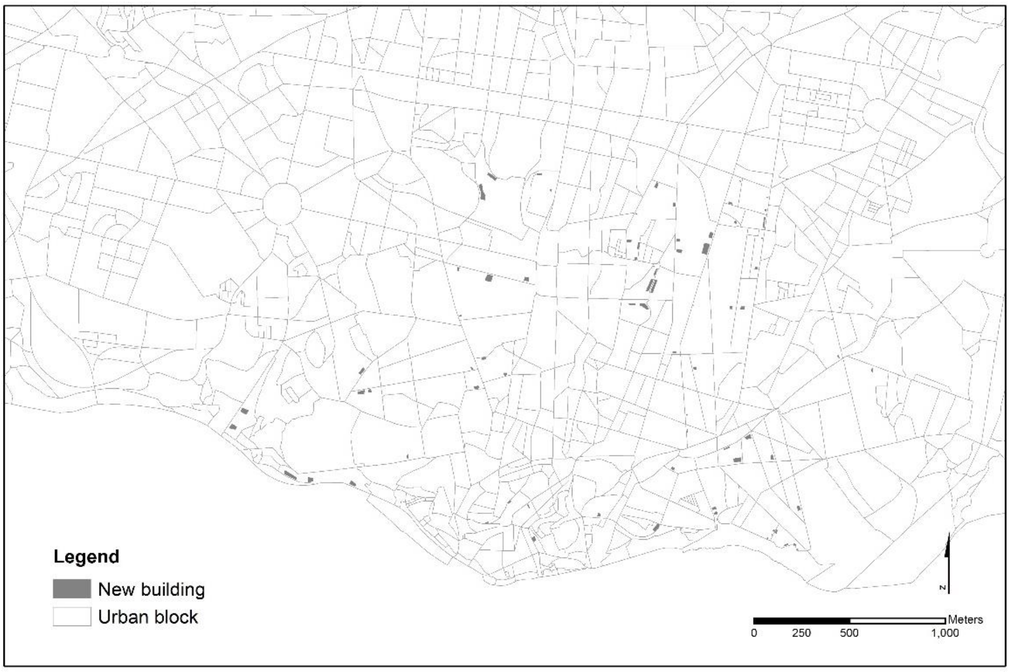

Figure 106. Infill development – location of the new buildings: 0.3% GFA. Porto.

In this case, it was assumed that the new buildings would keep the average height of the urban block (following the masterplan's guidelines). This allowed for the calculation of the new GFAs and of the remaining indicators, to be inserted in the Porto ANN model.

Alternative 2 – Consolidated development

The consolidated development alternative consists of promoting density through increasing the average building's heights in areas of the city designated in the masterplan as "in the process of consolidation". This is a strategy of urban containment, which is expected to promote reductions in the energy demand for the transport and building sectors.

Here, two options or two manifestations of the same alternative will be explored, reflecting two ways under which consolidated development may take place (Buxton and Tieman, 2005). The first is a concentrated consolidation process (Figure 107), corresponding to the promotion of higher densities in strategic development areas. This is likely to take place under the form of a planned process promoted by the local authority, in designated urban areas or urban blocks.

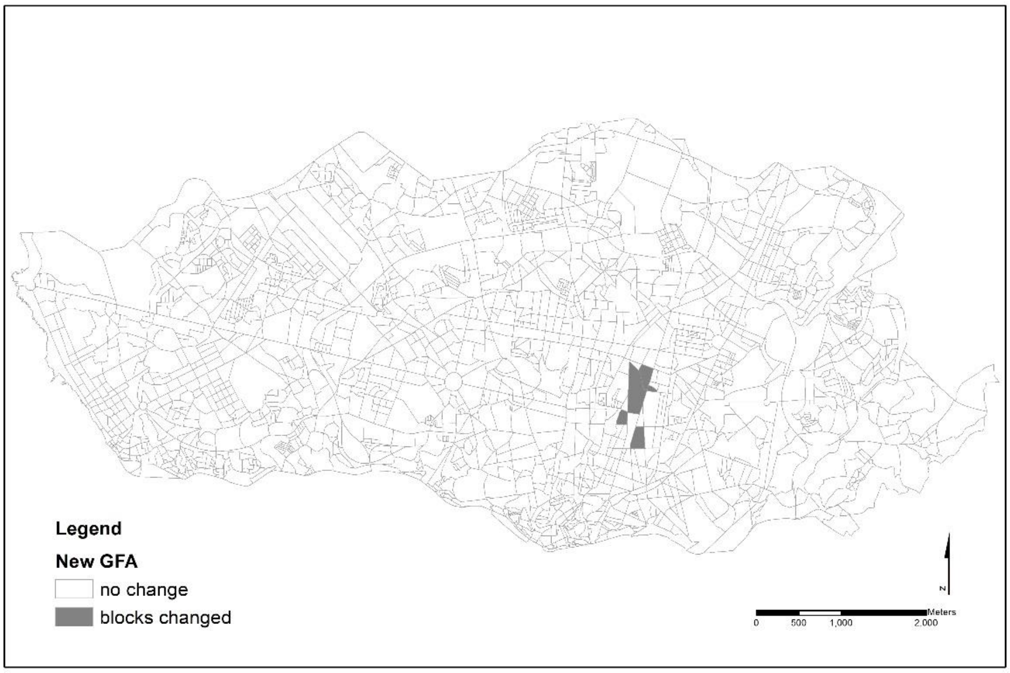

Figure 107. Consolidated development (concentrated): 0.3% GFA. Porto.

The second option is a random, or dispersed manifestation of the consolidated development. This is likely to take place in an unplanned and unstructured way, mostly led by the real estate market (Figure 108).

Figure 108. Consolidated development (random): 0.3% GFA. Porto.

The urban blocks selected for the two manifestations of this alternative at a reduced scale of implementation refer to the same urban tissue (urban areas in the process of consolidation). In this case, it was considered that the average building height would increase by one floor. Accordingly, the urban form indicators affected by this change were recalculated.

<u>Alternative 3 – Modern development</u>

Modernist urban forms are here included as a development alternative, so that a type of development that has been taking place in worldwide cities in the last decades can also be assessed. This alternative is implemented in the areas of the masterplan designated as "areas of isolated buildings", characterized by built-up structures interspersed with areas of open space. These, in the case of Porto, are mostly medium-rise and located outward the city's ring road.

Due to the fact that this urban tissue is typically medium-rise, this alternative consists of adding, in average, two floors to the urban blocks considered. This will enable to assess the effect of higher densities that, conversely to the previous alternatives, are located in more peripheral areas, farther to the CBD, and which are already dominantly residential.

There are three conspicuous nuclei corresponding to this type of tissue in Porto. One is located in the northern side of the city, and two in its western side (one north of *Avenida da Boavista* and the other to the south of this road axis). The latter was selected because it better reflects a dominantly residential area with poor access to public transport infrastructure, meeting the initial purpose of this analysis (the selection of a distinct area could have led to different results). Figure 109 shows the location of the urban blocks considered for a development of small scale magnitude under these conditions.

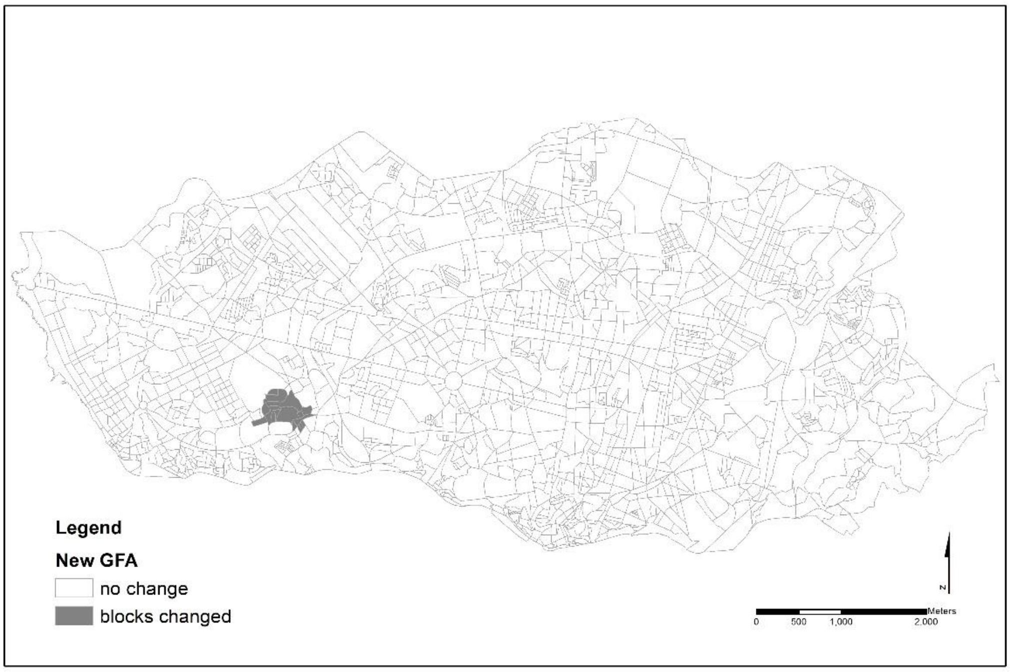

Figure 109. Modern development: 0.3% GFA. Porto.

Alternative 4 – Multi-family housing

The purpose of this alternative is to assess the impact of acting upon an urban tissue with a high demand of space, and likely the one using the urban space less efficiently (also advocated to create inefficiencies in the use of energy both for buildings and mobility) according to the urban sprawl literature. Multi-family housing has been widely advocated to counteract the sprawl phenomenon. Its application will take place in the urban tissue designated as "areas of single-family housing", which are mostly residential neighbourhoods located all over the municipal territory.

It is anticipated that the market (reflecting personal preferences) would offer some resistance to the reconversion of single-family buildings. This justifies the smaller increase in the average building height (0.5 floors), comparing to those considered for the previous alternatives. Note that, because the increase in building heights is smaller, the number of urban blocks intervened is necessarily higher than in the previous cases, in order to keep the same total GFA.

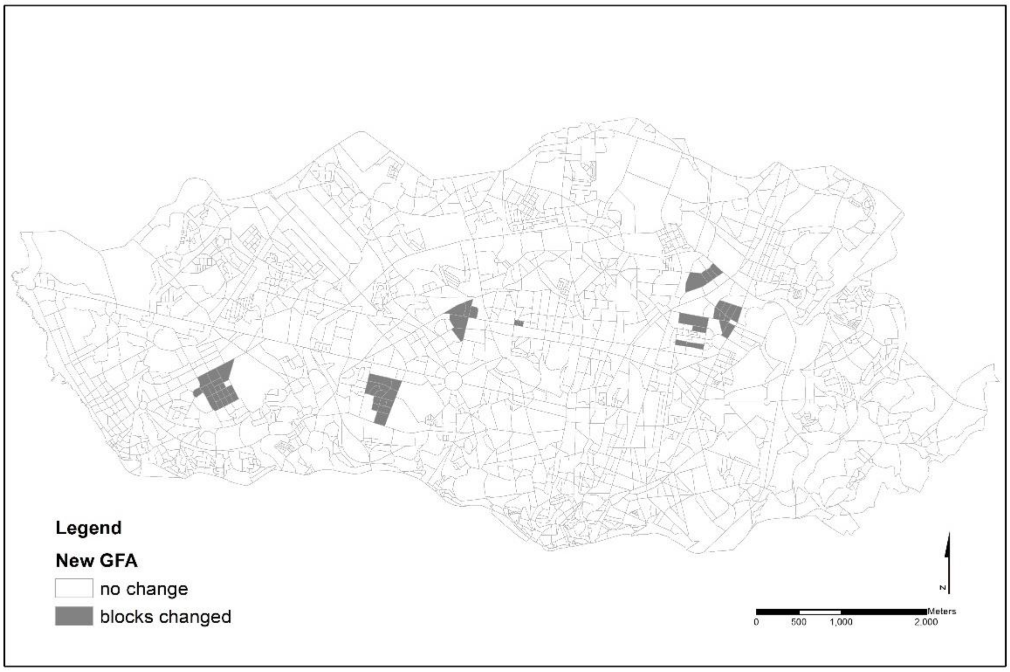

Figure 110. Promotion of multi-family housing: 0.3% GFA. Porto.

Alternative 5 – Transit-oriented development

The transit-oriented development is not going to be developed as an individual alternative at a small magnitude scale. This is because it is already implicit in some of the previous alternatives, notably in the alternatives 2 (consolidated development) and 4 (multi-family housing), which include blocks that are located in the vicinity of metro stations. This alterative will be considered later, under the framework of a larger development scale, i.e. the transformation of urban tissues as a whole.

Alternative 6 – Green Infrastructure

An alternative based on new green infrastructure aims at assessing the extent to which it can contribute, *per se*, to reducing energy demand for buildings and transport. This is made by adding new green infrastructure to the city without changing additional indicators related to the built environment. As a result, the green infrastructure alternative is implemented upon the base case scenario. In order to determine where the new infrastructure should be located, it was considered a buffer of 200 meters from the existing green areas of the city. As such, the areas left outside the buffer are suitable places to create new green spaces, depending on the existing free space. Figure 111 shows the green areas from Figure 33 (representing the spatial distribution of the existing ones), enveloped by the buffer (in orange), whereas the new green areas considered for alternative 6 are highlighted in green.

Figure 111. Location of the new green areas. Porto.

6.3.1.2. Transformation of an urban tissue as a whole

This subsection refers to a larger scale development magnitude, aiming at assessing the effect of urban development options over a longer-term time horizon, comparing to the one described above. The gross floor area (GFA) of the city is now considered to increase by roughly 10%, with an increase of about 2.350.000 m^2 of new built-up area. This change is estimated to correspond to a 25 to 30 year future, given the INE statistics on new yearly construction and the construction types of the case study.

As mentioned, under this development magnitude, the alternative A1 (infill development) becomes unfeasible due to the lack of free construction sites within the urban core. Hence, it will not be analysed at this scale. All the alternatives were analysed under scenario line A and B, except for A6. Table 44 and Table 45 summarize the changes considered in each of the alternatives under the two scenario lines for the case study of Porto and for the transformation of an urban tissue as a whole.

Table 44. Description of the development alternatives for the transformation of urban tissues as a whole (line A). 10% GFA. Porto.

Urban tissue		**Alternative**				
	Base case	**A2**	**A3**	**A4**	**A5**	**A6**
	Current policies	**Consolidated Development**	**Modern development**	**Multi-family housing**	**Transit-oriented develop.**	**Green infrastruct.**
Areas in process of consolidation	+ 1 floor	+ 1 floor	-	-	+ 1 floor	+ 1 floor + GI
Isolated buildings	+ 2 floors	-	+ 2.3 floors	-	+ 1 floor	+ 2 floors + GI
Detached housing	+ 0.5 floors	-	-	+ 2.75 floors	+ 1 floor	+ 0.5 floors + GI

Table 45. Description of the development alternatives for the transformation of urban tissues as a whole (line B). 10% GFA. Porto.

Urban tissue	**Alternative**				
	Base case	**B2**	**B3**	**B4**	**B5**
	Current policies	**Consolidated Development**	**Modern development**	**Multifamily housing**	**Transit-oriented develop.**
Areas in process of consolidation	+ 1 floor	+ 1 floor	-	-	+ 1 floor
Isolated buildings	+ 2 floors	-	+ 2.3 floors	-	+ 1 floor
Detached housing	+ 0.5 floors	-	-	+ 2.75 floors	+ 1 floor

The implementation of the remaining alternatives to the Porto's territory, leading to an increase of 10% of its GFA is described in the following paragraphs.

Base Case

The base case considered under the light of the 10% increase in the GFA follows the same rationale as the one given a smaller scale development magnitude. The new development is located in a random way throughout the territory, without privileging any specific urban tissue or urban form. It falls within the three main tissues with more "available space" and fewer formal limitations. Specifically, it considers the initial increases in the number of floors for each of the three urban tissues (Figure 112).

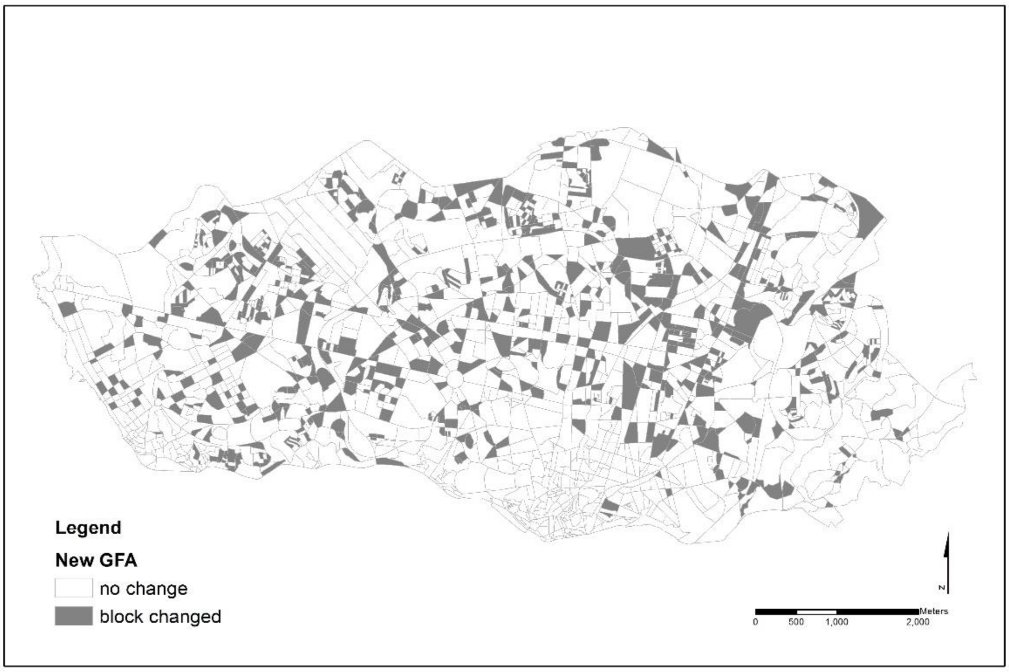

Figure 112. Base Case: 10% GFA. Porto.

Alternative 2 – Consolidated development

Similarly to the previous subsection, the consolidated development will promote higher densities by increasing the average building's heights in the areas of the city designated in the masterplan as "in the process of consolidation". An increase of one floor in average is considered for the coloured urban blocks depicted in Figure 113.

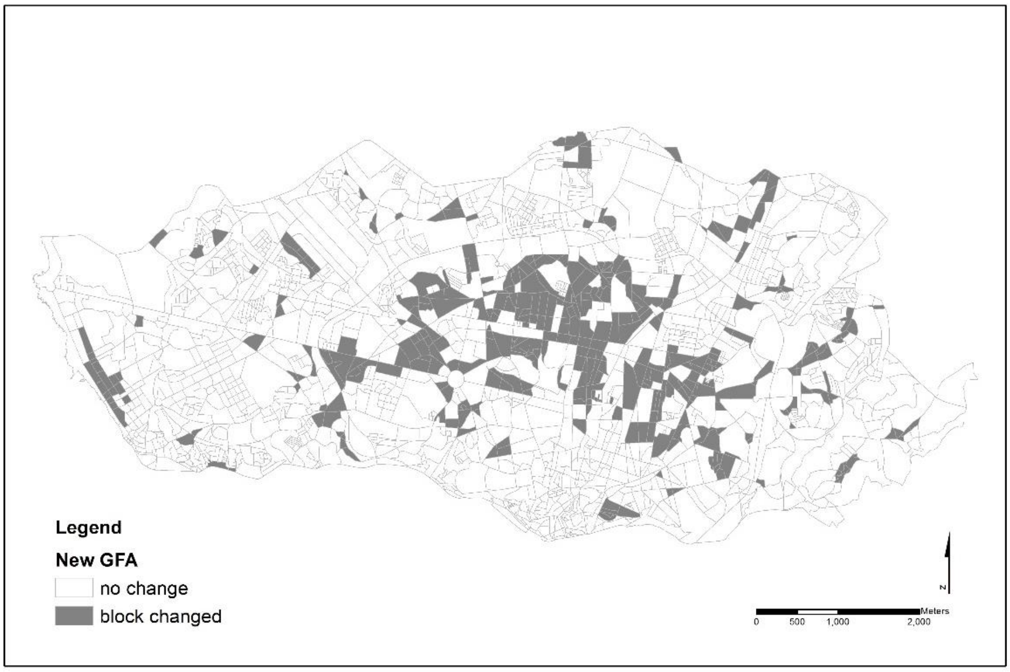

Figure 113. Consolidated development: 10% GFA. Porto.

Alternative 3 – Modern development

This alternative is implemented in the areas of the masterplan designated as “areas of isolated buildings”, which are mostly medium-rise in the case of Porto. In this case, keeping the increase of 2 average floors in this urban tissue wouldn’t return the total amount of new gross floor area required (i.e. 10% of the total GFA of the city), it was necessary to increase the average number of floors up to 2.3, in order to meet this value. The urban blocks intervened are depicted in Figure 114.

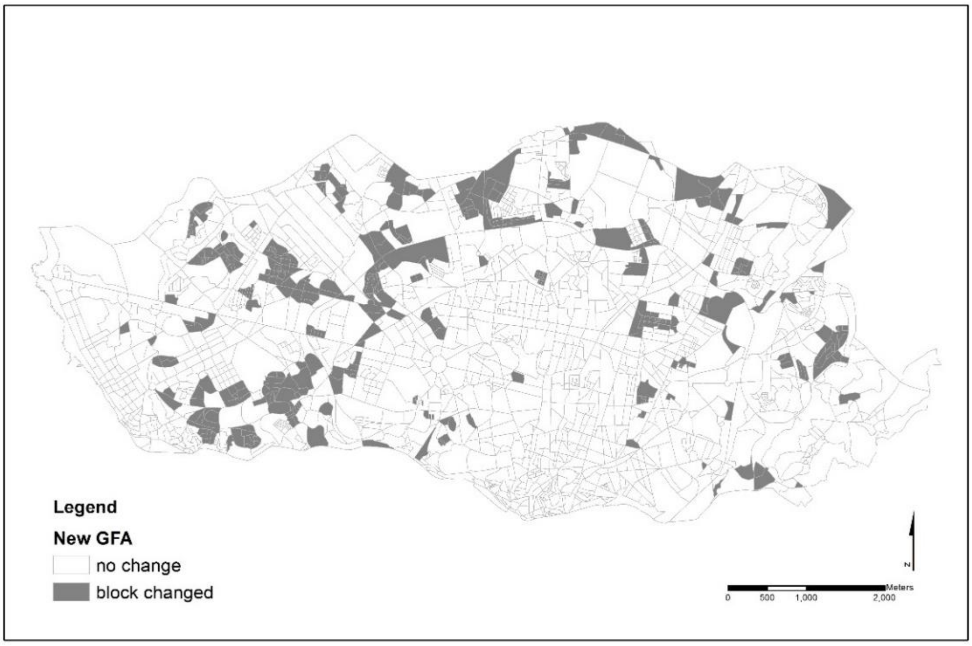

Figure 114. Modern development (peripheral): 10% GFA. Porto.

Alternative 4 – Multi-family housing

The application of Alternative 4 takes place in the urban tissue designated as “areas of single-family housing”. In order to achieve an increase of 10% of the existing GFA, while keeping the new development in these areas, it was necessary to consider an increase of 2.75 average floors in relation to the existing average building height. As a result, these areas would significantly change their nature in this scenario, and it would hardly be achieved, unless targeted policies arise, either promoting the new development in these areas, or discouraging the development in other areas. Figure 115 shows the location of the urban blocks where this alternative was implemented.

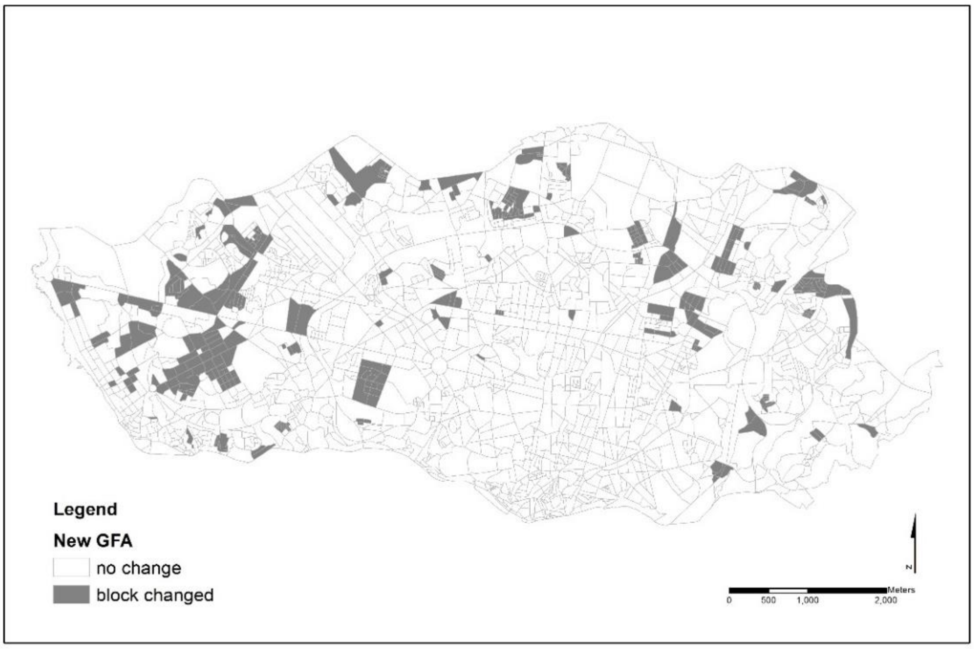

Figure 115. Promotion of multifamily housing: 10% GFA. Porto.

Alternative 5 – Transit-oriented development

The alternative referring to transit-oriented development (Figure 116) consists of promoting new development around key public transport hubs (which, in Porto, correspond to the light-rail stations). A typical service area for the light-rail in Europe is about 416m, or a 5 minute walk (Poelman and Dijkstra, 2015). Still, in order to keep the 10% increase in GFA, and increasing buildings' height by one floor in average, a catchment area of 200m from the existing light-rail stations is considered (400m would exceed the GFA needed for comparability purposes). According to El-Geneidy et al. (2014) around 90% of passengers walk to transit within a 200m distance.

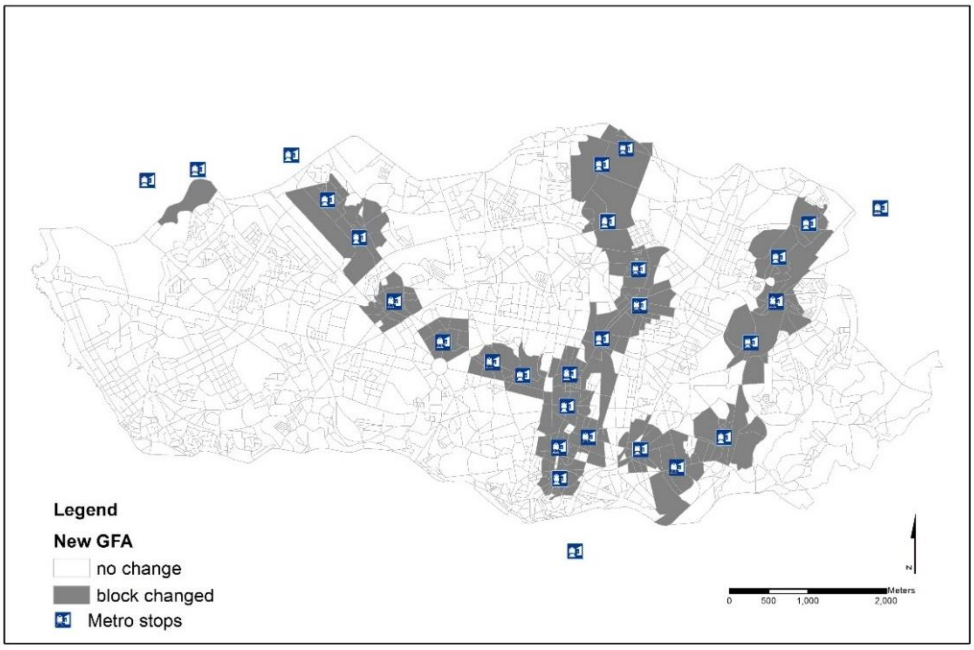

Figure 116. Transit-oriented development: 10% GFA. Porto.

Alternative 6 – Green infrastructure

Again, the alternative considering new green infrastructure aims at analysing the effect of changing only the indicators related to this urban amenity. The same green areas, as illustrated in Figure 111, were analysed by changing the corresponding indicators in the base case scenario described below.

6.3.2. Lisbon

The development scenarios considered for the city of Lisbon are similar to those of the city of Porto. Six urban development alternatives are assessed along two main scenario lines (A and B). Line A considers the impact of adding only residential space, while the line B analyses the impact of adding 80% of residential space and 20% of non-residential space. This framework is replicated considering two development magnitudes: one is a smaller scale development, which may represent a nearer future, and the other represents a larger scale change in the urban environment, which may correspond to a more distant urban future.

Nevertheless, the definition of the urban tissues in Lisbon's masterplan is different from the one of Porto. Here, two main categories of urban tissues are distinguished: consolidated areas and areas in the process of consolidation. The first category comprises four types of urban configurations. Type A mostly corresponds to the historical areas of the city (with an "organic" design), type B are planned urban tissues in central areas of the city, which have emerged in the surroundings of the historical areas. Type C corresponds to modern urban tissues, mostly including isolated buildings and larger urban blocks. Type D consists of types of single-family housing. The second category (areas in the process of consolidation) is mostly located in the outer areas of the municipality, however, it can also be found in central areas of the city. The following subsections present the description of the alternatives in the territory of the city of Lisbon.

6.3.1.1. Acting upon a specific set of blocks in a given urban tissue

Similarly to the case of Porto, a lower development magnitude in Lisbon comprises an increase in the gross floor area of *ca.* 0.3%, now amounting to 150.000 m^2 of newly built space. The same increase percentage from the previous case study was kept, since there was sufficient space available to build the alternatives in a comparable way.

The urban development alternatives are analysed under two scenario lines (A – 100% residential and B – 80% residential and 20% non-residential), except for the first (infill development) and the last (green infrastructure) alternatives, which are not considered under scenario line B, for the reasons explained in the Porto case study. Table 46 and Table 47 below summarize the changes involved in each urban development alternative for the city of Lisbon.

Table 46. Description of the development alternatives for a set of blocks in specific urban tissues (line A). 0.3% GFA. Lisbon.

Urban tissue	**Alternative**						
	Base case	**A1**	**A2.1**	**A2.2**	**A3**	**A4**	**A6**
	Current policies	**Infill develop.**	**Consolid. Development (concentrat.)**	**Consolid. Development (random)**	**Modern develop.**	**Multi-family housing**	**Green infrastruc ture**
Historic or consolidate d areas	-	New buildings with same # floors	-	-	-	-	-
Areas in process of consolidation	+ 1 floor	-	+ 1 floor	+ 1 floor	-	-	+ 1 floor + GI
Isolated buildings	+ 2 floors	-	-	-	+2 floors	-	+ 2 floors + GI
Detached housing	+ 0.5 floors	-	-	-	-	+0.5 floors	+ 0.5 floors + GI

Table 47. Description of the development alternatives for a set of blocks in specific urban tissues (line B). 0.3% GFA. Lisbon.

Urban tissue	**Alternative**			
	Base case	**A2.1**	**A2.2**	**A3**
	Current policies	**Consolidated Development (concentrated)**	**Consolidated Development (random)**	**Modern develop.**
Areas in process of consolidation	+ 1 floor	+ 1 floor	+ 1 floor	-
Isolated buildings	+2 floors	-	-	+2 floors
Detached housing	+0.5 floors	-	-	-

Base Case

The base case follows a random development pattern, where the new development is located in any of the urban tissues considered in the following alternatives (i.e. alternatives 2, 3 and 4). It merges different development intensities located in different urban tissues (Figure 117). The base case works as a reference to compare the remaining alternatives, which, conversely to this case, are thought of with a development goal in mind, and located in strategic urban areas or in specific urban tissues.

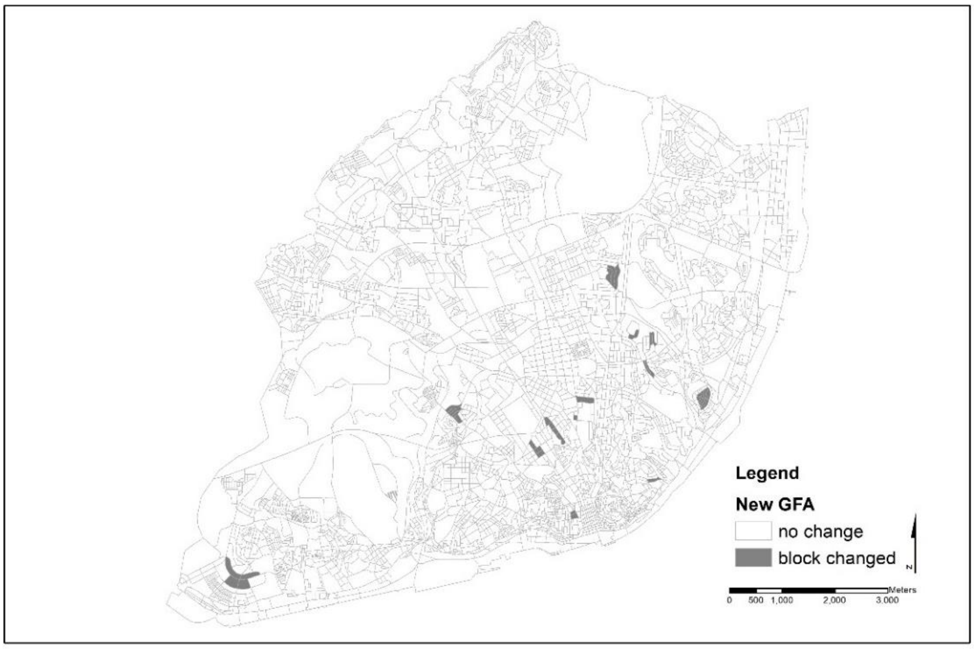

Figure 117. Base Case: 0.3% GFA. Lisbon.

Alternative 1 – Infill development

The infill development was envisioned to take place in the most central areas of the city, with available space. The new buildings are distributed through three different urban types. It was possible to include some new buildings in the historical areas of type A, however there is very limited space available for new development here. Thus, the additional free lots identified are located in the type B areas, which are still very centrally located, and in the areas in the process of consolidation that are in close proximity to the urban core. Figure 118 illustrates the location of the new buildings considered for A1.

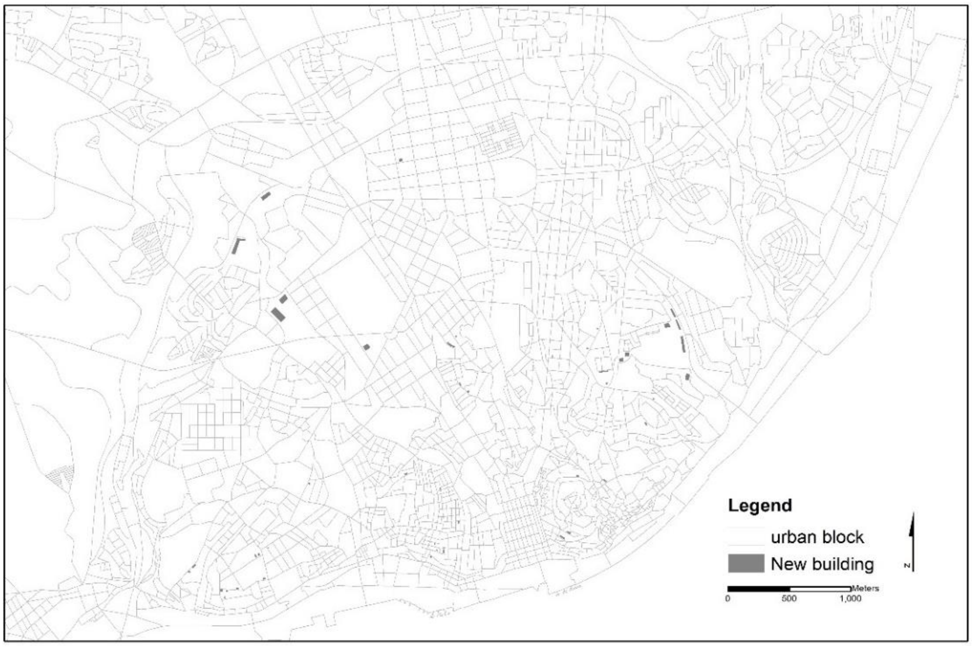

Figure 118. Infill development – location of the new buildings: 0.3% GFA. Lisbon.

In this case, it was assumed that the height of the new built structures would be the same as the one of the urban block to where they belong. This enables to compute the remaining indicators of urban form for this alternative.

Alternative 2 – Consolidated development

Similarly to the case of Porto, and because the consolidated development may usually take place in the urban tissue with the largest territorial expression, two different possibilities were analysed, corresponding to different evolution situations (Buxton and Tieman, 2005). One refers to a concentrated consolidation process (Figure 119), entailing the definition of strategic development areas for creating higher densities. The second situation refers to a more spontaneous development that typically happens pulled by the real estate market forces (Figure 120).

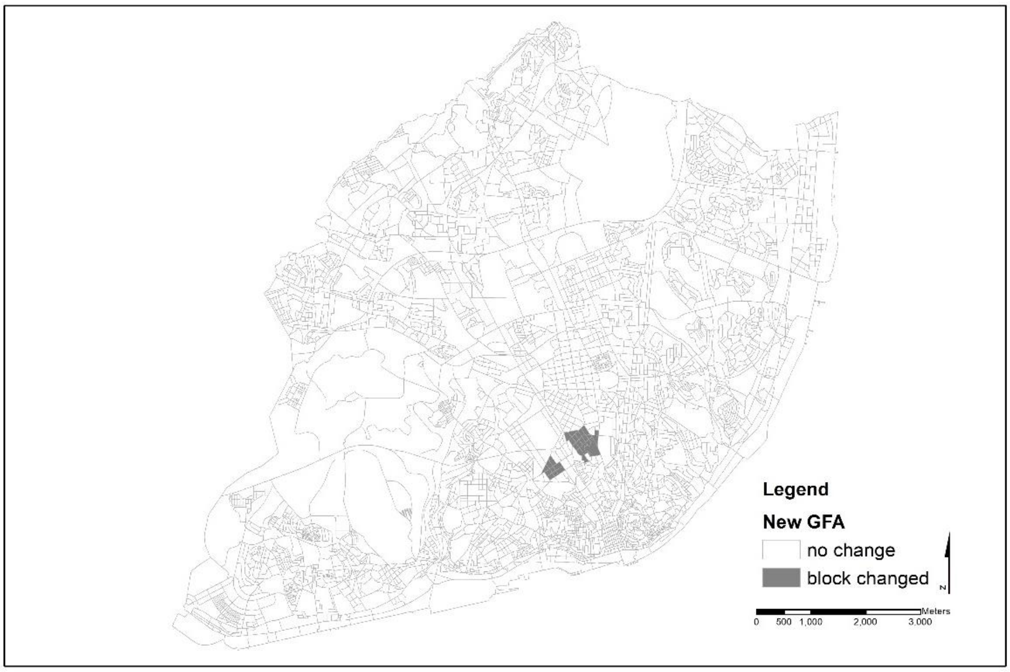

Figure 119. Consolidated development (concentrated): 0.3% GFA. Lisbon.

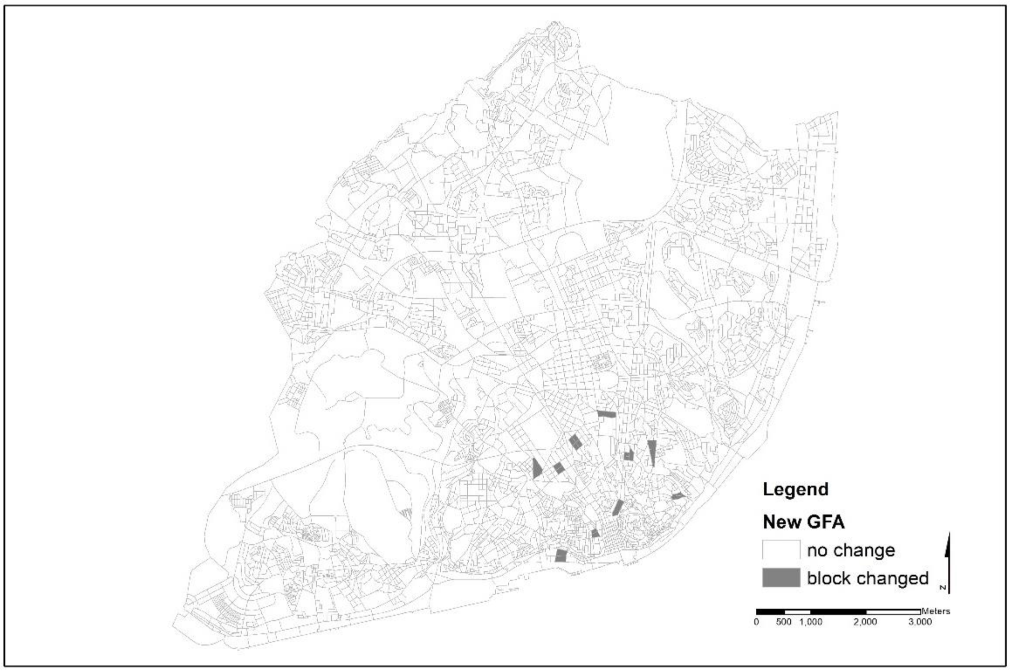

Figure 120. Consolidated development (random): 0.3% GFA. Lisbon.

In both cases, the urban blocks selected are from the type B (a type of consolidated areas) or from centrally located areas designated as “areas in the process of consolidation”. In both cases, it was considered an increase of one average floor, allowing to recalculate the urban indicators accordingly.

Alternative 3 – Modern development

The development alternative 3 follows the principle of the modern construction patterns, characterized by areas of isolated buildings and larger urban blocks. As a result, this alternative is envisioned to take place in the areas of type C (according to the masterplan), largely corresponding to this description.

In order to be coherent with the alternatives developed for the Porto case study, these areas will see their average building height increase by two floors. Figure 121 shows the location of the urban blocks considered for a development of small scale magnitude in these conditions.

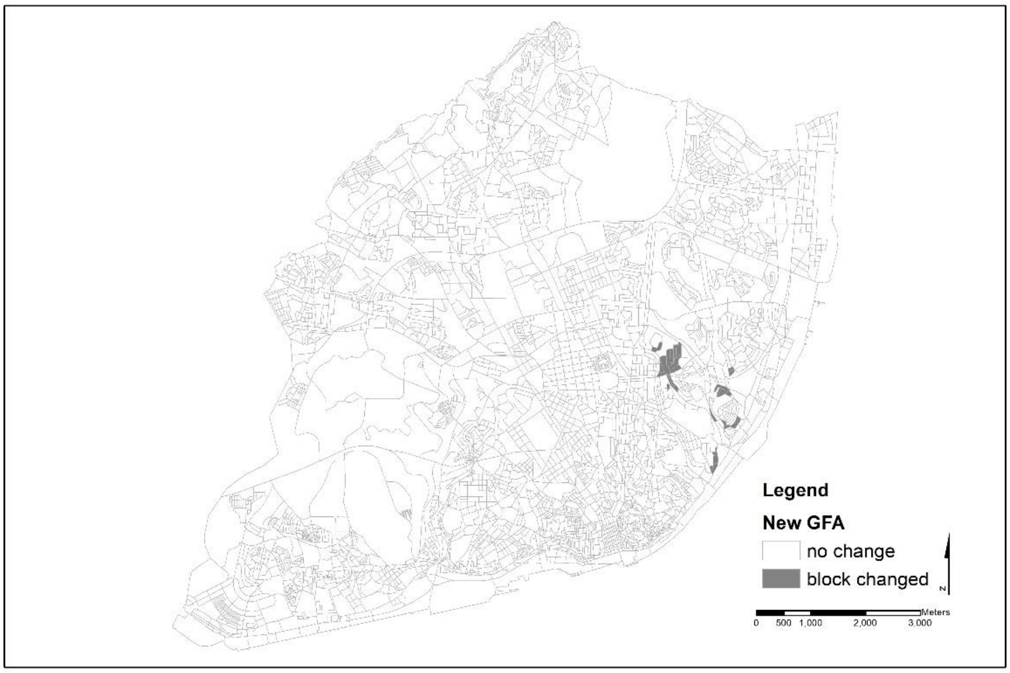

Figure 121. Modern development (peripheral): 0.3% GFA. Lisbon.

Alternative 4 – Multi-family housing

Alternative 4 foresees the impact of converting single-family into multi-family housing. Since this type of buildings is clearly identified in the masterplan (type D), it was quite straightforward to locate this alternative in the territory (Figure 122), giving preference to the urban blocks of type D that are located closer to the city centre. The change considered was an increase of 0.5 average floors in the urban blocks selected.

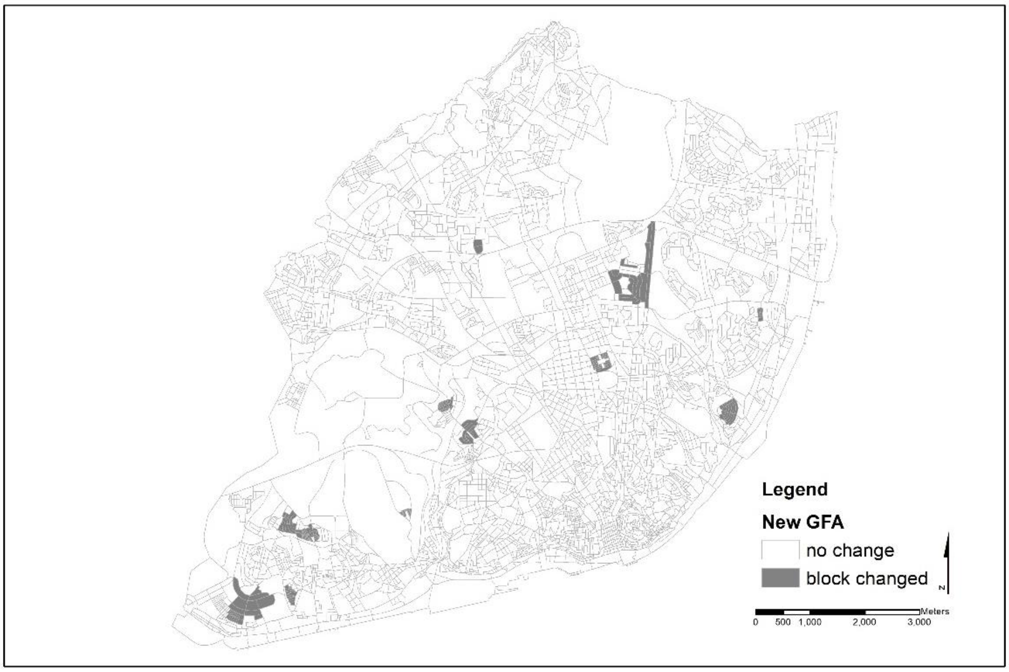

Figure 122. Promotion of multifamily housing: 0.3% GFA. Lisbon.

Alternative 5 – Transit-oriented development

Again, alternative 5 is not considered at a small magnitude scale, for the same reason as before. It is already implicit on some of the previous alternatives, notably in the alternatives 2 (consolidated development) and 3 (modern development), in which the urban blocks to be changed are located in the vicinity of the metro stations. Alternative 5 is developed in the next section under a larger scale urban development.

Alternative 6 – Green Infrastructure

Alternative 6 considers a single change in the urban environment consisting of adding new green infrastructure. In order to hold comparability, it is implemented upon the base case scenario (described below). The location of the new green infrastructure is depicted in Figure 123, and was determined by creating a buffer of 200 meters around the existing green areas (in line with Figure 75). The new green spaces are placed outside this buffer, where available sites were found.

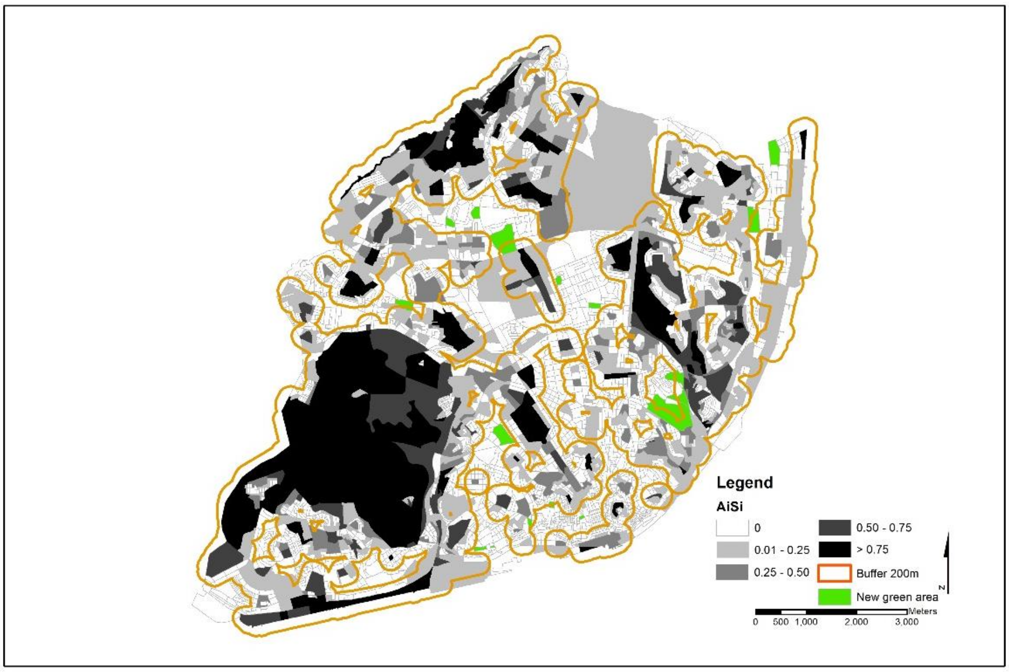

Figure 123. Location of the new green areas. Lisbon.

6.3.1.2. Transformation of an urban tissue as a whole

This subsection describes the implementation of the development alternatives at a larger territorial scale. The gross floor area (GFA) of the city is considered to increase by *ca.* 10% (the same proportion as in the Porto case study), corresponding to about 4.750.000 m^2 of new floor space.

Due to the lack of construction sites available within the urban core, alternative 1 (infill development) cannot be taken into consideration under such a development magnitude. Table 48 and Table 49 summarize the changes considered regarding the two scenario lines (A and B), respectively. The implementation of the remaining alternatives considering the transformation of an urban tissues as a whole is described in the following paragraphs.

Table 48. Description of the development alternatives for the transformation of urban tissues as a whole (line A). 10% GFA. Lisbon.

Urban tissue	Alternative					
	Base case	**A2**	**A3**	**A4**	**A5**	**A6**
	Current policies	**Consolidated Development**	**Modern development**	**Multi-family housing**	**Transit-oriented develop.**	**Green infrastructure**
Consolidated areas and areas in the process of consolidation	+ 1 floor	+ 1 floor	-	-	+ 1 floor	+ 1 floor + GI
Isolated buildings	+ 2 floors	-	+ 2 floors	-	+ 1 floor	+ 2 floors + GI
Detached housing	-	-	-	N/A	+ 1 floor	-

Table 49. Description of the development alternatives for the transformation of urban tissues as a whole (line B). 10% GFA. Lisbon.

Urban tissue	Alternative				
	Base case	**B2**	**B3**	**B4**	**B5**
	Current policies	**Consolidated Development**	**Modern development**	**Multi-family housing**	**Transit-oriented develop.**
Consolidated areas and areas in the process of consolidation	+ 1 floor	+ 1 floor	-	-	+ 1 floor
Isolated buildings	+2 floors	-	+2 floors	-	+ 1 floor
Detached housing	-	-	-	N/A	+ 1 floor

Base Case

The base case, working as a reference for comparing the remaining alternatives, results in a mix of development intensities in different parts of the city with different characteristics. It aims at representing a random development pattern with no particular representation of a type of urban tissue. The urban blocks that are subject to changes in this scenario comprehend three distinct urban tissues (type B, type C and areas to be consolidated), and are highlighted in Figure 124.

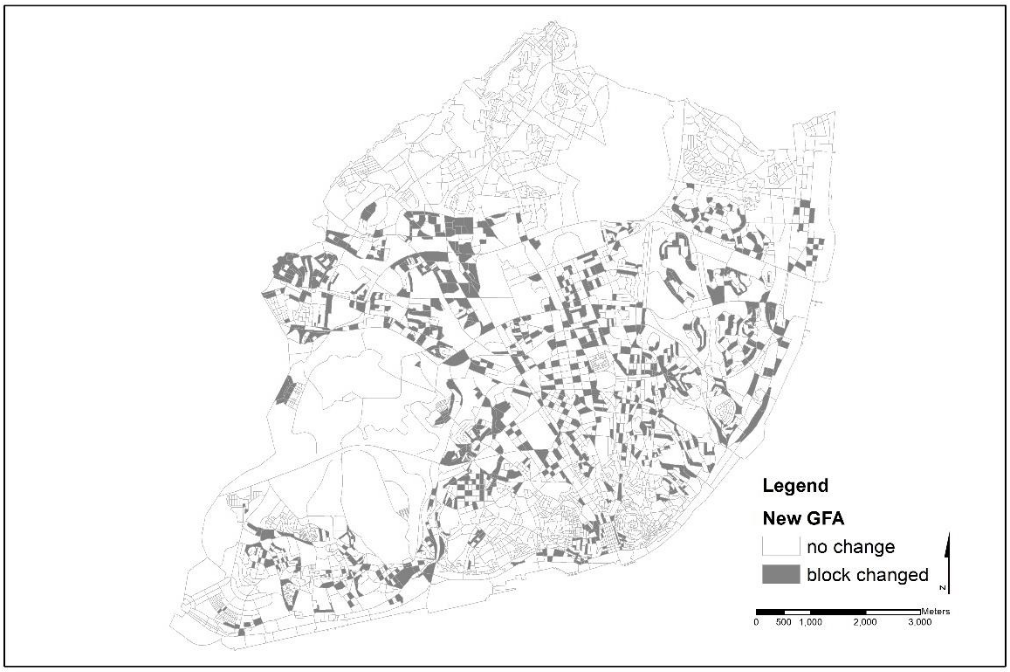

Figure 124. Base Case: 10% GFA. Lisbon.

Alternative 2 – Consolidated development

Here, the consolidated development promotes higher densities in the areas of the city designated as “type B”, i.e. consolidated areas, as well as in areas of the city that are classified as “areas to be consolidated” that are located close to the city centre. In this case, the average building height increases by one floor in average. The urban blocks intervened are depicted in Figure 125.

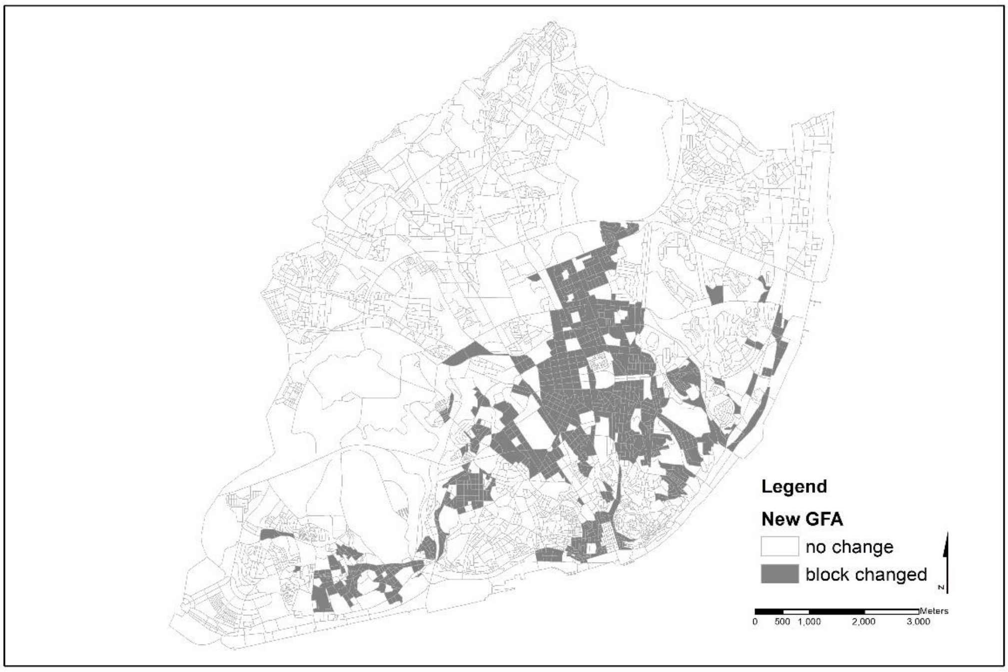

Figure 125. Consolidated development: 10% GFA. Lisbon.

Alternative 3 – Modern development (peripheral)

A suitable location for the implementation of alternative 3 are the areas of the masterplan designated as “type C”, which correspond to areas of isolated buildings (located in outer areas of the city). In order to implement this alternative while keeping the same amount of GFA, the increase in the average floors was of 2 floors. The urban blocks intervened in alternative 3 for the city of Lisbon are illustrated in Figure 126.

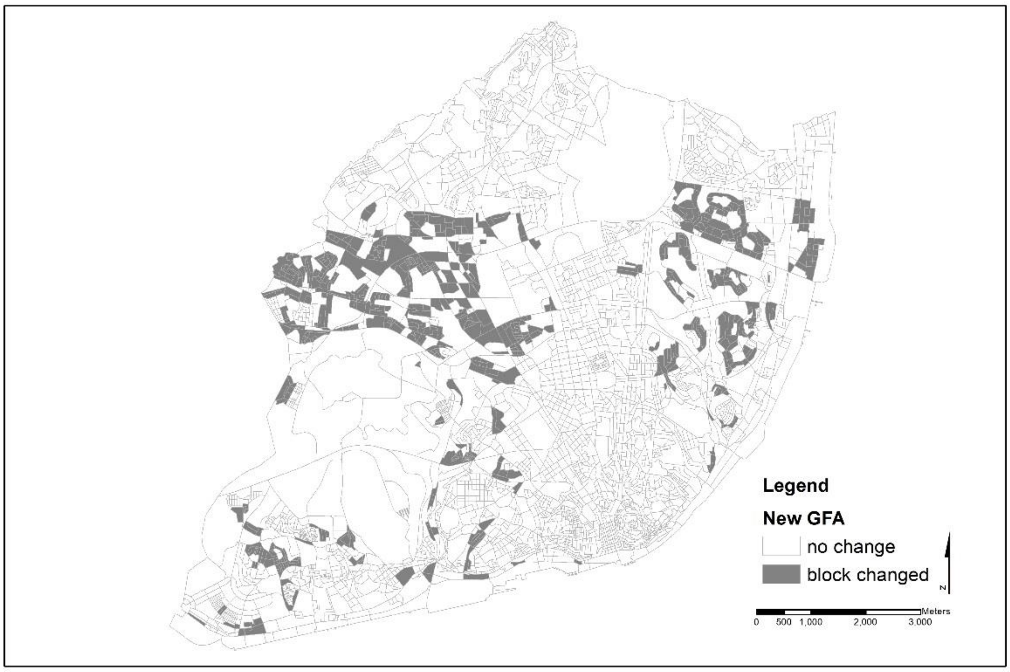

Figure 126. Modern development (peripheral): 10% GFA. Lisbon.

Alternative 4 – Promoting Multi-family housing

In the case of Lisbon, the areas of single-family housing have a very limited territorial expression, comparing to the proportion of the equivalent land use type in Porto. In order to keep this alternative with the same development magnitude of the remaining alternatives, i.e. a 10% increase of the total GFA, the average number of floors would have to increase by at least seven to eight floors in these areas. While an increase of two to three floors (as applied in the case of Porto) is an unlikely but still possible future, here it is considered that an increase of eight floors in the areas of single-family housing would be virtually impossible. For this reason, alternative 4 was discarded in the case study of Lisbon.

Alternative 5 – Transit-oriented development

Alternative 5 consists of a transit-oriented development, under which the new built structures should be clustered around the main public transport infrastructure. Although the rail plays an important role in Lisbon regarding the metropolitan transportation landscape, it is considered that within the municipal boundaries, it is the metro the most prominent mean of public transport, being the transport of masses *par excellence*. Accordingly, it was considered that the new development would take place within a walking distance (200m) of the exiting metro stations, with an increase of one floor, in average. Figure 127 shows the expression of this alternative in territory.

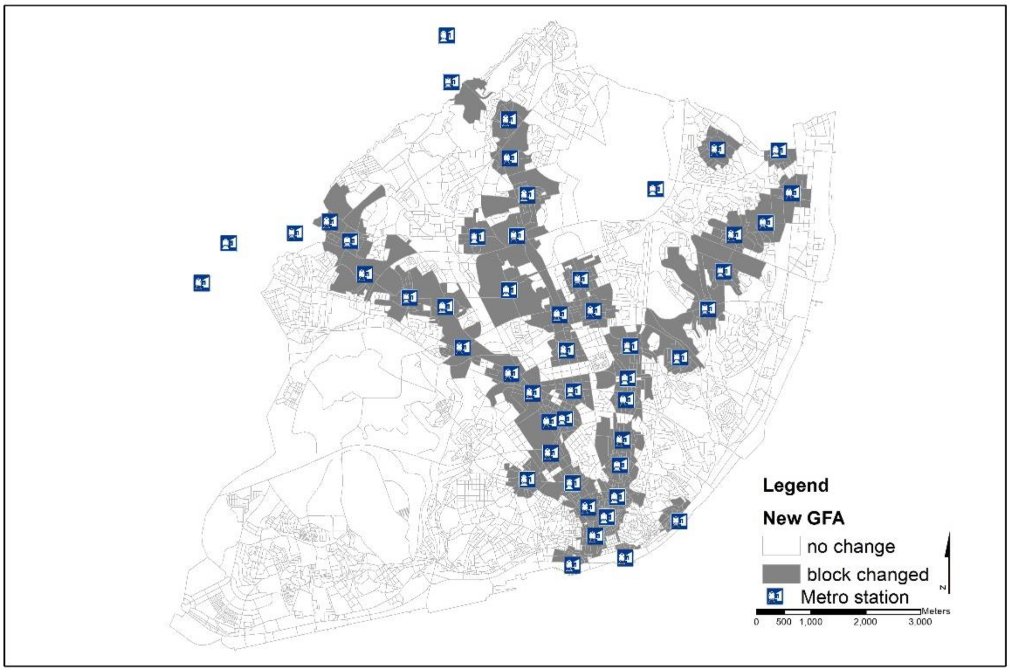

Figure 127. Transit-oriented development: 10% GFA. Lisbon.

Alternative 6 – Green infrastructure

Similarly to the scenario considering a small scale development magnitude, the impact of green infrastructure is analysed by adding the corresponding urban elements (trees and green areas) to the base case alternative. The location of the new green areas is illustrated in Figure 123.

The following section presents and discusses the results obtained from the application of the ANN models developed for the case studies of Porto (Chapter 4) and Lisbon (Chapter 5) to the urban development alternatives described.

6.4. Application of the ANN models: Results and Discussion

The application of the ANN models to the urban development alternatives consisted of the replacement of the original input vectors (corresponding to the current situation) by the new indicators of urban form computed in the GIS, referring to the physical characteristics of the urban development alternatives. As a result, the model returned new outputs, enabling to quantify the expected changes in the energy demand for the three energy end-uses (ambient heat and cooling in buildings and mobility).

In order to properly estimate the energy impact resulting from the different urban configurations, the model outputs obtained for each development alternative are compared with the ones obtained for the base case scenario (given the respective scenario line and development magnitude). This is done in order to ensure that the different urban scenarios have similar land use intensities, i.e. that the total GFA and urban functions are the same among the different possible futures, and so, that the changes obtained are not due to structural differences between the scenarios. It would not be accurate if the urban alternatives were compared with the present situation.

The changes in the indicators of urban form take place either in a set of specific urban blocks and in an urban tissue as a whole. Here, the energy demand (for heating, cooling and mobility) resulting from such changes is presented for the whole city. There are two reasons why the city-scale is adopted at this point: the first is that, although the overall urban energy performance is made of the behaviour of the individual urban blocks, it is the city, as a whole, that strives for achieving energy conservation and efficiency targets and it is at a municipal administrative level that the development decisions are taken. Second, considering the city as a whole enables to account for possible trade-offs between the variations taking place for the different urban blocks.

6.4.1. Porto

Following the urban development alternatives presented in Section 6.3.1., the results are presented first for a specific set of blocks in an urban tissue, and then for an urban tissue as a whole.

6.4.1.1. Acting upon a specific set of blocks in a given urban tissue

The results are presented in two formats. Table 50 shows the primary energy use estimated for the different urban development alternatives and the respective global variation, as well as the change for the each of the three end uses considered. The changes in the energy use are also illustrated in Figure 128.

Table 50. Estimated energy use in Porto under different development alternatives on a specific set of blocks (scenario line A, 0.3% GFA).

Energy use	Current Situation	Base Case	A1 IN	A2.1 CD	A2.2 CD	A3 MD	A4 MFH	A6 GI
Heating (GWh)	655	659	654	659	659	658	659	658
Cooling (GWh)	24.5	24.5	24.6	24.5	24.5	24.5	25	24.5
Mobility (GWh)	394	397	395	396	396	399	397	396
H+C+M (GWh)	1074	1081	1074	1080	1079	1081	1080	1079
Δ Heating			-0.7%	0.0%	0.0%	-0.2%	-0.1%	-0.1%
Δ Cooling			0.4%	0.0%	0.0%	-0.1%	0.0%	0.0%
Δ Mobility			-0.5%	-0.3%	-0.3%	0.5%	0.0%	-0.3%
Δ H+C+M			-0.6%	-0.1%	-0.1%	0.1%	0.0%	-0.2%

(Δ in relation to the base case)

Regarding a relatively small-scale development for the city of Porto, with an increase of 0.3% in the overall GFA, it is evident that the infill alternative carries the largest reductions in energy needs. Mobility needs reduce significantly, possibly because the development is located in centrally located areas of the city, with the highest levels of pedestrian and public transport accessibility. In addition, the infill development enables to attain more compact urban forms, which may be linked to the significant reductions in the heating needs (although with an increase in the cooling needs). The overall energy balance from this alternative is a reduction of 0.6% in energy needs while an increase of 0.3% GFA takes place.

Other advantageous alternatives to be considered are the one entailing the development of the green infrastructure and also the consolidated development (Figure 128). The latter may involve a similar explanation as the one from the infill development result, although with a lower magnitude, mostly due to smaller effects on mobility. With regard to the green infrastructure, it seems that the model associates its presence with lower energy needs from transport. In addition, both the needs for heating and cooling decrease, as green areas are advocated to maintain the amenity of the urban climate.

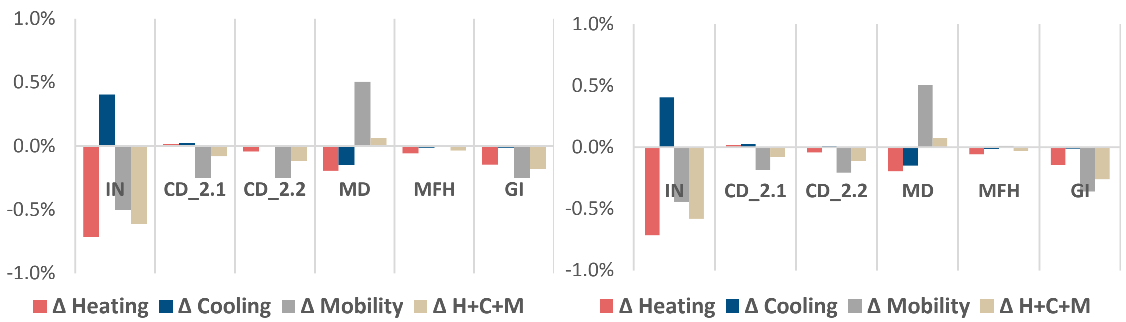

Figure 128. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on a specific set of blocks. Scenario line A. 0.3% GFA Porto.

In fact, the only alternative that does not present interesting results in terms of energy performance is the one considering a modernist-type of development. Although the energy performance of buildings seems to improve (which may be explained by the more recent construction period in these areas), it brings attached significantly higher mobility needs, leading to a global increase of the overall energy use.

The approach described above was replicated for scenario line B, considering a proportion of 80% of residential uses and 20% of non-residential uses. From Table 51 and Figure 129, it is possible to conclude that adding non-residential uses to the development areas considered retrieves no significant changes to the results obtained above for scenario line A.

Table 51. Estimated energy use in Porto under different development alternatives on a specific set of blocks (scenario line B, 0.3% GFA).

Energy use	Current Situation	Base Case	A2.1. CD	A2.2. CD	A3 MD
Heating (GWh)	655	659	659	659	657
Cooling (GWh)	24.5	24.5	24.5	24.5	24.5
Mobility (GWh)	394	397	396	396	399
H+C+M (GWh)	1074	1080	1079	1079	1081
Δ Heating			0.0%	0.0%	-0.2%
Δ Cooling			0.0%	0.0%	-0.1%
Δ Mobility			-0.3%	-0.3%	0.5%
Δ H+C+M			-0.1%	0.0%	0.1%

(Δ in relation to the base case)

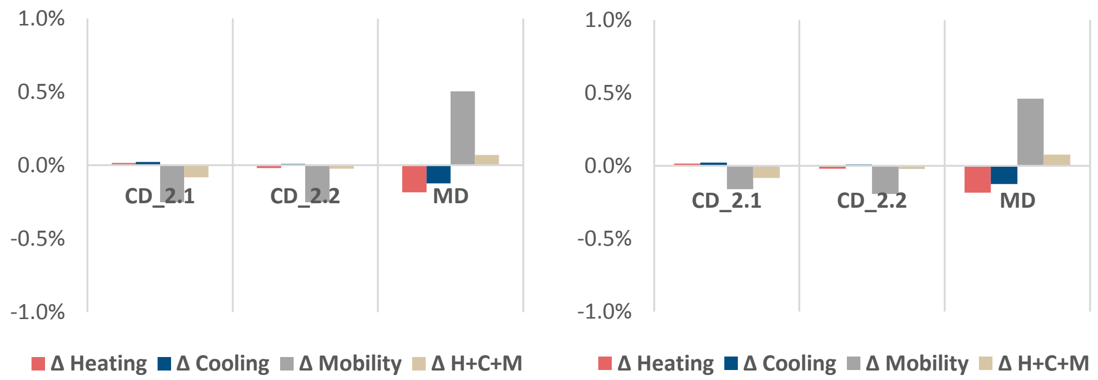

Figure 129. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on a specific set of blocks. Scenario line B. 0.3% GFA Porto.

It is expected that changing the mix of uses at a larger scale may return more significant changes in the energy needs (especially those related to mobility). The next subsection will present the results of the application of the same ANN model to such a development magnitude.

6.4.1.2. Transformation of an urban tissue as a whole

Now, an increase of 10% in the total gross floor area of the city was considered. In this case, the infill development alone could not meet such a development magnitude, and hence it was removed from the analysis. Conversely, at this scale, it makes sense to consider a transit-oriented development alternative. The results obtained for the different urban alternatives considered are presented in Table 52.

Table 52. Estimated energy use in Porto under different development alternatives transforming an urban tissue as a whole (scenario line A, 10% GFA).

Energy use	Current Sit.	Base Case	CD	MD	MFH	TOD	GI
Heating (GWh)	655	695	715	694	700	710	694
Cooling (GWh)	24	26.2	26.5	26.0	26.6	26.5	26.2
Mobility (GWh)	394	470	428	480	463	420	468
H+C+M (GWh)	1073	1191	1169	1200	1189	1157	1188
Δ Heating			3%	0%	1%	2%	0%
Δ Cooling			1%	-1%	1%	1%	0%
Δ Mobility			-9%	2%	-1%	-10%	0%
Δ H+C+M			-2%	0.9%	-0.1%	-3%	-0.2%

(Δ in relation to the base case)

Overall, when considering a larger-scale development, the size of the potential energy savings is not proportional to the magnitude of the urban growth. This may result from the fact that, at a larger scale, there are less development options because changes are being considered in a larger number of blocks at the same time.

The most successful development alternative is the transit-oriented development. Although the model predicts higher energy needs in buildings (probably due to the existing urban configurations in these locations), it is significantly more efficient in terms of energy for mobility (with a decrease of 10% of total primary energy use). Still, the overall balance has a smaller magnitude (-3%). The results for the consolidated development are in line with the ones obtained earlier for a specific set of urban blocks, representing the second best alternative for Porto. The modern development option is the one performing worst. However, the increase in the mobility needs under a large development magnitude (Figure 130) is not as evident as in the development a limited set of urban blocks, when comparing to the variation of the remaining alternatives.

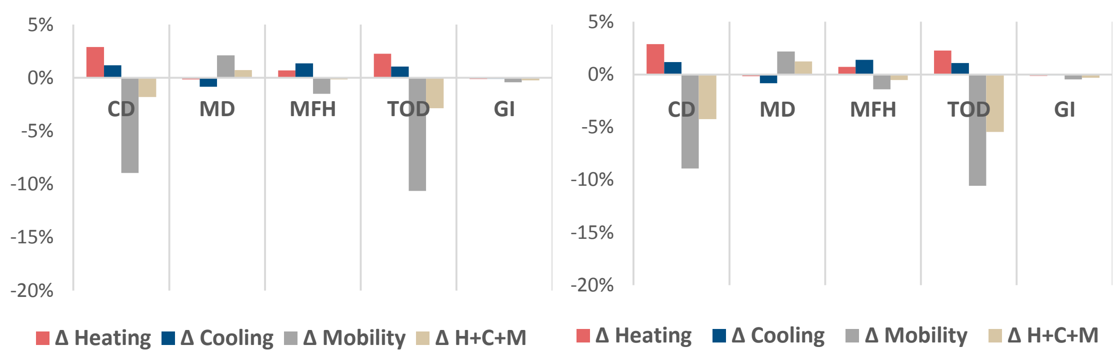

Figure 130. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on urban tissues as a whole. Scenario line A. 10%GFA. Porto.

The transformation of single-family into multi-family housing shows trade-offs between the building and the transport sectors, with an overall effect almost null. With regard to the green infrastructure, it is the same as considered in section 6.4.1.1. However, in this case, its effects become less important when compared to larger scale rearrangements of the built environment.

Table 53 and Figure 131 show the results obtained for scenario line B. Except in the case of CD, increasing the mix of land uses in expected to retrieve higher energy savings for travel (Figure 131), and this is especially efficient in the case of TOD scenario. Still, the best alternatives remain TOD and CD.

Table 53. Estimated energy use in Porto under different development alternatives transforming an urban tissue as a whole (scenario line B, 10% GFA).

Energy use	Current Sit.	Base Case	CD	MD	MFH	TOD
Heating (GWh)	655	682.0	705.4	697	698.1	698.4
Cooling (GWh)	24	25.9	26.4	26.0	26.3	27.3
Mobility (GWh)	394	465	434	463	451	368
H+C+M (GWh)	1073	1173	1166	1186	1175	1094
Δ Heating			3%	2%	2%	-1%
Δ Cooling			2%	1%	2%	3%
Δ Mobility			-7%	0%	-3%	-15%
Δ H+C+M			-1.0%	1.0%	0.0%	-7%

(Δ in relation to the base case)

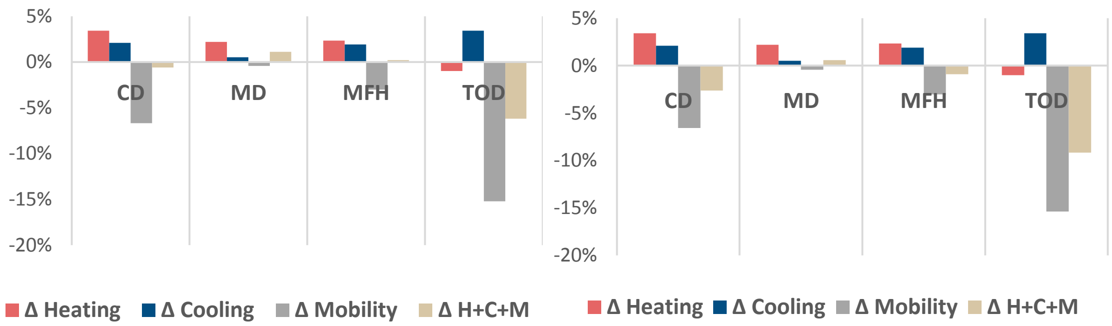

Figure 131. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on urban tissues as a whole. Scenario line B. 10%GFA. Porto.

Note that, although it was previously tested a model including a variable on the construction period of buildings, without a significant increase in its explanatory power (Chapter 4), it is possible that the energy demand estimated for the building sector by this ANN model may somehow reflect the thermal behaviour of the buildings located in a specific area of the city, given their average energy performance. If the alternatives CD or TOD are pursued, while considering additional efficiency measures that are not related to urban form, notably thermal insulation in buildings, their net benefits could be even more significant. For this reason, it makes sense to give more importance to the impact of the alternatives on mobility.

Another remark is that the results presented refer to the estimated yearly variations in energy use. Nevertheless, it is important to bear in mind that their impact is a cumulative one and spans over a larger period, which, in cities, typically concerns several decades.

6.4.2. Lisbon

The subsections below present the results for a specific set of blocks in a given urban tissue (6.4.2.1.) and for the transformation of an urban tissue as a whole (6.4.2.2).

6.4.2.1. Acting upon a specific set of blocks in a given urban tissue

The urban development alternatives tested in the case study of Porto were equally considered for the case study of Lisbon. Table 54 presents the estimated energy use in Lisbon across the different development alternatives considered.

Table 54. Estimated energy use in Lisbon under different development alternatives on a specific set of blocks (scenario line A, 0.3% GFA).

Energy use	Current Situation	Base Case	A1 IN	A2.1 CD	A2.2 CD	A3 MD	A4 MFH	A6 GI
Heating (GWh)	1012	1018	1013	1017	1017	1017	1025	1018
Cooling (GWh)	94	95	94	95	95	95	95	95
Mobility (GWh)	393	394	393	393	394	394	394	394
H+C+M (GWh)	1499	1506	1500	1505	1505	1506	1514	1507
Δ Heating			-0.4%	0.0%	-0.1%	-0.1%	0.7%	0.1%
Δ Cooling			-0.6%	0.1%	0.0%	-0.1%	0.6%	0.0%
Δ Mobility			-0.1%	-0.1%	0.0%	0.1%	0.0%	0.1%
Δ H+C+M			-0.4%	0.0%	0.0%	0.0%	0.5%	0.1%

(Δ in relation to the base case)

Similarly to what happened in the case of Porto, an infill solution is expected to be the most efficient option, given a lower-scale development magnitude. However, in this case, the energy savings for mobility are significantly lower. The most important reductions arise from the building sector, likely due to the influence of more compact forms[9] (Figure 132). Also, both the consolidated development options are aligned with the results obtained for Porto. Still, it is visible a slightly better performance in the case of mobility for the first option referring to the concentrated consolidation, in relation to the random consolidation.

A significant difference is the fact that the multi-family housing option is now the worst development option. This comes at the expense of the building sector, both for heating and cooling. The increase in the heating needs could be explained two-fold: first, by the fact that solar

[9] The model is predicting significant reductions in the cooling needs for the development of central areas of the city. However, it is important to bear in mind that the thermal performance of the buildings in these areas are also associated to a type of construction and materials (dominantly bricks). It is anticipated that the reductions for cooling may not be as significant if the construction materials are changed to materials with higher thermal inertia.

gains may be an important heat source in single-family housing (particularly given the local climatic conditions), that are now significantly reduced by adding more building floors. Second, the new building types would not become more compact. Keeping its exposed surfaces may, thus imply loosing significant amounts of heat to the outside environment in the cold season. With regard to the increase in the cooling needs, these may be explained by the fact that solar incidences in summer may still be quite high due to geometry.

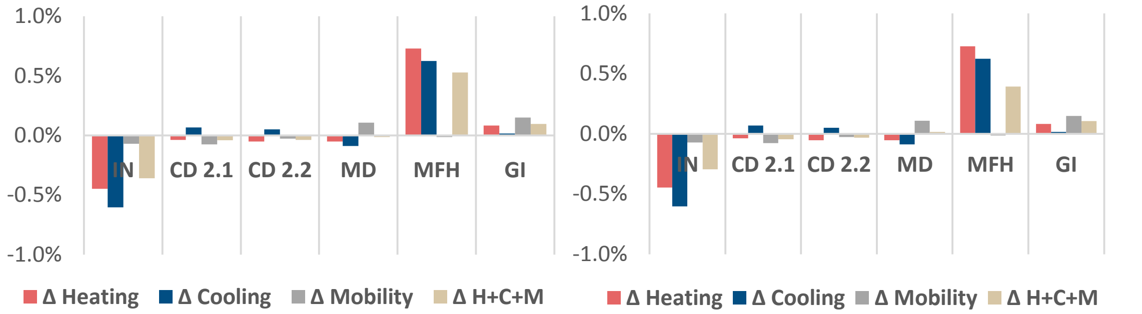

Figure 132. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on a specific set of blocks. Scenario line A. 0.3% GFA. Lisbon.

Table 55 and Figure 133 show the variations retrieved by considering the scenario line B, i.e. a proportion of residential and non-residential uses for the same alternatives (except the infill and MFH).

Table 55. Estimated energy use in Lisbon under different development alternatives on a specific set of blocks (scenario line B, 0.3% GFA).

Energy use	Current Sit.	**Base Case**	**A2.1. CD**	**A2.2. CD**	**MD**
Heating (GWh)	1017	1017	1016	1016	1017
Cooling (GWh)	94.6	94.6	94.6	94.6	94.6
Mobility (GWh)	394	394	393	393	394
H+C+M (GWh)	1505	1504	1505	1504	1505
Δ Heating			0.0%	-0.1%	0.0%
Δ Cooling			0.0%	0.0%	-0.1%
Δ Mobility			0.0%	0.0%	0.1%
Δ H+C+M			0.0%	0.0%	0.0%

(Δ in relation to the base case)

Again, at this development magnitude, no significant changes were found between the two scenario lines. Still, one can note that increasing the share of non-residential areas in the case of CD (2.1 and 2.2) offsets the energy savings for mobility obtained in scenario line A – in line with the case of Porto (such blocks may have already a significant proportion on non-residential uses).

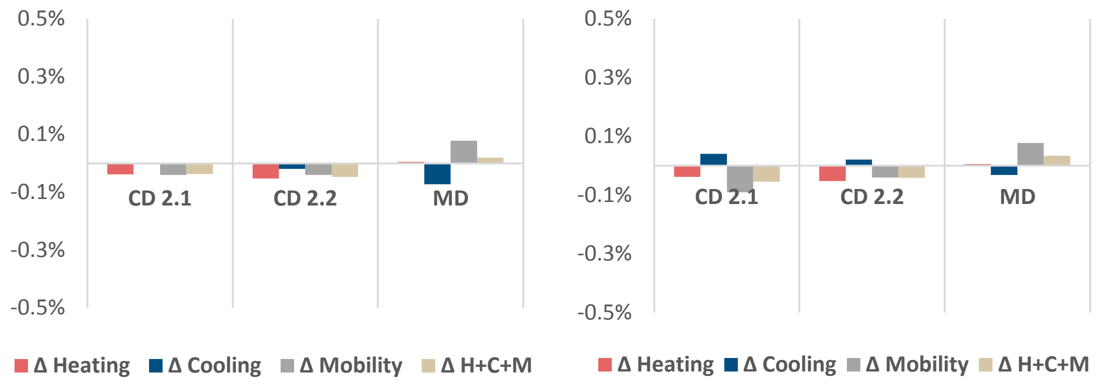

Figure 133. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on urban tissues as a whole. Scenario line B. 0.3% GFA. Lisbon.

6.4.2.2. Transformation of an urban tissue as a whole

For the transformation of urban tissues as a whole, comprising a 10% increase in the gross floor area of the city, two development alternatives become unfeasible. They are the infill development, due to the lack of free space in the urban core, and the multi-family housing, also due to an insufficient representation of these areas in the city. Table 56 and Figure 134 present the results for the remaining urban alternatives considered.

Table 56. Estimated energy use in Lisbon under different development alternatives transforming an urban tissue as a whole (scenario line A, 10% GFA).

Energy use	Current Sit.	Base Case	CD	MD	TOD	GI
Heating (GWh)	1012	1084	1091	1080	1077	1085
Cooling (GWh)	94	103	105	102	103	103
Mobility (GWh)	393	422	424	420	436	422
H+C+M (GWh)	1499	1609	1620	1601	1616	1610
Δ Heating			1%	0%	-1%	0%
Δ Cooling			2%	-1%	0%	0%
Δ Mobility			1%	0%	3%	0%
Δ H+C+M			1%	-0.5%	0.4%	0.1%

(Δ in relation to the base case)

While the results obtained for the city of Lisbon under a small scale-development are in line with those obtained for the city of Porto (notably for the alternatives of infill and consolidated development), the results obtained for a larger-scale development are quite surprising.

Recall, that in the case of Porto, the transit-oriented development alternative was the one with the best energy performance, the second being the consolidated development. However, Figure 134 shows that these are the two urban development alternatives performing worse for the city of Lisbon.

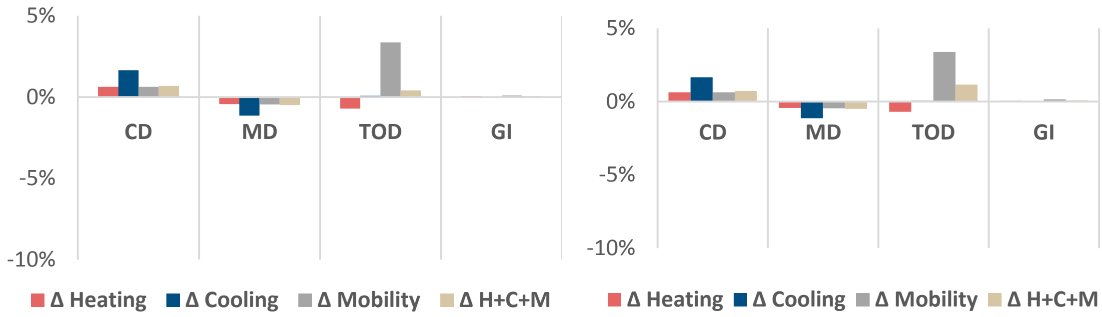

Figure 134. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on urban tissues as a whole. Scenario line A. 10% GFA. Lisbon.

The results suggest that the effect of increasing densities in Lisbon is largely dependent on where such densities will be located. While the consolidated development in specific blocks of the city centre decreases the overall energy needs (Figure 132), when considering a generalized increase throughout extensive areas of the city, the model predicts an increase of energy use, notably for mobility (in the case of CD and TOD). Although the city centre is largely accessible by walking mode and public transport, these areas also coincide with those having the largest mobility needs by private motorized traffic.

Recall that the increase is relative to the base case scenario. In the case of mobility, the results suggest that the urban core of Lisbon is already too packed, as the new development in this area is globally associated to higher needs for mobility (in relation to a more scattered development pattern throughout the whole city). The only urban development alternative with an expected decrease in the energy use for mobility is the modern development (MD). Although these areas are considered to be located outside the urban core, they still keep a significant proximity to non-residential uses within a walking distance (especially the areas of *Benfica*, *Nova de Lisboa*, *Olaias* and *Olivais*), and are fairly well served by public transport, while avoiding the overcrowding and congestion of the city centre. There is some literature suggesting limits to density (although this is not a consensual issue). Although further research on the topic is needed, the results suggest that this may be true. In Lisbon, at least in some parts of the city, it seems that there is no room for increasing densities.

With regard to the increase in the thermal needs of buildings (CD), since the consolidated development is located in more central areas of the city (corresponding to older urban tissues), it is expected that the increase may be reflecting a lower thermal performance of the buildings located in these areas (typically older), when compared to more recent (and typically more efficient) buildings located in outer areas of the municipality.

Finally, Table 57 and Figure 135 shows the results for scenario line B, which again, are not significantly different form scenario line A. This suggests that increasing non-residential uses is not an evident solution for an urban area as a whole, especially in areas with already a good mix of uses. It is also interesting to note that the energy needs for space heating decrease by adding non-residential uses. In fact, there is the possibility that non-residential uses constitute a relevant source of heat to the households located in the same or in adjacent buildings (e.g. having a bakery on the ground floor may decrease the heating needs of the apartments located on the first floor).

Table 57. Estimated energy use in Lisbon under different development alternatives transforming an urban tissue as a whole (scenario line B, 10% GFA).

Energy use	Current Sit.	Base Case	CD	MD	TOD
Heating (GWh)	1012	1071	1069	1067	1056
Cooling (GWh)	94	101	103	100	101
Mobility (GWh)	393	421	424	420	437
H+C+M (GWh)	1499	1593	1596	1587	1594
Δ Heating			0%	0%	-1%
Δ Cooling			2%	-1%	-2%
Δ Mobility			1%	0%	3%
Δ H+C+M			0.2%	-0.4%	-0.1%

(Δ in relation to the base case)

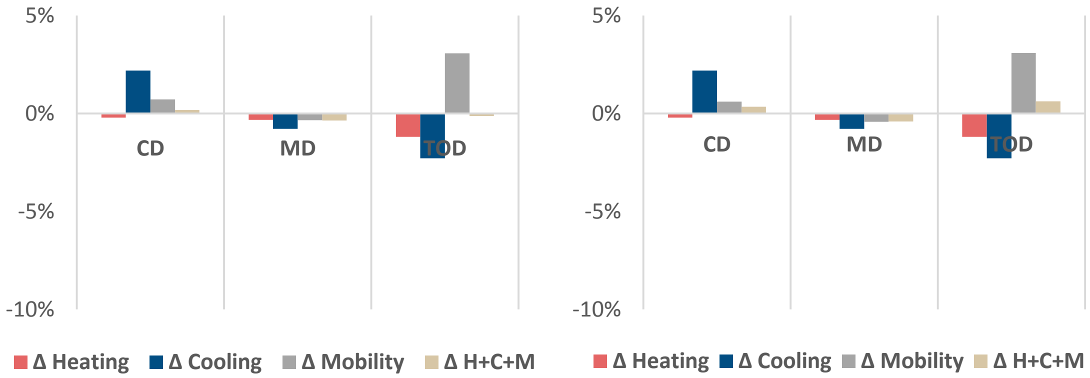

Figure 135. Variation (%) of the primary energy demand (left) and GHG emissions (right) for the development alternatives on urban tissues as a whole. Scenario line B. 10% GFA. Lisbon.

In this section, the ANN models built for the two case studies under analysis were used to assess the energy impact of different urban development alternatives. However, it is expected that changing the physical structure of the city, in addition to changes in the energy performance of the urban environment, affects further domains of the urban landscape. In order to account for such effects, the appraisal of the urban development alternatives will be extended to additional criteria besides energy in the following chapter.

6.5. Synthesis

Chapter 6 presented and explored different development options for the two case studies: Porto and Lisbon. The urban development alternatives focus on three main attribute clusters. They analyse different manifestations of density, different mix of land uses and accessibility, and also the effect of green infrastructure. These were analysed under an energy conservation perspective (PES), resorting to the ANN models presented in Chapter 4 and 5.

From the energy point-of-view, most of the potential energy savings from densification are related with mobility (particularly in the city of Porto). However, the preference for specific development options varies between the two case studies. In Porto, the urban development options located in the city centre (recall that centrality was an influential indicator for this case study) perform better than the remaining. Nevertheless, Lisbon behaves differently regarding its mobility patterns. Higher development intensities in the urban core seem to increase mobility needs in the city (Lisbon´s core may be already too packed). This, together with the fact that centrality had little explanatory power in the case of Lisbon (which has a more evident polycentric character than Porto) suggests that there is no advantage in increasing densities in central Lisbon, and that its development pathways should potentiate its polycentric nature.

Overall, increasing the mix of land uses leads to lower energy needs for mobility, except in the urban blocks which already have a quite large share of non-residential uses (evidenced by the results from the CD alternative). This suggests that there may be an efficient threshold for the mix of urban functions. Finally, the results for the green infrastructure alternative are not conclusive. In Porto, it is expected to leverage some slight energy savings, although in the case of Lisbon the model is predicting slightly higher energy needs. In either case, comparing with the impact of a large scale densification, its effect becomes negligible. Still, this development option should not be discarded, as green infrastructure has several co-benefits to the urban environment beyond its effect on energy.

In the case of buildings, some development options lead to significant reductions on the expected energy use, notably the infill development. This is frequently advocated in the literature, in spite of its limited implementation scope. Also, both the consolidated development and the modern development options seem to reduce thermal needs in buildings. In the first case, it may be due to the fact that compact forms have less envelope area and thus tend to be more efficient (for heating). In the case of modern development, it is possible that the models may be implicitly identifying some spatial trends on the energy performance of buildings, related to their construction period (with modern constructions typically being more efficient).

The results suggest that planning for the urban development to take place in specific areas of the city generally leads to a better urban energy performance than random development patterns throughout the urban territory. Nevertheless, the most suitable locations and urban configurations may vary for different cities, and should be considered case by case.

Although it was found, in Chapters 4 and 5, that urban form explains the variability of energy needs with a share always higher than 10% for the three end uses considered in both case studies (and up to 48% in the case of heating and mobility), it doesn't mean that such variability impacts the overall energy demand in the same magnitude. Here, the evaluation of the different urban alternatives, constrained by the existing urban environment, shows that such variability impacts the overall energy demand more modestly. It was found that, considering changes in urban form only, the primary energy use could decrease up to 15% for mobility, and significantly less for heating and cooling, with roughly 3% and 1%, respectively. In the case of buildings, this is significantly less than the difference found by Ratti et al. (2005). They found a 10% difference in the annual per-metre energy consumption between Toulouse and Berlin, due to the effect of urban form. Two possible explanations for this variation are either the lower-scale nature of their analysis (done at a floor by floor level and including parameters such as the orientation of buildings' façades, and the obstruction and irradiation from surrounding buildings), or the fact that Ratti et al. (2005) compare completely distinct urban realities. The result may be a combination of both. Although it is acknowledged that the energy performance of buildings is largely affected by detailed features of building design, it should be kept in mind that this research analysed varying alternatives for the same city, where the existing urban environment is partially kept. This necessarily imposes limitations to improving the energy performance of the city as a whole, resorting only to changes in its physical structure.

After accounting for the energy impact of the urban development alternatives, Chapter 7 includes additional criteria in the analysis (resorting to a composite indicator of urban performance), so that the dominant alternatives may be identified. In addition, because there may be difficulties in communicating the results of foresight studies to decision makers (Nehme et al., 2012) the last stage of the research (Chapter 7) tries to provide this study with a strategic character. It draws on the results from the appraisal here performed, in order to identify suitable spatial planning policy mechanisms for the implementation of the best urban development alternatives.

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CHAPTER 7. ENERGY CONSERVATION IN CITIES: IMPLICATIONS AND IMPLEMENTATION

The methodological framework proposed in this research enabled to characterize, in a comprehensive way, the effect of urban form on three main energy end uses. Following the appraisal of the urban development alternatives under an energy performance perspective, it is anticipated that changes on the physical structure of the city, may bring about changes upon further domains of the urban landscape. In this sense, additional criteria will be considered alongside energy in order to identify *which* could be sensible urban development pathways for the two case studies. In a second instance, the possibilities of *how* to get there (i.e. the implementation mechanisms) will be discussed and matched to the urban alternatives considered.

Energy and sustainability policies at urban level should focus on where the action provides the largest leverage effects, notably on urban form and density, on the quality of the built environment and on urban transport policy (Grubler et al., 2012). Although the literature has been supporting that the way that cities are planned and built has important energy implications, little has been done, in the international political landscape, to incorporate spatial planning policies in the action plans for climate change mitigation worldwide (Seto et al., 2014) and vice-versa. It is often found that the existing climate plans for cities are grounded on measures of energy efficiency with a strong technological nature (both regarding the energy supply- and demand-sides), whereas the promotion of energy conservation through structural measures is frequently lacking. The level of uncertainty with regard to the outcomes of land use changes in energy conservation and in the reduction of GHG emissions, together with the long turnover of such changes, may have been contributing to this fact.

This issue has been addressed in this work, by providing new empirical evidence on the nature of the urban form-energy link. It was confirmed that urban form significantly influences energy demand for ambient heating and mobility, whereas the attributes and variables of urban form with greater importance in a given city have been identified. In addition, the analysis of several urban development alternatives (Chapter 6), enabled to conclude on energy-sensible pathways for the future. This creates room for identifying applicable and suitable policy mechanisms that may be put into practice in each case.

Section 7.1 extends the analysis of the urban development alternatives (from Chapter 6) to additional criteria related to the cohesion of the urban environment. Section 7.2 reviews a set of strategies and programs in order to investigate the level of interaction between territorial and energy policies. Section 7.3 deals with the problem of *how* land use strategies may be put into practice, i.e. it draws on spatial planning policy mechanisms for energy conservation. Section 7.4 discusses the advantages and drawbacks of the different types of mechanisms, and proceeds to bridging the urban alternatives selected in section 7.1 with the mechanisms identified in Section 7.3. Finally, Section 7.5 concludes with some remarks from the work developed in Chapter 7.

7.1. Implications of the development alternatives on additional urban criteria

After the analysis of a set of urban development alternatives with regard to their energy performance, it is acknowledged that energy isn't and arguably should it be the only criteria when deciding among a set of possible development pathways.

In addition to the effects on energy demand (assessed in Chapter 6), there is empirical evidence that the attributes of urban form place their influence upon further urban domains. A literature review enabled to identify a set of six additional domains influenced by urban form, along with the potential implications/ impacts of specific urban configurations (allowing to establish a parallel with the urban development alternatives from Chapter 6). The nature of such impacts was characterized according to whether they are positive or negative. The analysis of the implications of the development alternatives on additional urban criteria allows to broaden the assessment of the urban development options considered in the previous chapter.

Subsection 7.1.1 describes, in brief, the additional urban domains influenced by the physical structure of urban areas. Subsection 7.1.2 evaluates the implications of the alternatives on such domains, using an approach inspired on multi-criteria decision analysis (MCDA).

7.1.1. Identification of additional domains influenced by urban form

The following paragraphs describe a set of six criteria found in the literature, which are potentially affected by the physical structure of urban areas. Under a social umbrella, three criteria are considered: social segregation, gentrification and urban vibrancy. Infrastructure costs belong to an economic sphere, whereas traffic congestion/noise and concentration of pollutants are considered under an environmental scope.

Social segregation

The built environment has been advocated to impact the social environment in several ways. It has been argued to affect the phenomenon of social segregation with different impacts on the health and quality of life of the overall population (Yang et al., 2017), depending on whether it refers to the separation of high or low income groups. Also, it has been argued to impact crime and fear of crime in urban areas (Lorenc et al., 2012). Sharifi and Murayama (2013) review relevant research on social sustainability, where social homogeneity has been pointed out as a relevant factor.

Massey and Denton (1988) refer to residential segregation as a multidimensional issue characterized by spatial patterns of evenness, exposure, concentration, centralization and clustering. The authors define it as the extent to which two groups live separated from one another. In addition, Smets and Salman (2016) claim that “the cleavages between richer and poorer sections of society can be seen in places of residence, in employment spheres, in transportation routes and means, in access to leisure areas, in access to political influence, in mutual negative imageries and in separated shopping areas.”

Glaeser and Vidgor (2001) noted that segregation decreases in areas facing a quick growth, because these areas are less likely to suffer from pre-determined residential patterns. However, it has been argued that new urban development taking place all at once leads to monotonous and homogeneous urban environments, lacking diversity among its residents (Jacobs, 1961). In addition, the existence of public spaces is advocated to promote meeting happenstances and foster tolerance (Fincher and Iveson, 2008), while the existence of green spaces has been associated to increased social cohesion (Branas et al., 2011) and lower rates of crime and violence (Bogar and Beyer, 2016). Fincher and Iveson (2008) claim that high-rise housing projects, many of which promoted under urban renewal regimes, have promoted spatial differentiation of urban inhabitants. In line with this, Watson (2009) claims that generally, modernist forms with high-rise buildings, separation of uses and free-flowing vehicular movement promote spatial and social marginalization. Finally, neighbourhoods with physical barriers such as gates and fences (typically housing higher income groups), such as single-family housing types or condos, create physical and social isolation from their surroundings (Smets and Salman, 2016).

Gentrification

Gentrification consists of the process of replacement or displacement of residents by relatively more advantaged social groups in formerly poorer neighbourhoods that suffered a renewal process (Glass, 1964). This author refers to an inverse relation between dwelling size and value in gentrified areas, mostly due to the social “status” that the renewed property acquired, and that is often inflated when compared to its previous valuation. Gentrification may ultimately promote social segregation (as it may lead to inequities in income distribution and in the access to resources and social services – see social sustainability criteria from Sharifi and Murayama, 2013), but it is a result of more specific urban transformations and different development choices than those previously discussed, which is why it will be treated within a distinct topic.

Gentrification frequently takes place in historic and inner-city areas (Hamnett, 2003; Lim et al., 2013; Avdikos, 2015). The term often refers to residential uses, but it is also applicable to commercial activities, whenever they get displaced by higher profit companies (Lim et al., 2013). It is, expectedly, a result of the development and renewal of core urban areas, leading to increasing rent and land value prices (Hamnett, 2003). The author adds that predictable consequences of gentrification are the decrease of poorer, less skilled and unemployed people in gentrified areas, while middle class residents come in. This phenomenon is expected to put pressure on elder people too (Buffel and Phillipson, 2016).

In addition, it is claimed to change the local working structure as it tends to increase jobs opportunities in restaurants and services, although reducing positions in manufacturing and wholesale (Lester and Hartley, 2014). Brown-Saracino (2010) draws attention to how the debate on gentrification amplifying economic inequalities distracts the audience from how long-time residents cope with this process – an example being changes in mobility patterns in gentrifying neighbourhoods, mostly determined by more advantaged residents (Ding et al., 2016). Regeneration tends to increase pedestrian movements, and accelerate land use changes to meet the demand of more affluent users (Lim et al., 2013). Venerandi et al. (2016) found common morphological structures among a set of gentrified neighbourhoods, which tend to be traditional, fine-grained physical settings.

Although the urban renewal process is a positive event *per se* (contributing to the preservation of the built heritage), gentrification, resulting from a mismatch between the physical improvements and the socio-economic structure of the local inhabitants, is here considered to produce a negative impact in terms of urban cohesion.

Urban vibrancy

Urban vibrancy may be seen as a subjective concept. Braun and Malizia (2015) see vibrant centres as "*downtown areas that maximize the density and diversity of land uses and activities; offer an interconnected street design to facilitate non-motorized travel; promote destination accessibility at the local and regional scales; and minimize distance to public transport through a dense network of public transport stations, stops, and routes*". These authors built a vibrancy index emphasizing the aspects related with the built environment and urban form to assess the relationship between vibrancy and mobility and health outcomes. Table 58 presents the features of vibrant city centres.

There seems to be a general agreement that vibrant urban areas are pedestrian-oriented, and typically characterized by dense environments with small lots (Alawadi, 2017; Norman, 2015). This is line with Jacobs (1961), who advocate frequent streets and enough ground coverage to support diverse and vibrant urban places. In addition, Norman (2015) refers to urban vibrancy as the areas fostering the movement of people and capital. This is claimed to be achieved mostly by reducing car-oriented space and focusing on using space for buildings and people instead. As Speck (2012) notes, walkability is the most meaningful indicator of urban vitality. In addition to the dense, diverse and walkable environments; green areas, such as parks, have also been advocated to be a feature of vibrant urban areas (Malizia and Stebbins, 2015). Aspects like the attractiveness of the public realm, mixed use and tenure, and sense of place and belonging have also been pointed out as criteria of social sustainability (Weingaertner and Moberg, 2014).

Table 58. Features of vibrant centres

Compact floor area ratios (over 1.0)
Mixed–use buildings
Multiple land uses near each other
Grid-type street pattern
Small block size with multiple connections
Connections to internal and external destinations
Parking maximums and structured parking
Relatively high density
Public spaces and outdoor open space
Transit-accessible destinations with a defined public realm
Discrete boundaries and edges
Critical mass: additional development increases vibrancy

(Adapted from Malizia and Stebbins, 2015)

Infrastructure costs

The relevance of urban form to infrastructure costs has been mainly addressed under the perspective of the distances to be bridged by the infrastructure, and the number of people served, which directly affects the revenues of public service companies, and thus the feasibility of the system at stake.

Nijkamp and Rienstra (1996) focus on the infrastructure costs of public transport networks. The authors claim that there is a minimum amount of passengers required between certain points to make an economically feasible public transport system. Density and compactness are pointed as important factors to meet such a requirement (Ewing, 2008). Higher densities are also expected to lower indirect infrastructure costs related to the use of private vehicles. Litman (1999) claims that low density developments have higher costs associated to road and parking facilities.

In addition to the transportation infrastructure, Fuseini and Kemp (2016) highlight the pressure caused by the urban expansion to peri-urban areas in a city in Ghana not only regarding the road network, but also the sanitary facilities. Furthermore, Ewing (2008) refers to additional costs related to public urban amenities like the police, firemen, schools, water supply and drainage services, which are largely dependent on the proximity, or the distances to be covered, by the development patterns.

Traffic congestion / noise

Traffic congestion is largely an issue raised by extensive private car usage. The effects of traffic are related to density, although its effect is not consensual: while density is associated to lower VMT, it is also associated to higher levels of traffic congestion (Ewing, 2008). The author argues that the net effect is dominated by the former. Again, and as discussed earlier, the mix of land uses is expected to provide alternatives to car-borne travel.

According to Jacobs (1961), "wherever people are thinly settled rather than densely concentrated, or wherever diverse uses occur infrequently, any specific attraction does cause traffic congestion. (…) The lack of wide ranges of concentrated diversity can put people into automobiles for almost all their needs. The spaces required for roads and parking spread everything out still farther, and lead to still greater uses of vehicles". In line with this, Levine and Garb (2002) argue that planning for accessibility and relatively high densities should be promoted, versus planning for mobility. Non-residential areas are natural trip attracters. The authors add that tackling congestion should walk hand in hand with a goal of enhancing accessibility to these areas in order to promote a shift from private motorized vehicles to public transport or soft modes.

Concentration of air pollutants

Air pollutants in urban areas are at a great extent caused by road traffic. The link between urban form and air emissions follow a similar rationale to the mobility patterns leading to traffic congestion.

Anderson et al. (1996) refer to three scenarios for development of the Greater Toronto Area, where the "central" scenario, compatible with a compact structure yields the greatest reductions of air pollutants such as CO, HC and NO_x. Similarly, the results from Cárdenas Rodríguez et al. (2015) suggest that fragmented urban areas experience higher concentrations of NO_2 and PM_{10}, although dense urban areas evidence high concentrations of SO_2[10]. Yet, Ewing (2008) claims that air pollution is less influenced by urban form than energy demand, since changes in urban form produce greater benefits in reducing the percentage of VMT than the cut-off percentage of pollutants emissions.

Another feature of urban form with linkages to air pollution is buildings' heights. Higher building heights are usually associated with a lower air quality, as it makes the dispersion of pollutants more difficult (Taseiko et al. 2009). In addition to the role of density and mixed uses in reducing motorized traffic, green infrastructure, notably trees, have been advocated to produce improvements in urban air quality by absorbing and uptaking air pollutants (Jayasooriya et al., 2017).

7.1.2. A multi-criteria approach for assessing the urban development pathways

In order to allow for a broader (not limited to energy) and objective assessment of the urban development alternatives, an approach based on multi-criteria decision analysis (MCDA) was considered, so that dominant solutions could be spotted.

MCDA has several advantages over informal judgement, particularly the fact that it allows scores and weights to become explicit. It establishes preferences between different options according to a set of measurable criteria in view of the achievement of specific objectives. Several techniques or approaches have been developed to date, including: MAUT – multi-attribute utility theory, AHP – analytical hierarchy process, ELECTRE – elimination and choice expressing the reality,

[10] While PM_{10} and NO_2 are mostly related to road transportation, SO_2 is mainly produced in electricity generation (Cárdenas Rodríguez et al., 2015)

PROMETHEE – preference ranking organization method for enrichment of evaluations, and DRSA – dominance-based rough set approach (Cinelli et al., 2014).

Typically, a weighting system is used, even if implicitly. An exception, where weights may not be required is in the presence of dominance[11] of one or more alternatives over the others (Department for Communities and Local Government, 2009). Table 59 describes typical steps in MCDA.

Table 59. Steps in a multi-criteria analysis

1. Establish the decision context. What are the aims of the MCDA?
2. Identify the options.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option.
4. Describe the expected performance of each option against the criteria. (*If the analysis is to include steps 5 and 6, also "score" the options, i.e. assess the value associated with the consequences of each option*.)
5. "Weighting". Assign weights for each of the criteria to reflect their relative importance to the decision.
6. Combine the weights and scores for each of the options to derive and overall value.
7. Examine the results.
8. Conduct a sensitivity analysis of the results to changes in scores or weights.

Source: adapted from (Department for Communities and Local Government, 2009).

The coupling of multi-criteria decision analysis and scenario planning has been advocated to be a powerful way of supporting strategic decision-making (Goodwin and Wright, 2001; Montibeller et al., 2006), although it has not been extensively used in real-word applications (Montibeller et al., 2006). This part of the research follows Goodwin and Wright (2001) in the sense that it couples the urban development alternatives (from Chapter 6) with an assessment approach based on MCDA.

The point is not to develop an in-depth MCDA, but instead to use its principles for ranking the alternatives while considering additional criteria besides energy, i.e. to perform a screening of the alternatives under a more structured decision environment. It aims at: i) selecting the best performing urban development alternatives, and ii) narrowing the possibility scope for the selection of the policy mechanisms for the implementation of the best-performing alternatives.

For the selection of the best alternatives under appraisal, as described in Section 6.2, two objectives are identified:

- To minimize the overall urban energy demand.
- To maximize the overall urban performance/ cohesion of the urban environment.

The first objective relates to the energy performance of the urban alternatives, and is measured by the ratio between the primary energy savings (PES) of an alternative in relation to the base case. This has been computed in Chapter 6. The second objective is characterized by the six urban criteria identified in the previous subsection, potentially influenced by the changes

[11] "One option dominates another option if it performs at least as well on all criteria and is strictly better on at least one criterion" (Department for Communities and Local Government, 2009).

considered in urban form, under the scope of the urban development alternatives. These are: social segregation, gentrification, urban vibrancy, infrastructure costs, traffic congestion/noise, and concentration of pollutants. It is characterized by a composite indicator of "urban performance" resulting from a weighted scoring of the aforementioned criteria for each urban alternative.

The scoring scale adopted is discrete and entails three possible values, referring to a negative influence (-1), a neutral influence (0) or a positive influence (1). Although the literature advances the nature of corresponding effects, it is considered that there is not enough evidence to support the adoption of a more disaggregated scoring scale, and it is out of the scope of this work to propose one.

Table 60 presents the scores of the urban performance criteria, concerning the different urban development alternatives. The scoring is attributed to the alternatives in a conceptual and abstract sense, as it grounds on the literature review from Section 7.1.1., i.e. without referring to a specific city or development magnitude. Hence, the "urban performance" indicator of a given alternative is the same for both case studies (the insights from the literature regarding the implications of urban form on the urban performance index equally apply to both cities). Conversely, the energy performance of the urban development alternatives varies between the two case studies.

With regard the weights assigned to the decision criteria, different possibilities are considered (Table 60). Although participatory approaches are frequently found in MCDA, it was deemed that, for the purpose of this analysis on the identification of sensible urban development pathways (and as a complementary analysis to energy performance), the lack of a participatory approach could be curtailed by a sensitivity analysis to changes in the weights selected. As a result, three weighting options (WO) are analysed:

1) equal weights for all criteria (WO1);
2) equal weights for the social, economic and environmental spheres (WO2);
3) higher weights to the social criteria – because the remaining criteria are more aligned with the energy dimension (WO3).

Table 60. Performance matrix

Criteria / Alternative		SOCIAL			ECONOMIC	ENVIRONMENTAL	
		Social segregation	**Urban vibrancy**	**Gentrifica-tion**	**Infrastructu-re costs**	**Concentration of air pollutants**	**Traffic congestion / noise**
A1	**IN**	1	1	-1	1	1	-1
A2	**CD**	1	1	-1	1	1	-1
A3	**MD**	-1	-1	0	-1	-1	1
A4	**MFH**	1	-1	-1	-1	1	1
A5	**TOD**	-1	1	-1	1	1	1
A6	**GI**	1	1	0	-1	1	1
Weights							
WO 1		0.17	0.17	0.17	0.17	0.17	0.17
WO 2		0.11	0.11	0.11	0.33	0.17	0.17
WO 3		0.20	0.20	0.20	0.20	0.10	0.10

Legend: (-1) negative effect; (0) neutral effect; (1) positive effect. IN – Infill development, CD – Consolidated development, MD – Modern development, MFH – Multi-family housing, TOD – Transit-oriented development, GI – Green Infrastructure.

After the overall values were derived for the urban performance index, both the urban performance and energy performance scores were normalized into a scale of 0 to 1. Because the urban performance is measured through a composite indicator, this approach is, in practice, evaluating the trade-offs between two criteria (energy and urban performance).

Plotting this data enabled to find the dominant alternatives for each case study. Figure 136 plots the urban performance of the development alternatives against the energy performance for the city of Porto, and Figure 137 for the city of Lisbon. The dashed lines link the dominant solutions according to the scores and weights considered. It can be seen as an efficiency frontier for the trade-offs between energy and urban performance (given the alternatives under analysis).

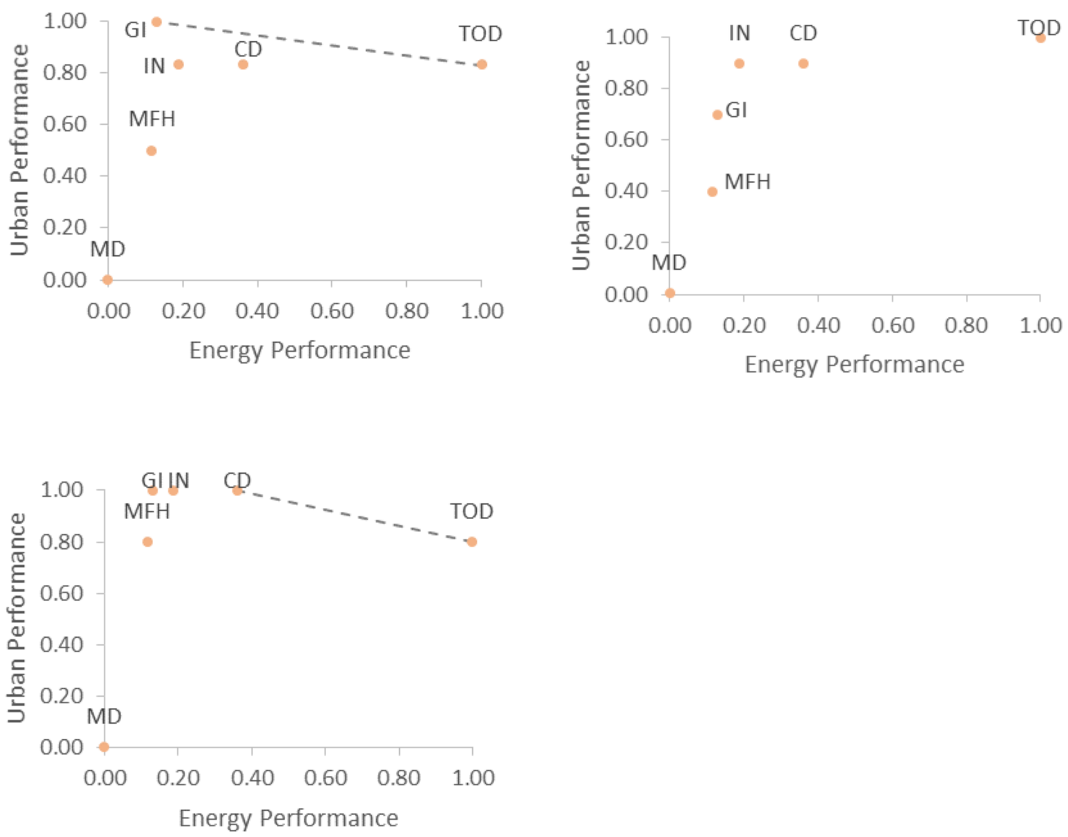

Figure 136. Performance of the urban development alternatives given different weighting options (upper left: WO1; upper right: WO2; lower left: WO3). Porto.

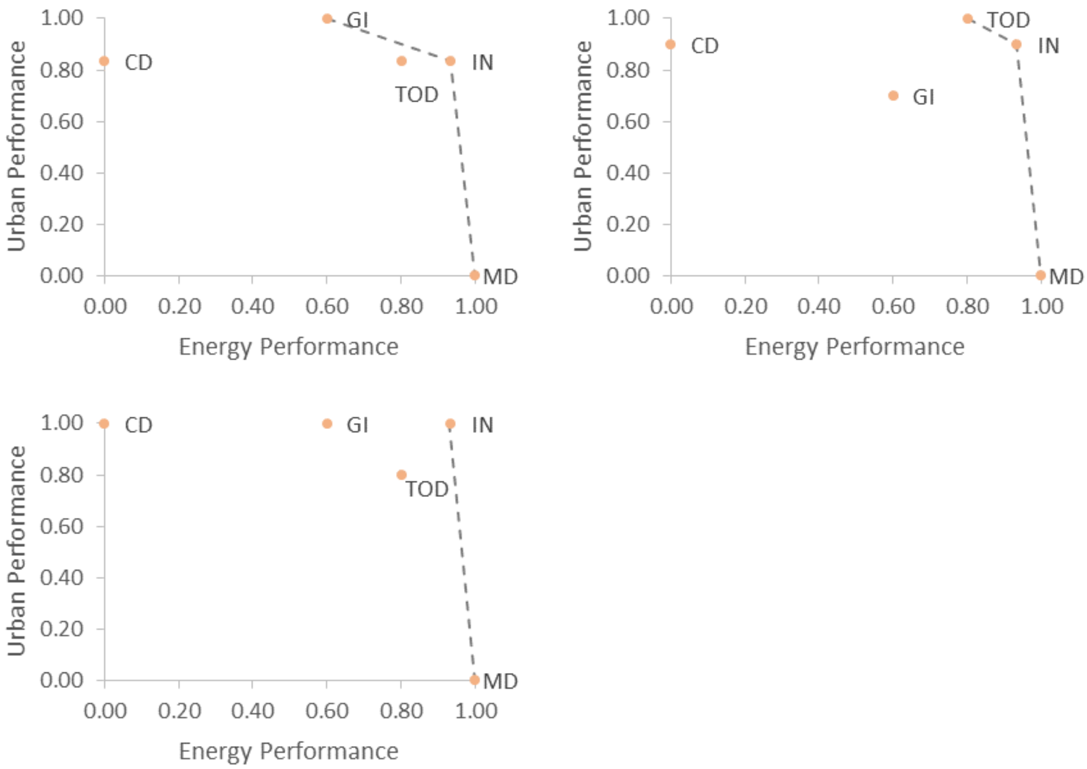

Figure 137. Performance of the urban development alternatives given different weighting options (upper left: WO1; upper right: WO2; lower left: WO3). Lisbon.

In the case of Porto (Figure 136), and for the three different weighting options, TOD is always a dominant alternative, i.e. it is always an efficient option regarding the two objectives previously defined. Given WO1 (i.e. equal weights for all the criteria of the urban performance index) the green infrastructure alternative is also dominant (although it has the lowest reductions on energy demand, it has several co-benefits). In the case of WO2 (i.e. equal weights for the three sustainability domains) only TOD is an interesting alternative. Whereas for WO3, i.e. a higher emphasis on the social dimension, GI switches positions with CD, and now both CD and TOD are considered efficient alternatives.

In the case of Lisbon (Figure 137), GI is also a dominant alternative, given WO1. However, TOD is no longer an interesting option, and it changes places with IN. Still, in this case, MD is also an alternative to be considered – although it has the lowest urban performance it also has the highest reductions in energy demand. In the case of WO2, three alternatives are again considered efficient (TOD, IN and MD). Finally, attributing a higher weight to the social dimension, pushes TOD away from the efficiency frontier.

It may be observed that only a couple of efficient alternatives are common to both cities (Table 61): TOD and GI. While TOD is expected to significantly reduce travel needs, GI has small advantages in reducing energy needs, but its urban co-benefits may turn it into an advantageous option. Regarding the overall ranking (dominance count), both IN and MD are tied in second place with a count of 3 (TOD is in first with 4 counts). Still, where IN hasn't been considered efficient

(Porto), it has been placed much closer to the dashed line than MD, in spite of its limited implementation scope. IN has been widely advocated to combine significant energy savings with additional benefits on the cohesion of the urban environment. Given the above, the results from Table 61 suggest that four alternatives should be considered as sensible development options, regarding both case studies. These are TOD, GI, IN and MD.

Table 61. Count of alternative dominance in both case studies

Alternative	Count Porto	Count Lisbon
IN	0	3
CD	1	0
MFH	0	0
MD	0	3
TOD	3	1
GI	1	1

The analysis indicates that it is possible to reconcile urban cohesion and the energy performance of the urban environment, reinforcing the relevance of including energy as a decision criterion in urban planning. The identification of sensible urban development alternatives now leaves room for exploring the means to achieve them in practice. Section 7.2 reviews the extent to which territorial planning and energy conservation governance are connected, whereas Section 7.3 reviews spatial planning policy mechanisms for energy conservation and climate change mitigation.

7.2. The contemporary landscape of territorial and urban governance for energy conservation and climate change

Different terms have been used in the literature to refer to the implementation of a given policy or plan (e.g. policy measure, policy instrument, and policy mechanism). However, their distinction is not always straightforward. For the remainder of this work *policy measure* will be applied to designate an action or change that is aimed at being achieved. *Policy instrument* and *policy mechanism* are often considered synonyms and used interchangeably, referring to the means of implementing a desired action or change. Still, for the sake of coherence, the term mechanism will be adopted. For instance, the implementation of a specific policy measure (e.g. "increasing urban density through increasing buildings' heights") may be promoted and accomplished by different means (e.g. by command and control mechanisms or financial incentives).

Before focusing on the spatial planning policy mechanisms (dealt with in Section 7.3), this section investigates the extent to which spatial planning has been included in energy and climate change mitigation plans, and vice-versa (i.e. the extent to which energy has been considered in spatial planning programs), at different governance levels (international, national and local). In order to do so, key strategies and programs addressing the territory and energy have been reviewed, which can be either ongoing or recently concluded. They are classified into four categories depending on their scope: 1. energy and climate change, 2. territory, 3. sectorial (e.g. if focusing on a specific sector like transports or buildings), and 4. cross-cut (if it has a broad nature, e.g. environmental).

Three governance levels are considered: international, national and local (city). At the local level, the strategies reviewed belong to the case studies analysed in the previous parts of the research (Porto and Lisbon). Thus, at the national level, strategies from the Portuguese context are examined. Finally, at the international level, the analysis mainly focuses on the European setting (the EU has been leading the way regarding energy and climate change political initiatives), although a couple of international strategies from the United Nations were also included due to its prominent influence in the world nations (e.g. the Paris agreement). Although it is acknowledged that these geographies may not be representative of the world political landscape, they provide an introductory picture of the existing strategic connections between the two fields.

The analysis grounds on a qualitative review of strategies/ programs addressing relevant themes (as *per* the categories described earlier) and aims at answering three questions (Table 62):

- Does the strategy/program acknowledge the spatial planning – energy link?
- Does the strategy/program propose spatial planning measures?
- Does the strategy/program propose spatial planning mechanisms?

Table 62. Review of key strategies and programs addressing the territory and energy fields

Program	Nature	Domain				Acknowledges the spatial planning – energy link?	Includes 'land use' mechanisms?	Includes 'land use' measures?
		Energy / CC	Territory	Sectorial	Cross-cut	Y/N	Y/N	Y/N
International								
Territorial Agenda of the EU 2020 (Ministers of Spatial Planning and Territ. Dev., 2011)	Strategic		X		X	No	No	No
European Spatial Development Perspective (EC, 1999)	Strategic		X		X	Yes[12]	No	Yes[13]
Energy 2020 (EC, 2010)	Strategic	X				No	No	No
Energy Roadmap 2050 (EC, 2012)	Strategic	X				Yes [14]	No	No
Energy Efficiency Directive (EC, 2012b)	Regulatory	X				No	No	No
Energy Efficiency Plan (EC, 2011b)	Strategic	X				Yes[15]	No	No
Roadmap to a Resource Efficient Europe (EC, 2013)	Strategic				X	Yes[16]	No	Yes[16]

[12] "Uncontrolled growth results in increased levels of private transport; increases energy consumption (..)".

[13] "Promotion of better accessibility in cities and metropolitan regions through an appropriate location policy and land use planning that will stimulate mixing of urban functions and the use of public transport"; "Promotion of energy-saving and traffic-reducing settlement structures, integrated resource planning (…) in order to reduce CO_2 emissions".

[14] Referred to as a suggestion to achieve higher energy savings.

[15] "The initiative will support large scale demonstration projects also including action on urban mobility, 'green' infrastructure (…)".

[16] "Avoid urban sprawl on fertile soil"; "Avoid additional land take (e.g. for urban sprawl)"; "Ensure sufficient and connected green spaces as part of green infrastructures"; "Reduce GHG emissions from buildings"; "better transport networks"; "Increase resource efficiency of infrastructures".

Program	Nature	Domain				Acknowledges the spatial planning – energy link?	Includes 'land use' mechanisms?	Includes 'land use' measures?
		Energy / CC	Territory	Sectorial	Cross-cut	Y/N	Y/N	Y/N
Roadmap for moving to a competitive low carbon economy in 2050 (EC, 2011c)	Strategic	X		X		Yes[17]	Yes[18]	No
Effort Sharing Decision (EC , 2009)	Regulatory	X				No	No	No
Paris Agreement 2015 (UN, 2015b)	Strategic	X			X	No	No	No
Environ. Action Programme to 2020 (EC, 2013)	Regulatory				X	Yes[19]	No	No
New Urban Agenda (UN, 2016)	Strategic				X	Yes[20]	No	Yes[21]
Towards a thematic strategy on the urban environment (EC, 2004)	Strategic				X	Yes[22]	No	Yes[23]
Smart Cities and Communities (EC, 2012c)	Strategic	X			X	No	No	No
Leipzig Charter on Sustainable EU Cities (MS Ministers UD, 2007)	Strategic				X	Yes[24]	No	No
White Paper. Roadmap to a	Strategic			X		Yes[25]	Yes[26]	No

[17] Refers to intelligent city planning for sustainable mobility. Although this is a vague concept it is admitted to fall within the scope of this review.

[18] "Emissions from road, (…) could in fact be brought back to below 1990 levels in 2030, in combination with measures such as pricing schemes to tackle congestion and air pollution, infrastructure charging, intelligent city planning and improving public transport, whilst securing affordable mobility. Improved efficiency and better demand-side management, fostered through CO_2 standards and smart taxation systems (…)".

[19] "In order to enhance the sustainability of Union cities, the 7th EAP shall ensure that by 2020: a majority of cities in the Union are implementing policies for sustainable urban planning and design, including innovative approaches for urban public transport and mobility, sustainable buildings, energy efficiency (…)"; "This requires, in particular: (…) developing and promoting a common understanding of how to contribute to improved urban environments by focusing on the integration of urban planning with objectives related to resource efficiency, (…), sustainable urban land-use, sustainable urban mobility (…)".

[20] "We recognize that urban form, infrastructure, and building design are among the greatest drivers of cost and resource efficiencies, through the benefits of economy of scale and agglomeration, and fostering energy efficiency, renewable energy, resilience, productivity, environmental protection, and sustainable growth in the urban economy." This strategy also proposes a vision for sustainable urban design (page 46).

[21] Please see points 51-54 and 97-100 of the agenda.

[22] "The favoured vision of high density, mixed use settlements with reuse of brownfield land and empty property, and planned expansions of urban areas rather than ad hoc urban sprawl (…)"; "Urban sprawl is a priority issue for Europe's towns and cities".

[23] "All Member States will be encouraged to: develop incentives to encourage the reuse of brownfield land over the use of greenfield land, create national databases of brownfield land and set challenging targets for its reuse, and provide support for the reuse of empty properties in urban areas"; " set minimum residential land use densities to encourage higher density use and limit urban sprawl"; " evaluate the consequences of climate change for their cities so that inappropriate developments are not begun (…)".

[24] Recognizes the need to "creating and ensuring high-quality public spaces"; improving the efficiency of the transportation infrastructure (including accessible and affordable urban transport, and cycling and pedestrian infrastructure), reconciling transport networks and land use; and achieving compact settlement structures. As well as of "pursuing strategies for upgrading the physical environment (to improve existing building stock in deprived neighbourhoods with regard to their design, physical conditions and energy efficiency)".

[25] "Demand management and land-use planning can lower traffic volumes. Facilitating walking and cycling should become an integral part of urban mobility and infrastructure design."

[26] "In the urban context, a mixed strategy involving land-use planning, **pricing schemes**, efficient public transport services and infrastructure for non-motorised modes (…) is needed to reduce congestion and emissions. Cities above a certain size should be encouraged to develop **Urban Mobility Plans**, bringing all those elements together."

Program	Nature	Domain				Acknowledges the spatial planning – energy link?	Includes 'land use' mechanisms?	Includes 'land use' measures?
		Energy / CC	Territory	Sectorial	Cross-cut	Y/N	Y/N	Y/N
Single EU Transport Area (EC, 2011d)								
EPBD 2002 (EC, 2002)	Regulatory			X		No	No	No
EPBD 2010 (EC, 2010)	Regulatory			X		Yes[27]	No	No
Resource efficiency opportunities on the building sector (EC, 2014)	Strategic			X		Yes[28]	No	No
National								
PNPOT (A.R., 2007)	R/S		X		X	Yes[29]	No	Yes[30]
PNAEE 2013-2016 (Presid. Cons. Ministros, 2008)	R/S	X		X		Yes[31]	Yes [32]	Yes[33]
PNAEE 2008-2015 (Presid. Cons. Ministros, 2013)	R/S	X		X		Yes[30]	Yes[34]	Yes[35]
PNAC (APA, 2015)	R/S	X			X	Yes[36]	No	Yes[37]
RNBC (APA, 2012)	Strategic	X			X	No	No	No
ENDS (APA, 2008)	R/S				X	Yes[38]	No	Yes[39]
Regulamento específico do domínio da sustentabilidade e eficiência no uso de recursos (Presid. Cons. Ministros e MAOTE, 2015)	Regulatory				X	No	No	No

[27] "Member States should enable and encourage architects and planners to properly consider the optimal combination of improvements in energy efficiency, use of energy from renewable sources and use of district heating and cooling when planning, designing, building and renovating industrial or residential areas"; "Energy performance of buildings includes passive heating and cooling, shading, and the design of the building".

[28] "Resource use is determined in large part by design decisions".

[29] The concerns expressed in the document include the inefficiency and lack of environmental and economic sustainability in the fields of transports and energy. However, these concerns on land use and energy are placed mostly on the supply side, while the territorial potential to reduce the demand is often neglected or superficially dealt with.

[30] Macro-scale and broad measures, including the coordination of open space with the urban systems and infrastructure networks, and the structuring of dispersed urban nuclei along the coast.

[31] Territorial concerns focused on mobility.

[32] While the former PNAEE grounded mostly on financial incentives, this program resorts in large part to regulatory frameworks and financial penalties such as taxation and fees. Still, it refers to some funding as well.

[33] Measures focused on promoting the use of public transport (PT), namely the development of public transport infrastructure, allowing a better offer and services (…) allied to restrictive measures to the circulation and parking of private vehicles; and the use of more efficient mobility solutions, including soft modes.

[34] Funding and taxation.

[35] Creating SUMPs for the main cities, building PT infrastructure (notably for metro).

[36] The patterns urban occupation form the last decades originated serious sustainability problems, namely concerning to GHG emissions.

[37] Relevant measures within two domains (mobility and sustainable cities). Examples for mobility include the creation of zones with low emissions, increasing the spatial coverage of PT, urban design, zoning, increase of 7% of the share of soft modes in the overall modal share, creating of infrastructure for the use of soft modes. Sustainable cities domain foresee preventing the reconversion of green areas, and urban regeneration.

[38] "Changing the economic growth model also involves the territory, finding innovative solutions (...) finding new forms of urbanism and new urban transport modes, more energy-efficient, promoting the accessibility of spaces, buildings and transports (...)".

[39] Vaguely stated. Agues for more attractive and sustainable cities, and for urban polycentrism at metropolitan level.

Program	Nature	Domain				Acknowledges the spatial planning – energy link?	Includes 'land use' mechanisms?	Includes 'land use' measures?
		Energy / CC	Territory	Sectorial	Cross-cut	Y/N	Y/N	Y/N
Cidades sustentáveis 2020 (MAOTE, 2015b)	R/S				X	Yes[40]	Yes[41]	Yes[42]
PE Transportes e Infraestruturas 2014-2020 (Min. Econ., 2014)	Strategic			X		No	No	No
Diretrizes Nacionais para a Mobilidade (IMTT, 2012)	Strategic			X		Yes[43]	Yes[44]	Yes[45]
CiclAndo – Plano Nacional de Promoção da Bicicleta e Outros Modos Suaves (IMT, 2012)	Strategic			X		Yes[46]	Yes[47]	Yes[48]
City								
PDM Porto (CMP, 2006a)	R/S		X			No	Yes[49]	No
PDM Lisbon (CML, 2012)	R/S		X			Yes[50]	Yes	No
SEAP Porto (CMP, 2010)	Strategic	X				No	No	No
Plano Estratégico de Desenvolvimento Urbano do Município de Lisboa (CML, 2016a)	Strategic		X		X	Yes[51]	Yes[52]	Yes[53]
Plano De Ação Mobilidade Urbana Sustentável Do Municipio De Lisboa (CML, 2016b)	Strategic			X		Yes[54]	Yes[55]	Yes[56]
Plano de Ação de Regeneração Urbana do Municipio de Lisboa (CML, 2016c)	Strategic		X			No	Yes[57]	No

[40] Includes a strategic line entitled sustainability and efficiency (including the categories of urban regeneration and rehabilitation; housing; urban environment, low carbon and climate change and risks).

[41] Presents financing schemes for each topic and encourages integrated territorial approaches, as well as the development of knowledge exchange platforms.

[42] The strategy includes four strategic lines, each including a set of measures within a set categories. As an example: "to reduce the energy intensity of cities, assuming differentiated responses to demand management, promoting the energy efficiency of the distinct urban agents and sectors (…)."

[43] Territorial concerns are largely present. The document aims at improving accessibility and mobility in urban territories.

[44] The mechanisms are part of the mandatory development of mobility and transport plans at municipal scale, where funding is highlighted.

[45] Measures are presented in Annex 2 of the strategy, under the title "Actions and Milestones".

[46] Promotion of cycling as a way of achieving environmental and energy yields.

[47] Examples include traffic calming mechanisms such as zone restrictions and speed limits.

[48] The plan includes 11 operational programs, each including a set of measures with timings and the identification of the implementation agents.

[49] The PDM of Porto entails mostly regulatory mechanisms such as density rules (e.g. maximum building heights) and restrictions to land uses (zoning).

[50] The article 20º of the PDM of Lisbon is focused on promoting the environmental and energy efficiency of urban planning practices.

[51] One of the three main objectives of the plan includes improving the energy efficiency of the building stock and increasing urban connectivity, optimization of urban systems and services and improving accessibility and sustainable mobility.

[52] Refers to land use mechanisms such as decreasing areas for car circulation, reducing speeds, and increasing green areas within the city.

[53] The document comprises an action plan with specific measures, deadlines and investment allocated to them.

[54] Draws on the role of the municipality in making and implementing land use policies for sustainable mobility (particularly soft modes).

[55] Mostly government-based mechanisms, such as creating new transport infrastructure.

[56] 14 Actions to be implemented, in particular urban areas (e.g. enlarging sidewalks, integrated PT ticketing…).

[57] Mechanisms dominantly focused on urban regeneration.

Table 62 shows that the large majority of the reviewed strategies, notably at an international scale somehow acknowledge and address the link between urban form and energy demand. However, the level of detail under which this topic is addressed varies at a great extent. It is often pointed out as a relevant field for future action; however, the existing recommendations are often vague at this governance level. The urban sprawl debate is one of the most frequent concerns (e.g. in the "*Roadmap to a Resource Efficient Europe"* or "*Towards a thematic strategy on the urban environment"*), although it is also common to find issues like the resource efficiency of (transport) infrastructure, and the quality of public spaces.

At the international scale, the proposal of specific policy measures or mechanisms is frequently lacking. Two interesting exceptions are "*Towards a thematic strategy on the urban environment"* and the "*Leipzig Charter on Sustainable European Cities*". This reinforces the importance of having specific strategies focused on cities and on the urban environment at this governance level. At the national level, it is found that the existing strategic discourse draws on the European guidelines, and often lacks enough detail in order to become relevant and duly implemented (except for specific sectorial strategies – like the one on the promotion of cycling and other soft modes).

Not surprisingly, spatial planning policy mechanisms are most frequently found at the local scale. However, their role and application towards energy conservation and climate change mitigation goals doesn't seem to have received proper attention from local authorities. There seems to exist a gap between the international and national guidelines (acknowledging the urban form-energy link) and the local contribution on how to meeting them, as the link between the aforementioned policy goals and the corresponding implementation mechanism(s) at local level is often missing.

The incorporation of energy and efficiency concerns in municipal master plans is still "optional", i.e. it depends on the municipal will or the decision-makers awareness to consider and state it as a development goal. For example, comparing the municipal masterplans of both case studies, Lisbon clearly declares resource efficiency as a strategic development goal, giving particular emphasis to the energy efficiency of buildings and public infrastructure, as well as to the municipal mobility policy. Conversely, Porto does not include such a concern, whatsoever, in its municipal master plan. In addition, Lisbon has recently produced an additional package of strategic documents for orienting the city's development, where energy and efficiency concerns, measures and instruments are included and described, although these are not binding documents.

With regard to the climate action plans of these two cities, although Porto has an approved sustainable energy action plan (under the voluntary commitment to the Covenant of Mayors), the potential contribution of spatial planning is not included there. Lisbon has submitted a similar proposal to this covenant, but it was not possible to access this document.

This analysis suggests that there is significant room for improvement in bridging spatial planning and energy conservation in cities at a strategic level. The international political landscape is an important background in setting the tone for action, however, its impact at the local scale may be disappointing.

In addition to the review of the strategies from Table 62, a complementary informal analysis was performed. *Word clouds* may be applied to help uncovering key words and thus, the most significant concerns in strategic documents (Ai Ng et al., 2017). In this case, the 100 most frequent words (after removing common words like *the, or*, *and…*) were identified, and represented graphically so that the size of the word is proportional to the amount of times that it is mentioned in the text.

This analysis was not performed for all the international programs included in Table 62, but instead for selected examples. It focused on the international strategies, because the documents are generally of a wider scope. The documents analysed aimed at covering strategies with a broader scope (like the *EU 2020*), to strategies focused on energy at large (*Energy 2020*) and energy efficiency (*Energy efficiency plan*) to documents particularly focused on cities, such as the *Thematic strategy on the urban environment,* and the objective 8 (sustainable cities) of the Environment Action Programme to 2020. Their respective *word clouds* may be found in Annex V (Figure 143 to Figure 147), highlighting the progress on the incorporation of the "urban" and "planning" topics in the strategies reviewed. They show that spatial planning is not extensively addressed both in the political discourse of broader strategies, and of those focused on energy. One can find territorial emphasis within specific documents or passages related to the urban environment and sustainable cities.

Although this analysis may not be representative of the large number of existing strategies on energy and on the urban environment worldwide, it somehow illustrates that spatial planning (and often cities, in general) is absent form broader action plans on energy and climate change. It suggests that there is room for a deeper and more serious consideration of the link between urban form and energy demand in the international political landscape, or else, current and new cities run the risk of getting locked-in inefficient urban structures for the next decades or centuries. The following section focuses on the means to do so, as it reviews the existing policy mechanisms that may help achieve more efficient cities through spatial planning.

7.3. Spatial planning policy mechanisms for energy conservation and climate change mitigation

Local urban-scale mechanisms hold a large potential to effectively tackle GHG emissions and promote energy conservation. From the application of a general equilibrium model, the OECD (2010) concluded that urban policy can significantly contribute to a least-cost strategy for meeting national reduction targets of GHG emissions. The report suggests that aggregate mitigation costs can be reduced if economy-wide policies are complemented by urban policies such as denser urban environments and congestion charges. Given the proven influence of territorial planning and management in energy use (especially for thermal uses in buildings and mobility), it becomes of major relevance to perform a systematic and comprehensive collection of the implementation mechanisms that are available to deliver the desired effects in terms of energy conservation in cities.

Nevertheless, the selection and the feasibility of the specific mechanisms to be adopted may depend on several factors, notably on the underlying governance model from the urban context at stake (Seto et al., 2014). Local action requires capacity and responsibility from the local authority in addressing urban energy and environmental problems, as well as a good communication and coordination with the local stakeholders for a participated decision-making process (Grubler et al., 2012).

The following paragraphs review policy mechanisms within the spatial planning field that may represent enabling instruments for climate change mitigation. Although both energy and territorial governance take place at different levels (ranging from supra-national to local), the policy mechanisms reviewed focus on the local scale, with regard to their implementation scope. This is because the ability to affect urban form through the street patterns, the land-use arrangement and the three-dimensional form of urban areas belongs mostly to local governments (Talen, 2012, p. 13).

There is no single way of categorizing the existing spatial policy mechanisms. Silva and Acheampong (2015) distinguish two broad types used across countries:

i) Development plans,

ii) Development management mechanisms

The first type, plans, typically have a strategic character aiming at prescribing the allocation of land uses, the most common at local scale being master plans and local/subdivision plans. The second type is usually applied to control and pursue desired development outcomes. It is not uncommon to find (management) mechanisms included in development plans, i.e. a development plan may entail a package of policy mechanisms to be implemented. Hence, the following review focuses on the second category of policy mechanisms, which is a broader one. These can be grouped into four main categories, as follows:

- *Regulatory*; typically command and control mechanisms such as rules and legislation;

- *Financial*; including carrots and sticks, i.e. carrots are financial incentives (such as subsidies, tax credits, loans or development rights) and sticks are financial penalties (like taxes and fees)[58];

[58] Taxes, conversely to charges, are unrelated to the provision of a service (Somanathan *et al*., 2014). This fact enables to distinguish between the financial and market-based mechanisms under the classification rationale adopted.

- *Market-based*; including pricing mechanisms and public and private partnerships. While pricing can also be viewed as a financial mechanism, it is distinguished from those by considering variable tariffs for higher uses or consumption levels invoking higher unit prices (IEA, 2010), which is in line with the "polluter pays" principle.

- *Government-based*; mechanisms that require direct action or investment by the local authorities, with notable examples being the provision of public goods or services or a direct state action upon land ownership (e.g. expropriation or compulsory acquisition).

Table 63 gathers a collection of spatial planning policy mechanisms for energy conservation and climate change mitigation from a set of key sources: Seto *et al*. (2014)[1], Silva and Acheampong (2015)[2], Rode and Burdett (2011)[3], Grazi and van den Bergh (2008)[4] and Talen (2012)[5]. The literature provides some evidence on their implementation success (discussed in subsection 7.3.1.). Accordingly, Table 63 is coded in different colours. The mechanisms that have evidenced only positive effects are highlighted in green. In yellow are those that have been evaluated, but for which there isn't a clear understanding of their impacts due to diverging perspectives found in the literature. They may have been successful in some cases and unsuccessfully implemented in others. Finally, black corresponds to mechanisms for which no considerations on their impact has been found. No mechanisms with categorical or proven negative effects only have been found.

The evaluation of policy mechanisms is not always a straightforward task. Specifically, in the case of spatial planning policies, the evaluation of the policy mechanisms (also referred to as policy implementation research) may be included within the broader field of evaluation in planning (for further reading see for instance, Talen (1996) and Oliveira and Pinho (2011)).

Two types of evaluation can be considered. While instrumental techniques ground on performance indicators targeted at measuring different sorts of policy outcomes (e.g. energy savings or reduction of GHG emissions) or public spending, interpretative approaches are mostly concerned with the impacts on the communities (Murtagh, 2001). Table 63 considers both types of evaluation.

Each of the policy mechanisms is briefly described in the paragraphs that follow, along with some remarks on their implementation success, in case such information was found. According to Grubler et al. (2012), many of these policy mechanisms are applicable to cities in both developed and developing countries, although their implementation degree may vary.

Table 63. A collection of spatial planning policy mechanisms for climate change mitigation

Implement. Scale	A. Regulatory (command and control)	B. Financial		C. Market-based (pricing or agent-based)	D. Government-based
		Taxes & fees	Incentives		
National	Emission standards[3,4]	(differential) Fuel taxes[3,4]		Carbon pricing	License plate auctioning[3]
National	Quota on vehicle registration [1]	Emission taxes per vehicle[4]		Differential vehicle tax[4]	
Metropolitan / Urban	Development moratoria[2] /Growth-phasing[2]	Sprawl taxes[1]	Targeted subsidies for retrofit. or green projects[3]	Joint ventures[1]	Purchasing pools[3]
Metropolitan / Urban	Development restrictions (UGB, USB)[1,2,3]	Tax-bases sharing[1]			
Metropolitan / Urban	Greenbelts[1, 2]				
Metropolitan / Urban	Affordable housing mandates[1]				
Corridor	-	Impact fees[1,2]			Urban rail, BRT[1,3,4]
District / Neighbourhood	Density rules[3,4,5]	Property tax[2]	Brownfield redevelopment incentives[2]	Road user charges[1,3,4]	Special planning powers[3]
District / Neighbourhood	Zoning [1,2,3,4,5]	Split-rate property tax[1,2]	Historic rehabilitation tax credits[2]	Zone toll[1,4]	Redevelopment districts[1]
District / Neighbourhood	Subdivision regulations[5]	Land value tax[2,4]	Density bonus[3]	HOT[6]	Green space[1]
District / Neighbourhood	Small lot designations[1]	Real estate transfer tax[2] /Capital gains tax[2]	Location-efficient mortgages[2]	Joint development[1,2]	Car-free developments[3]
District / Neighbourhood	Use rules[1,4,5]	Land development taxes [2,3]	Conservation easements[2]	Transfer of Development Rights[2]	
District / Neighbourhood	Zone capacity / Road entry restrictions[1,4]	Dedications[2]	Use-Value Tax Assessment[2]		
District / Neighbourhood	Speed limits[3,4]	Linkage fees[2]	TIF[2]		
District / Neighbourhood			Land auctioning[3]		
District / Neighbourhood			Special Improvement Districts[1]		
Street / urban block	Design codes[1,5] / design standards[1]	Special Assessment tax[2]/ Benefit assessment[1]		Parking (sur)charges[1,3,4]	Sidewalks[1], pedest.facilit.[1], bike infrast.[1], P&R, GI[1]
Street / urban block	Building codes[1,5]			Design competitions[1]	
Street / urban block	Parking standards[3,5] / location[4]				

Key: Green – Evaluated. Positive effects; Yellow – Evaluated. Controversial effects; Black – Not evaluated.

[1] Seto et al. (2014), [2] Silva and Acheampong (2015), [3] Rode and Burdett (2011), [4] Grazi and van den Bergh (2008) and [5] Talen (2012).

Adapted from Seto et al. (2014)

7.3.1. Description of the spatial planning mechanisms

Metropolitan/ Urban Scale

A. Regulatory

Development moratoria denies or caps new development in specified areas, often based on specific criteria, such as minimum service levels for certain amenities. It may be an adequate mechanism for regulating fast growing communities (Silva and Acheampong, 2015). Bento *et al*. (2007) claim that moratorium regulations have been successfully limiting growth within a couple of years after being enacted (in Maryland, USA). Conversely, Turnbull (2004) claims that future development moratoria may have distortive effects, such as speeding the pace of development in different property types. In this case, local governments may have an important role, related to licensing and permitting and to tackling market speculation.

Limits to growth may also be achieved through rate of growth controls, setting limits to the issuance of building permits, or growth-phasing regulations also setting limits to growth, but in a coordinated time schedule in relation of the provision of public facilities or infrastructure (Bengston *et al*., 2004, Cervero, 1989).

Development restrictions, such as urban growth boundaries (UGB) and urban service boundaries (USB) are targeted at urban containment. Both UGB and USB consist of boundary lines to growth, whereas the in the case of USB, the boundary is set depending on the access to specific infrastructure services (Silva and Acheampong, 2015). Still, there seems to be no agreement with regard to their effectiveness in preventing urban sprawl (Jun, 2004). According to Dawkins and Nelson (2002), urban developers do not always respond to higher land prices by increasing density. In cases where regulations don't allow higher density thresholds, UGBs may even result in lower densities.

Greenbelts are buffers of green spaces around urban areas, aiming at containing the urban development within their boundaries, which have been extensively used across the globe (Silva and Acheampong, 2015). Nevertheless, their efficacy is not consensual. They have been criticized due to the lack of empirical evidence on their efficacy in maintaining compact urban forms (Siedentop et al., 2016), and because they have been argued to promote higher land prices (Dawkins and Nelson, 2002) and thus a leapfrogging effect extending the development to outer areas beyond the belt (Vyn, 2012).

Affordable housing mandates are directives imposing the creation of housing within certain price limits. These may be a way of promoting densities, since constructors tend to split fixed land costs by more housing units (Cervero, 1989). Conversely to urban containment policies, which tend to increase land prices, higher densities, usually decrease housing prices. The development of new office areas is also a good opportunity to negotiate affordable housing with project developers, as a way to bring people close to their jobs (Aurand, 2010).

B. Financial

Sprawl taxes are special taxes upon development of land outside specified areas. These are advocated to be effective in tackling scattered development patterns (Brueckner, 2000; Bento et al., 2006). Urban sprawl is claimed to originate from market failures in accounting for the social costs of sprawl, notably considering open space uptake, congestion and infrastructure development costs. Development taxes may be a solution for internalizing the negative impacts of sprawl.

Tax-bases sharing consists of the ability from communities within a given metropolitan administrative unit to share the tax base of commercial-industrial development, so that the competition between these areas gets reduced (Martin and Schmidt, 1983). It has been suggested as a way to split the benefits of new development, regardless of where the growth occurs (Hunt, 1987). Although this makes sense in theory, it has been argued that such policies haven't been effective, mostly because communities are able to freely decide their individual tax rates, keeping competition issues on the play.

Targeted subsidies for retrofitting or green projects are incentives for projects with improved energy and environmental performance, which are becoming popular worldwide. Green retrofitting may significantly reduce GHG emissions at a relatively low cost and high uptake rates (Jagarajan et al., 2017). Although these may represent a good incentive for more efficient standards (for instance the EU JESSICA fund), they have also been criticized, notably in the presence of large upfront investments (not accessible to the common citizen's pockets) and due to the transfer of the retrofitting costs to taxpayers (Trencher et al., 2016).

C. Market-based

Joint ventures between public and private bodies are frequently found in redevelopment or infrastructure projects. They have been advocated to be provide a flexible and efficient alternative for local powers to use their resources, taking advantage of skills lacking in the public sector, and to reduce financial risk. A downside is the difficulty of keeping track of project performance (Sagalyn, 2007). Although there is no guarantee of success, it is advocated that they typically lead to more successful projects than concessionary arrangements.

D. Government-based

Purchasing pools is a mechanism under which cities can get more efficient uptake costs for different types of public investment (Rode and Burdett, 2011). This drives local governments to work together in order to purchase goods and services at lower costs. A good application of this mechanism in the Portuguese context could be the investment in bike-sharing systems and bike infrastructure that could be leveraged at metropolitan level.

Corridor Scale

B. Financial

Impact fees are exactions applied to land developers aiming at collecting revenues to pay for the impacts of growth, notably related to infrastructure and public facilities. These are common practice in many countries (Silva and Acheampong, 2015). One advantage is the shift of the cost burden of growth from existing taxpayers to developers and/or newcomers (Evans-Cowley, 2006). Impact fees may be used to encourage more efficient land use patterns, in the sense that higher fees may be charged in non-serviced areas and vice-versa (Bengston et al., 2004).

D. Government-based

Urban rail / Bus Rapid Transit are examples of investments in public transport infrastructure. This is considered a mechanism *per se*, used by governments to shape urban form (Suzuki et al., 2013). A renowned example is the Curitiba system, reinforced together with local government mandates for all medium to large-scale developments to be located along a Bus Rapid Transit (BRT) corridor (Seto et al., 2014). Despite successful implementations of BRT (Curitiba, Bogotá, Guangzhou…), developed countries seem to have a preference for rail systems (Hidalgo and Gutiérrez, 2013). Still, heavy rail systems can cost *circa* 10 times more and light rail up to 4 times more than BRT (Suzuki et al., 2013). BRT projects have been successful in reducing urban congestion (e.g. Bogotá, Lagos, Guangzhou, Johannesburg, and Curitiba) (Seto et al., 2014).

District / Neighbourhood Scale

A. Regulatory

Density rules are rules targeted at controlling minimum and / or maximum allowed densities in a given urban area. These may refer to the number of dwellings, the floor area on a parcel, and often to the building height/ number of floors. Height rules may be based on factors such as the street width and the zoning district (Talen, 2012). While maximum building heights (caps) may improve light exposure, they are more likely to promote dispersed urban patterns (Brueckner and Sridhar, 2012). Setting minimum values for heights is expected to promote more compact patterns (Talen, 2012).

Zoning is a frequent mechanism to control building types and uses in specific areas of the city. According to Talen (2012), zoning translates into "building codes adapted to location. (…) Under zoning, one area of the city was allowed to be denser, taller, and more diverse while another area was required to be sparsely populated and more homogeneous." As zoning policies often have this intrinsic nature of regulating the type and height of a building, they may also be a way of limiting urban growth.

Silva and Acheampong (2015) differentiate three types of zoning to promote compact urban areas: up-zoning (increasing densities), Minimum density zoning (sets minimum limits to building heights or floor areas), and mixed-use zoning focuses on mixing urban functions, instead of the single-use zoning often found in the US (Seto et al., 2014).

Subdivision regulations consist of establishing limits to the subdivision of land, i.e. to the number of plots or urban parcels. According to Talen (2012, pp9), this mechanism aims at producing "striking economies and land-use efficiencies". Also, the author claims that subdivision regulations, along with zoning have been the most obvious rule types in the control of pattern, use, and form of cities (Talen, 2012, pp13). This is related to the rules for plot size dealt with below.

Small lot designations are mentioned by Seto et al. (2014) as a way to promote urban regeneration, possibly because it may bring more residents to the area designated. Small lot designations should define maximum lot size, instead of minimums. Nonetheless, Talen (2012, pp.49) refers to a drawback of this mechanism. In Chicago, lot size rules had been adapted in order to respond to market pressures and individual preferences. In this case, the market had higher demand for larger lots, and so rules had allowed for increased lot sizes.

Use rules may be included in zoning, as it is common practice since the beginning of the twentieth century (Talen, 2012, pp.90). Nevertheless, because zoning is a broader concept, land uses will be explored in separate. Generally, land uses are part of local development plans, which are strategic mechanisms. These plans typically contain maximum and minimum amounts of land uses (e.g. maximum/minimum residential floor area) (Silva and Acheampong, 2015).

Use restrictions are also frequent, especially in the US. Although they may have positive effects (e.g. Phoenix, AZ) in preventing the adjacency of "incompatible" land uses (Talen, 2012, pp.62), the opposite also happens, i.e. use restrictions may prevent a beneficial mix of uses (e.g. Urbana, IL prohibits the combination of multifamily housing and commercial areas). Use restrictions are not frequently applied in Europe, whereas mixed uses tend to be encouraged (Seto et al., 2014).

Zone capacity restrictions is a mechanism limiting the access of certain types of vehicles to specific city zones, typically urban centres. The access may be limited due to vehicle size (e.g. trucks) or emissions intensity (e.g. prohibiting the circulation of vehicles older than a given year – Figure 138) (Grazi and van den Bergh, 2008). In addition, restrictions may refer to entering specific roads or streets instead of a zone (Seto et al., 2014). Circulation restrictions may apply to non-residents, or to all vehicles in the case of creating pedestrian areas, as a traffic calming intervention.

Figure 138. Zone restriction to the access of pre Euro 3 vehicles in specific day hours. Lisbon.

Speed limits establish maximum allowed speeds at which vehicles can circulate. Lower speeds may not only reduce emissions, but also noise. This can be applied at large in urban centres, residential neighbourhoods, or individual streets with specific morphologic characteristics. Figure 139 shows a speed limit sign (city of Porto) in a narrow urban street surrounded by tall buildings (which could easily trap air pollutants). This is combined with a particular design of the road infrastructure (similar to the sidewalks) aiming at discouraging road traffic (traffic calming) in the street (one can see a pedestrian walking along the road, instead of using the sidewalk).

Figure 139. Traffic sign enforcing a speed limit in a canyon street. Porto.

B. Financial

Property taxes are a type of tax typically collected for the property ensemble, including the land, the building and real estate improvements (Silva and Acheampong, 2015). These constitute important public revenues worldwide, although more popular in richer OECD countries (Bird and Slack, 2002). One of the reasons pointed for their effectiveness is that real property is immovable, i.e. it cannot change location to avoid or seek lower taxation schemes. On the other hand, land value taxes are levied upon the land only, excluding the value of the building and improvements.

Alternatively, split-rate property taxes are levied differently on land and built structures, usually with a higher rate on the value of the land (Seto et al., 2014). These are advocated to promote compact urban patterns, promoting higher development intensities (Seto et al., 2014) as well as encouraging redevelopment by penalizing vacant lots (Silva and Acheampong, 2015). Figure 140 shows a journal news with a similar taxation scheme, penalizing landlords of abandoned and decaying buildings (with a 3-fold increase). Although this taxation type has been increasingly used (Grazi and van den Bergh, 2008), with successful implementation examples (Somanathan et al., 2014),Silva and Acheampong (2015) claim that it may lead to premature land conversion. Property-based taxes are often changed, due to three main reasons: i) to increase the simplicity of the tax system, ii) to raise more revenues from property taxes, or iii) to remove inequities in the system (Bird and Slack, 2002).

Prédios devolutos vão pagar IMI a triplicar em 20 municípios

Entre as autarquias que vão aplicar a taxa de IMI a triplicar estão Lisboa, Porto, Cascais, Sintra ou Almada.

PÚBLICO · 19 de Dezembro de 2016, 7:24

EVR ENRIC VIVES-RUBIO

São vinte as câmaras municipais que vão aplicar, em 2017, a taxa de Imposto Municipal sobre Imóveis (IMI) a triplicar para as casas ou prédios abandonados, vazios ou em ruínas, entre as quais Lisboa, Porto, Cascais, Sintra ou Almada, noticia esta segunda-feira o *Diário de Notícias/Dinheiro Vivo*.

Se por um lado, no próximo ano, nenhum município vai aumentar a taxa de IMI, no caso dos chamados imóveis devolutos o objectivo é aumentar em três vezes a taxa aplicada para fomentar a colocação destas casas no mercado e a sua reabilitação.

Segundo o *Diário de Notícias/Dinheiro Vivo*, esta é uma possibilidade que está já prevista no Código do IMI, mas este ano acrescentou-se a obrigatoriedade de as empresas fornecedoras de electricidade, água e gás informarem as autarquias daqueles imóveis sem contratos de fornecimento ou com níveis de consumo muito baixos. Com esta informação, as câmaras podem solicitar, junto do fisco, a aplicação do IMI a triplicar.

Figure 140. News of a property tax aiming at penalizing owners of decaying buildings – to be applied in Lisbon and Porto

Source: Jornal Público (December 19th, 2016).

Real estate transfer taxes are levied upon the transfer of property ownership. The rates typically depend on the property type (e.g. urban or rural) and on its value (for the Portuguese case see PricewaterhouseCoopers, 2015). Similarly, the Capital Gains Tax is collected for the profit of an economic transaction, whenever a good has increased in value. This tax is levied specifically for the monetary gain, instead of the overall transaction value (Gov UK). Tian (2014) refers to the "land capital gains tax" introduced in 1994 in China, to calm down the real estate market and capture surplus land value. This mechanism helps avoiding market speculation, whereas a temporary exemption, as the author states, may promote the resale market.

Land development taxes are levied on the release of new land to be developed. They are targeted at intensifying land use and may contribute to financing new green infrastructure (Rode and Burdett, 2011). In a similar sense, Silva and Acheampong (2015) refer to development exactions as a burden for developers, placed by local authorities, often constituting a prerequisite for land development. Their goal is to make urban growth financing new or improved public facilities. Here, key aspects to account for are equity issues and the destination of the revenues (Evans-Cowley, 2006). These may also be called subdivision exactions (Pavelko, 1983).

Dedications are a policy mechanism under which developers are required to donate a portion of land for public use or to create public facilities (Silva and Acheampong, 2015). Dedications may also be seen as a type of exaction (Pavelko, 1983), being the least controversial type. They are often used to create public infrastructure, such as sidewalks and roads, but may also be used to create schools, public open space and parks. The author claims that this mechanism benefits all the parties: developers, the future residents and the community.

Linkage fees are used to collect funds to pay for the impacts of large scale urban developments (commercial, industrial of multifamily projects), especially in places where the cost of housing is fairly high. This fee is typically used to finance social projects and services, such as affordable housing, day care services and the creation of jobs, and is based on the assumption that people working on new developments need to afford housing nearby (Evans-Cowley, 2006).

Incentives for brownfield redevelopment, aim at promoting new development in abandoned or degraded areas (often suffering from environmental contamination). In fact, the incentive may have a diverse nature. However, the literature tends to consider this as an independent category. It often takes place in inner city districts, preventing development in greenfield sites. Brownfield development has been credited for several benefits (environmental protection, urban revitalization, and compact development, and liveable communities), although some barriers to their uptake may be identified: legal liability for contamination; uncertain clean-up standards; availability of funding for redevelopment (including demolition costs and the expensive land prices in urban cores); and complicated regulatory requirements (McCarthy, 2002). Investment in these areas requires incentives from local governments, such as changing decontamination liability (Page and Rabinowitz, 1994), providing technical support for environmental remediation, or funding and promoting strategic partnerships with banks and insurance agencies.

Historic Rehabilitation Tax Credits are incentives for the conservation and rehabilitation of historic areas, under which owners see a portion of their investment compensated by a reduction on the tax due. Alternatively, deductions constitute a net reduction on the overall taxable value, as the developer may declare the investment amount to deduct tax obligations (McCleary, 2005). Successful examples on the application of this policy mechanism are given in Serageldin et al. (2001) for Brazil and the Netherlands.

Density bonuses are incentives for developers, allowing to build higher or increasing floor areas, in return of an interest condition, such as creating affordable housing or commerce and service areas (Rubin and Seneca, 1991). Cervero (2013) claims that density bonuses in Curitiba have supported mixed-use development, while Talen (2012) points out that density bonuses under the 1957 Chicago law have promoted islands of tall buildings around public plazas. Seto et al. (2014) argue that this mechanism has the drawback of allowing individuals with density preferences to relocate accordingly.

Location-efficient mortgages (LEM), as defined by Blackman and Krupnick (2001) "*allow families who want to live in densely populated, transit-rich communities to obtain a larger mortgage with a smaller down payment than traditional underwriting guidelines allow*". Attractive mortgages may provide an enabling environment for a desired relocation process of housing from lower-income residents. Despite some positive implementation cases, it may have some perverse effects, such as the fact that new residents may be unaware of the LEM purpose, and keep long commuting distances (Krizek, 2005), as well as higher estimated auto costs (Blackman and Krupnick, 2001).

A conservation easement is a legal agreement between a property holder and a conservation institution or a local authority to protect a property for land preservation (Gustanski and Squires, 2000). It may be permanent or temporary. The owner may receive financial benefits for complying with some use or maintenance restrictions, while keeping the property rights. According to Bengston et al. (2004), these policy mechanisms should be used together with additional ones, such as zoning, so that adjacent areas don't become too attractive for development.

Use-value tax assessment constitutes an incentive for landowners to maintain agricultural uses in urban and peri-urban areas. This is done by attributing a value to the land, for taxation purposes, considering its present use, instead of the full market value that could reflect the land development potential (Anderson and Griffing, 2000). As a result, agricultural uses are subject to lower taxation schemes which is thought to remove or attenuate the market pressure for urban development.

Tax increment financing (TIF) applies when local authorities want to perform a public improvement project, for which they should define an improvement zone (TIF zone), to be approved by a superior hierarchical body, in order to collect additional tax revenues from other fiscal jurisdictions, for the properties within the TIF zone (Brueckner, 2001). Properties earmarked in the TIF zone are typically subject to higher taxes under the premise that their value will grow faster than those of properties located outside the TIF zone. This is referred to as a way of implementing value capture (Seto et al., 2014). However, some empirical analysis has suggested the opposite (Dye and Merriman, 2000).

Land auctioning is suggested by Rode and Burdett (2011) as a way of limiting over-consumption of land through capping the release of new land to be developed. Community land auctions are considered an incentive tool for addressing housing shortfalls in a competitive way (Leunig, 2011).

Special Improvement Districts (SID) are created to generate funding to urban improvements, such as street paving or public space. Specifically, business improvement districts (BIDs) are a type of SID under a sophisticated form of stakeholder-based public realm management scheme (De Magalhães, 2012).

C. Market-based

Road charges and Zone tolls are both considered congestion charges. The first, involves paying a fee for the use of busy roads, for instance during peak hours. The second, charges the access to specific urban areas, usually central city districts (Grazi and van den Bergh, 2008). Charges may be paid by entering a pre-specified area or based on the distance travelled within such area (OECD, 2010). Either way, this mechanism involves managing traffic demand and adjusting vehicle levels by charging the use of private vehicles (Rode and Burdett, 2011).

In the short-term, congestion pricing may lead to spill-over effects to times or areas with lower travel costs (Guo et al., 2011). In the long-term, however, relocation choices by households and firms are effected. The authors claim that congestion pricing should be complementary, rather than substitutive to land use planning, as the greatest reductions in VMT by congestion pricing were found in dense and mixed use neighbourhoods. Two main critiques are pointed to this mechanism: i) outcome uncertainty (users may eventually be paying for congestion), and ii) unfair redistributive aspects. Still, congestion charges have been successfully implemented. A renowned example is the one from London (congestion charging scheme – CCS), in spite of its large running costs (Jansson, 2010). GHG emissions between the year before the CCS (2002) and after the CCS (2003) decreased by 19.5% (Beevers and Carslaw, 2005). Another example is the one from Stockholm's electronic road pricing (ERP) introduced in 2004, with a 13% cut (OECD, 2010).

High Occupancy Vehicle (HOV) lanes are highway lanes in which only vehicles with a minimum number of passengers (usually 2-3 people) are allowed to circulate. This mechanism was intended to promote carpools, however, it has proven to be ineffective in some regions of the globe, like the US. In this case, it is being replaced by High Occupancy Toll (HOT) lanes, where vehicles with a small number of passengers may travel if they pay a toll (OECD, 2010).

Joint development is considered a value-capture mechanism (Seto et al., 2014). Focusing on the transport sector, Cervero (1994) describes it as "*any formal, legally binding arrangement between a public entity and a private individual or organization that involves either private-sector payments to the public entity or private-sector sharing of capital or operating costs, in mutual recognition of the enhanced real estate development potential or higher land values created by the siting of a public transit facility*". The author presents this as a strategy to help financing new metro stations.

Cervero and Murakami (2008) point out the "Rail + Property" model in Hong Kong. Here, there was no direct investment by the government, but instead, a land grant was given to the transport company, who capitalized it by developing the properties adjacent to the rail stations. In this case, property development represents the largest share of revenue of the transport company, whereas rail ridership has significantly increased.

Transfer of Development Rights (TDR) enables the voluntary transfer of development rights from places where development should be prevented in order to preserve resources (such as historical neighbourhoods, and green areas) to places where the development is desired (e.g. around public transport nodes) (Seto et al., 2014). There are several examples of successful implementation of TDR. Pruetz and Standridge (2008) identify success factors of implementation, including demand for bonus development in receiving areas, and customized receiving areas to work within the physical, political and market characteristics of the community. Additional important factors are the presence of additional market incentives and regulations that limit development in "sending" sites. Tavares (2005) claims that TDR is a low cost technique but requires significant administrative capacity. He identified potential to implement this US-borne mechanism in Europe and found that TDR is more consensual than traditional command and control mechanisms.

D. Government-based

Special planning powers consist of creating urban development institutions or urban regeneration companies with some decision autonomy, to enable and to foster green projects (Rode and Burdett, 2011).

Redevelopment districts are designated districts where urban redevelopment is to be prioritized. Interesting examples promoting new urbanism principles are found in Belize, Jamaica, Bhutan, and South Africa (Seto et al., 2014).

Increasing green space and carbon sinks is proposed by Seto et al. (2014) as a land management mechanism. Since local governments typically own land, they are in privileged position to increase green areas. Whereas the benefits of green spaces on energy demand have been discussed earlier (Chapter 2), Seto et al. (2014) mention additional co-benefits on property values, water cycle regulation, biodiversity, and well-being.

Car-free developments refer to urban areas where private-vehicle circulation is discouraged (all plans known to date seem to be either voluntary or impermanent, often limited to specific time periods). Goodwin et al. (1998) found that in spite of short-term disturbances in neighbouring areas, the simple reduction of road space enabled to achieve traffic reductions of up to 25%. Several cities worldwide have announced car-free plans, whether referring to specific urban zones, mostly urban centres (e.g. Hamburg, Oslo, Helsinki, and Madrid) or car-free days with visible reductions on pollution levels, in the case of Paris (Nieuwenhuijsen and Khreis, 2016). Lower scale initiatives have been tested as early as 1972 in two districts in Stockholm (Brambilla and Longo, 1977).

Despite car-free areas are considered *per se* a policy mechanism (Seto et al., 2014), they may require additional incentives combined into an ensemble policy package (Cathcart-Keays, 2015). In this sense, Rode and Burdett (2011) refer to car-free developments as areas of high density and public transport density, while Nieuwenhuijsen and Khreis (2016), claim that public transport availability, provision of cycling infrastructure, green space and safe and pleasant pedestrian areas is being packed into plans for car restrictions, with effective results.

Street / urban block scale

A. Regulatory

Design codes and design standards are often employed with similar meanings. Both include a set of rules aimed at shaping not only the type of buildings existing in a certain area or in a whole city, but also street patterns and the characteristics of the public realm. Thus, codes have the power to create (or not) coherent portions of urban fabric. In the case codes are specific to a designated area, they are the same as zoning (Talen, 2012). She points out that codes may apply to a diversity of urban design elements: building location and setback, street width, sidewalks, parking, trees…

Although design codes and standards typically aim at solving specific urban issues like promoting pedestrian environments (Seto et al., 2014), some ironies may be found. For instance, in Baltimore, rules promoted the existence of open space around buildings for health reasons, and now compact urban form is the “new” healthy (Talen, 2012). Still, this is due to a change in preferences, instead of a failure of the mechanism itself.

Building codes are also worth mentioning, although its understanding may vary. Building codes, referring to building design, can be seen as a type of design code influencing building form and consequently the arrangement of built structures in a given urban area, as seen above. This is what Talen (2012) refers to, when she states that building codes affect urban patterns. In other cases, building codes may refer to the energy performance of buildings (Seto et al., 2014). These often concern specific building design elements, such as insulation materials, that affect overall building energy demand, as well as requirements for the generation of renewable energy on-site (OECD, 2010). In this context, building codes are usually enforced by additional mechanisms, such as labelling or certification programs.

Parking standards and parking location rules can be considered a type of design code, although parking codes are often dealt with in separate due to their specific effect in traffic patterns. A striking example is the definition of minimum or maximum levels for parking provisions depending on the existing land uses, or the zone considered. Talen (2012, pp3) gives examples of rules that may help tackling the negative effects of parking. These include prohibition of creating parking between buildings and on-street, parking maximums, limits on parking size, and shared parking credits.

Parking rules are a mobility management mechanism, accredited to significantly affect the use of private vehicles (Asian Development Bank, 2011). Excessive suburban parking supply has been promoting urban sprawl and the use of private cars (Willson, 1995). Conversely, suburban parking close to public transport nodes is advocated to promote sustainable commuting (Asian Development Bank, 2011). An interesting example is the one from London, which changed from a minimum off-street parking policy to a maximum-oriented one in 2004. Parking supply was reduced by around 40% (Guo and Ren, 2013).

B. Financial

A special assessment tax, or benefit assessment value capture mechanism (Seto et al., 2014), defined by Silva and Acheampong (2015) as a tax collected from property owners in special circumstances, i.e. when there is a benefit from an improvement in public facilities, such as public transportation services, or pavement improvements in sidewalks. It usually applies to lower scales, i.e. confined areas, lower than the district scale. It may be generally called a value capture tax, applicable when a property value increases due to public infrastructure development. They can be imposed or set under agreement, and be charged either by an annual regime or as a one-time tax (OECD, 2010).

C. Market-based

Parking (sur)charges or tariffs are targeted at reducing parking demand, and thus the use of private vehicles (Rode and Burdett, 2011). There are different strategies for addressing parking charges, including increasing hourly prices, limiting allowed parking time, and tariff differentiation between residents and non-residents (Grazi and van den Bergh, 2008).

According to OECD (2010), parking charges have successfully decreased car trips – e.g. a 20% reduction of car trips in Ottawa and a 38% increase of carpooling in Portland. Similarly, parking surcharges represent aggravations in already existing parking charges, for specific reasons, such as parking in peak-hours, or in congested areas (OECD, 2010).

Design competitions are usually public tenders for the development of a project. These are advocated to promote higher-quality and more efficient urban projects (Ratcliffe et al., 2004). The Greenwich Millennium Village is a successful example (mixed use and transit-prone) resulting from an international competition for the development of a brownfield site (Foletta, 2011). The evaluation of tenders should not only consider the achievement of short-term goals, but mostly long-term project accomplishments (Zheng, 2010).

D. Government-based

Pedestrian facilities (e.g. sidewalks), bike infrastructure, Park & Ride, and green infrastructure are design elements targeted at reducing urban traffic, whose development may be seen as a policy mechanism in itself (Seto et al., 2014). These facilities (with the exception of P&R) are typically implemented by local governments, often representing important public investment works.

The review performed collects and systematizes the most important spatial planning policy mechanisms. Although it may not be exhaustive, it highlights the variety of policy mechanisms across different scales of implementation (from metropolitan to the urban block). Their selection may differ according to the policy goal, or with the contextual governance conditions. The next section identifies the strengths and weaknesses of the policy mechanism categories considered, and draws on Table 63, selecting applicable and endorsed mechanisms to meet the sensible urban alternatives identified in Chapter 6.

7.4. Selection of a package of policy mechanisms

7.4.1. Strengths and weaknesses of the categories of policy mechanisms

The previous section presented and described spatial planning policy mechanisms for energy conservation and climate change mitigation. The array of mechanisms collected are categorised into four main types (regulatory, financial, market-based and government-based).

Although their individual effectiveness may depend on the particularities of the urban area at stake, it is possible to draw some overall considerations on their strengths and weaknesses, depending on the category to which they belong (Table 64). The paragraphs that follow briefly discuss the differences among these four categories and their potential outcomes. This is expected to contribute to facilitate decision-making.

Table 64. Strengths and weaknesses of the different categories of policy mechanisms

Policy Mechanism		Strengths	Weaknesses
A. Regulatory (command and control)		- Low cost (Seto et al., 2014) - Usually effective	- Lower flexibility than incentive-based approaches (Somanathan et al., 2014) - Difficult implementation in cases of lack of devolved authority or appropriate responsibility (OECD, 2010) - Regulations may have side effects on markets (e.g. urban containment policies may lead to the inflation of housing market) (Dawkins and Nelson, 2002) - Regulations affecting prices may also lead to a rebound effect (Somanathan et al., 2014)
B. Financial	**Taxes & Fees**	- Generation of public revenues that may be earmarked for special purposes (OECD, 2010) - Creates price signals for increased efficiency, especially if paid according to different use levels (OECD, 2010) - Simplicity and broad scope (Somanathan et al., 2014) - Consumers are usually price elastic, which makes them effective (Somanathan et al., 2014)	- Lack of awareness on the purpose of the tax leads to low acceptance (Somanathan et al., 2014) - Distributional effects may be "unfair", affecting mostly low income people (Grazi and van den Bergh, 2008)
	Incentives	- Are typically targeted at removing economic barriers, such as high investment costs or perceived financial risk. - Loans, subsidies and tax credits enable to share economic risks (World Energy Council, 2008) - Reduces market imbalances between more efficient solutions with higher costs, and less efficient but cheaper solutions (World Energy Council, 2008)	- Tax credits and deductions may have a poor performance in economies in recession or in transition (World Energy Council, 2008) - Lack of appropriate funding may be a problem (IEA, 2010) - May have distortive effects (OECD, 2010; (IEA, 2010). - Rebound effect (Somanathan et al., 2014) - Free ridership (Somanathan et al., 2014)
C. Market-based (pricing and agent-based)		- Pricing mechanisms enable internalizing negative externalities (OECD, 2010) - Consumers are usually price elastic, making pricing mechanisms effective (Somanathan et al., 2014) - Agent-based mechanisms like joint ventures and joint development are a way to share investment risk.	- Distributional effects of pricing mechanisms may be "unfair", affecting mostly low income people (Grazi and van den Bergh, 2008)
D. Government-based		- Avoids risks of lobbying and privileging private interests	- Public investment is typically high cost or has long term payback period (Seto et al., 2014) - Burdens public budgets - Local action may not reduce GHG emissions, but instead the cost of achieving GHG reductions (Somanathan et al., 2014) - Lack of transparent procurement practices may be an issue (Grubler et al., 2012).

The analysis of Table 64 reveals that the selection of a single type of policy mechanism is not a straightforward task. All of them have advantages and drawbacks. What seems to be consensual in literature is that a bundle of different types of complementary mechanisms is preferable and has greater impacts than using a single technique (Bengston et al., 2004; World Energy Council, 2008). It has been advocated, for instance, that regulations and government provision are complementary to pricing mechanisms, rather than substitutive (Guo et al., 2011) and that they work better together to remove barriers and to reducing social costs. Multiple policy mechanisms should, however, address different market failures, otherwise they would become redundant (Somanathan et al., 2014). The selection of strategy bundles should be adapted to the specific legal, political and cultural landscapes of the urban area that is being considered, and requires institutional capacity for implementation (Seto et al., 2014).

Specifically, some nuances with regard to a few mechanisms can be considered. While regulations appear to have many drawbacks, they are, without a doubt, necessary to control and manage urban areas (Talen, 2012). They also help removing barriers for energy efficiency, more specifically when firms and consumers have difficult access to information on energy investments or have split incentives (Somanathan et al., 2014). Also, because regulatory approaches entail some market-like features, the distinction between regulations and economic instruments is not so clear (Somanathan et al., 2014).

With regard to taxes, while their misuse may lead to distortions (e.g. the property tax may result in the inefficient urban expansion (OECD, 2010), they have been a widely used mechanism, maybe because they are also an important source of financing for local authorities. The existence of a transparent purpose for tax revenues, especially if used to fund energy efficient programs, is expected to help achieve higher levels of public acceptance (OECD, 2006; Somanathan et al., 2014). For instance, differential taxes (like a split-rate property tax) may be more effective in addressing this issue, as they enable targeting goods or services in different ways. Also, some design details may matter. Somanathan et al. (2014) claim that higher taxes that grow slowly are usually preferable to low taxes that rise very fast.

Incentives are also a financial mechanism, but instead of being “sticks” (punishment), they are considered “carrots” (motivations). Subsidies or tax credits are a common type of financial incentive. These, however, demand public funds, which is *per se* a disadvantage. There is also the issue of free-ridership in the presence of financial incentives, referring to individuals and organizations that use the incentives provided, but that would have behaved efficiently regardless of the existence of the incentive (Weinstein et al., 1989). Subsidies, particularly, may be suited for cases with high upfront costs and can be defined in different ways: fixed amount, as percentage of investment, or as a percentage of savings (World Energy Council, 2008). Also, the access to the subsidy may rely on a bureaucratic process or may not be well disseminated amongst target audiences (World Energy Council, 2008). Using loans and mortgages instead, may help removing the barrier of access to information.

Market-based instruments are targeted either at creating price signals for energy conservation (through charges) or, alternatively, at providing synergies between market agents (for instance through institutional arrangements) in order to foster investment in energy efficiency.

Finally, government-based incentives, through public investment, are a fundamental mechanism type anywhere in the globe, but they are dependent of the funding capacity of the governmental institution. Also, it has been claimed that although the action of local governments is fundamental to creating more efficient infrastructure, it has limited power to reduce GHG emissions *per se*. Instead, it reduces the cost of achieving GHG reductions (Somanathan et al., 2014).

7.4.2. Selection of suitable policy mechanisms for the implementation of the urban development alternatives

This subsection attempts to bridge the insights from the analytical and the strategic dimensions of this work. Table 65 matches the policy mechanisms from Table 63 to the set of four sensible urban development alternatives (TOD, GI, IN and MD) identified in subsection 7.1.2. Table 65 presents the mechanisms that apply to the implementation of each alternative based on whether it meets the alternative's principles and goals. Furthermore, a narrower set of endorsed mechanisms is proposed in Table 65 (highlighted in bold) according to three main criteria:

- Evidence of implementation success in other geographies (i.e. privileging those mechanisms in green in Table 63)
- The relevance of the mechanism's strengths and weaknesses (Table 64) in relation to the implementation context (Portugal).
- Keeping a certain diversity of mechanism types (regulatory, financial, market-based and government-based), which is a widely advocated practice in the literature.

Although it is acknowledged that the final selection of policy mechanisms into a final package belongs to the decision-makers according to their own preferences and criteria, the paragraphs that follow propose and discuss the choice of a narrower set of mechanisms, based on the authors' analysis of the literature reviewed, and based on the criteria above.

Table 65 provides no indication of the implementation degree of each mechanism outlined. For instance, when indicating that creating speed limits could be a suitable option (for instance, for traffic calming purposes in residential neighbourhoods), it is considered that the specification of the new speed limit is beyond the scope of this analysis. This decision should be tailored to each particular case, and is left for decision-makers.

Table 65. Selection of a package of applicable policy instruments to the urban development alternatives

Alternative / *Policy Instrument*	*Regulatory*	*Financial*		*Market-based*	*Government-based*
		Taxes and fees	**Incentives**		
TOD	- **Affordable housing mandates**; - Density rules; - Use rules setting min non-residential areas; - **Zoning**; - Building codes with min. building heights, - Design standards; - Parking standards - Road entry restrictions	- Tax-bases sharing; - Increase property tax in monofunctional areas; - Benefit assessment - Split-rate property taxes	- Location-efficient mortgages **- Tax credits for TOD densification projects**; - Free/special fare PT tickets for nearby residents	- **TDR;** - Joint development/ joint ventures; - **Zone toll**; - Road charges; - **Parking surcharges**	- P&R in peripheral city areas - Car-free developments - Sidewalks, pedestrian facilities, GI
IN	- Development moratoria for urban outskirts; - Affordable housing mandates; - Density rules; - **Subdivision regulat. / small lot designations;** - Design standards; - Zone capacity / road entry restrictions	**- Increasing land taxes for undeveloped lots (city centre)**; **- Increasing property taxes for abandoned buildings (city centre);** - Split-rate property taxes	- Location-efficient mortgages; - Conservation easements; - Targeted subsidies for retrofitting - **Historic rehab. tax credits** - Density bonuses for retrofitting developers; - TIF; **- Waiver of development taxes**	**- Joint redevelopment projects in strategic areas**; - TDR; - Parking surcharges	**- Redevelopment districts** - Special planning powers
GI	- **Design standards** setting min. green space densities, private green space per lot, and tree planting	**- Dedications**	**- Conservation easements;** - Subsidies for tree planting; - Special Improvements Districts around parks	- Joint development for rehab. of public space	**- Acquisition of car parking to create green spaces**; - Sidewalks, pedestrian facilities, GI
MD	**- Growth-phasing;** - Density rules; - Zoning; **- Building codes with min. building heights;** - Affordable housing mandates; **- Design standards;** - Parking standards; - Speed limits	- Subdivision exactions; - Reduced development taxes **- Split-rate property taxes**	- Location-efficient mortgages; - Land auctioning; - Density bonuses	- Joint development; - TDR; - Design competitions **- Parking (sur)charges**	- Special planning powers; - Car-free developments

NOTE: Mechanisms in **bold** refer to those selected for implementation in the Portuguese context.

Table 65 shows that each of the urban alternatives considered may be implemented resorting to a relatively small group of policy mechanisms. The paragraphs that follow present the rationale for their selection. According to Grubler et al. (2012), restrictive instruments should be combined with proactive ones (incentives). Also, "soft" mechanisms (like fees or tariffs) should be complemented by "hard" (i.e. infrastructural investment) ones.

In the case of TOD two regulatory mechanisms were selected. Affordable housing mandates have been advocated in the literature as an effective way of promoting densities. This allows counteracting the expected increase in housing prices in the vicinity of public transport, as a result of a higher demand in the real estate market. In addition, although zoning may be argued to have undesirable effects, these are dominantly caused by zoning targeted at the separation of urban activities, which is not the case here. In fact, zoning is one of the most widespread an important mechanisms in spatial planning (Talen, 2012). In the case of TOD, zoning would allow guiding development patterns towards desirable urban configurations in the areas at stake (nearby public transport). These are both low-cost enforcement options. In addition, financial incentives such as tax credits for TOD densification are proposed, along with parking surcharges and zone tolls, which would allow internalizing congestion externalities, while constituting a source of public revenues. Finally, TDR have evidenced successful implementation examples, and would allow a voluntary transfer of development rights. This is also a low-cost scheme, expected to yield a good acceptance.

With regard to the IN, because it takes place in urban areas that are already developed, it is expected that density rules and design standards are already established in such areas. Nevertheless, subdivision regulations and small lot designations (with maximum lot sizes), as advocated by Seto et al. (2014), may be an effective way of bringing more residents to a place. Additionally, increasing taxes for undeveloped land and abandoned properties in central urban areas of the city is expected to accelerate urban regeneration, while increasing public revenues. This, in fact, is under implementation in the case studies. In their turn, incentives like historic rehabilitation tax credits have proved successful outcomes, as well as development taxes (and in this case, their waiver). Finally, joint development solutions have been argued to effectively trigger private capital in projects of public interest, whereas the definition of redevelopment districts allows prioritizing areas for infill development and urban regeneration.

The development of green infrastructure, is typically dependent on public investment and initiative, unless some mechanisms are established for the creation and maintenance of green spaces and plantation of trees by private actors. As such, design standards comprising the creation of green areas in private and semi-private properties, as well as rules for tree planting could be a way of enforcing new green infrastructure. Additionally, as a type of exaction, dedications have been argued to work effectively and being widely accepted by inhabitants. These could be used to create new green space. Alternatively, conservation easements constitute good incentives to the maintenance of existing green areas of private domain. Under the scope of public investment, the acquisition and conversion of parking land into public green areas is a good example to promote the GI alternative.

The last alternative, modern development, was considered interesting only for the case study of Lisbon and, should be carefully considered in distinct urban contexts. Here, it is considered that modern development should not be subject to any particular financial incentives, because it is the least interesting alternative in terms of urban performance. Instead, regulations may represent an effective way of controlling the configuration of the new development. In order to prevent scattered development patterns, growth-phasing is expected to allow consolidating specific urban areas before initiating development in new ones. This mechanism has proven successful implementation in additional urban contexts. Also, it is common, in Portugal, to have maximum building heights while minimum figures are seldom existent in spatial plans. It is here deemed suitable to start including minimum building heights is urban areas that are aimed at being densified. Also, because modern development patterns are often criticized for being unattractive, design standards (including the specification of mixed land uses) would allow controlling for the spatial configuration of these urban areas. Additionally, the application of split-rate property taxes (with higher taxation indexes in land than in built structures) in areas to be consolidated is expected to encourage higher development densities, while creating public revenues. Finally, parking (sur)charges, are a restrictive mechanism to the use of private vehicles while allowing to internalize the negative impacts of their use.

The spatial planning mechanisms reviewed and selected are expected to promote improved urban energy performances. Energy conservation and climate change mitigation strategies typically bring about important co-benefits (Table 66). These co-benefits are also important drivers for the adoption of such strategies/actions (Somanathan et al., 2014), enlarging the scope of spatial planning decisions, and evidencing the relevance of promoting inter-sectorial institutional cooperation for policy-making.

Table 66. Potential co-benefits arising from energy conservation and climate change mitigation policies

Effect of mitigation policies on additional objectives or concerns		
Economic	**Social**	**Environmental**
Energy security	Health impact (air quality and noise)	Ecosystem impact
Employment impact	Energy / mobility access	Land-use competition
New business opportunity / economic activity	(Fuel) poverty alleviation	Water use / quality
Productivity / competitiveness	Food security	Biodiversity conservation
Technological spill-over / innovation	Impact on local conflicts	Urban heat island effect
	Safety / disaster resilience	Resource / material use impact
	Gender impact	

Source: Somanathan et al. (2014)

7.5. Synthesis

In a first instance, this chapter extended the analysis of the urban development alternatives to assessing their impacts on a set of additional criteria concerned with the overall urban cohesion, or the so-called *urban performance*. This analysis was based on an MCDA, involving different scorings and weights for the alternatives considered.

It enabled to grasp that although only a couple of efficient alternatives are common to both cities (TOD and GI), a set of four alternatives (TOD, GI, IN and MD) could be considered sensible urban development pathways, in both case studies (Table 61).

In a second instance, and before drawing on spatial planning policy mechanisms, the extent to which territorial and energy / climate change policies are connected was analysed, by reviewing a set of strategies at different governance levels. The analysis confirmed that the link between the physical structure of cities and energy demand is a frequent concern found in the international political landscape. However, it seems that there hasn't been an evident and structured follow up of these concerns at the local scale. Local-scale strategies are still lacking an evident compromise between territorial planning and energy conservation with an operational nature.

This reinforces the role of spatial planning policy mechanisms, as it is at the local scale that spatial planning strategies are typically enforced and adopted, and where local authorities have the capacity to take action. These policy mechanisms can be grouped into four main categories or types (regulatory, financial, market-based and government-based), all of which have strengths and weaknesses. It is widely agreed that adopting a bundle of different types of mechanisms usually leads to more successful results than resorting to a single type. Still, the choice belongs to decision-makers and may depend on the specificities of the local background (e.g. taxation schemes may be an issue in developing countries).

From the diversity of spatial planning mechanisms, it was possible to identify and to select a package in order to meet the goals of the urban development alternatives previously identified, which may also be combined in the case of the adoption of multiple strategies. This significantly reduces the spectrum of options available and may constitute a significant contribution to inform and target decision-makers' actions according to a selected urban development pathway.

CHAPTER 8. CONCLUSIONS

This research was geared towards the characterization of the effect of urban form on the energy needs for three relevant urban end uses (heating and cooling in buildings, and mobility). Aiming at assisting in the evaluation of the energy performance of future urban projects or plans, a decision-support tool was developed, for a comprehensive assessment of the energy demand resulting from the physical structure of the city. The research extended the state of the art by bringing together the two most relevant urban sectors (buildings and transport), by simultaneously considering a diversity of attributes and indicators of urban form, by being spatially-explicit, and by linking the physical analysis to a strategic dimension.

This last chapter presents the main insights drawn from the work developed, and is structured into three main sections. Section 8.1 summarizes the main conclusions of the research, presenting the insights obtained, in line with the research questions. Section 8.2 highlights the real-world implications and applications of the work developed, and illustrates relevant examples for the planning practice. Section 8.3 suggests possible developments for future research in the field.

8.1. Conclusions

Grounding on the hypothesis that there is a significant relationship between the physical form of a city and its energy performance, this research allowed building a model (both exploratory and predictive) for evaluating the energy performance of urban areas, resorting to the physical features of the built environment and transport networks. The model has the advantage of being spatially-explicit and multi-scale, in the sense that it allows analysing urban areas as a whole, and also considering its constituent parts (i.e. urban neighbourhoods, districts …) at a high-resolution level. Ultimately, such model is targeted at identifying more efficient development pathways, and contributing to achieving more sustainable urban areas.

In a first instance, this research *identified a set of energy-relevant urban attributes*, grounded on a comprehensive review of the body of research on urban form and energy demand (Chapter 2), which focused on the two main urban sectors: housing and mobility. The review confirmed that the influence of urban form takes place at different scales (the building, the block, the neighbourhood, and the whole city). In the case of housing, urban form determines building types (and surroundings) and the UHI effect, with an important influence on thermal needs (heating and cooling). In regard to transport, urban form influences modal choice, distances travelled, and trip frequency, with an impact on the overall energy needs for travel.

The literature review allowed to:

i) identify the energy-relevant urban attributes belonging to the built environment (*density, granularity, diversity, green areas, compactness, passivity, shading and orientation*) and transport networks (*accessibility, proximity to PT, centrality, and design*),
ii) identify where possible trade-offs between the built environment and transport may take place (Table 3),
iii) select a set of suitable indicators of urban form to be used in an energy-sensitive analysis (Table 4). This is expected to constitute a departing framework for a comprehensive quantitative evaluation of urban settings, which may be useful for planners and researchers.

It was possible to conclude that while micro attributes are most important in buildings (except for density), in the case of mobility, it is at the meso- to the macroscale (neighbourhood, district, and the city as a whole) that the effects of urban form are mostly felt.

The second issue that this research sought to shed some light on was the *suitability of different approaches or techniques to model the effect of a comprehensive set of urban form attributes on energy demand, altogether*. There are several methods and approaches for modelling urban energy demand, varying in complexity and detail, as well as in the incorporation of urban form factors. It was observed that engineering models are most frequently applied to model energy in buildings, whereas statistical models are common approaches to evaluate the effect of urban form on travel.

This research tested and compared different modelling techniques for characterizing the influence of urban form on the energy demand, both accounting for the overall effect and for the effect on specific end uses (heating and cooling in buildings, and travel). The techniques tested included a Multiple Linear Regression (MLR), Structural Equation Models (SEM), and Artificial Neural Networks (ANN). These were assessed under the framework of an application to two case studies, corresponding to two cities in Portugal (Porto and Lisbon). The application of these techniques grounded on a high-resolution spatial analysis to collect the relevant urban form indicators.

From the modelling options tested, ANN were considered the most suitable technique to model the research problem, returning better results than the remaining (MLR and SEM) approaches, which are closer to traditional statistics. It allowed to identify relationships of higher magnitudes, while delivering a higher accuracy, for the three energy end uses, and for both case studies (see Table 21 and Table 22, from Chapter 4, and Table 38 and Table 39 from Chapter 5). The results confirmed the existence of significant links between urban form and energy demand, supporting the relevance of addressing energy needs for buildings and mobility together.

On the methodological level, this research advanced the state of the art by offering a framework that extensively describes the urban environment, modelling a set of variables from the built environment and transport networks at the same time. This comprehensive approach, i.e. modelling buildings and transport together, has proven to be more accurate than considering them in separate (leading to lower errors and higher determination coefficients). It is also expected to provide a more realistic characterization of the effect of the urban form on energy demand, accounting for the diversity of variables involved and the complexity of urban areas. It combines the advantages of a high-resolution spatial analysis with the accuracy of a machine learning technique (constituting a pioneer application of machine learning to this field).

From the application of the methodological framework to the two case studies, it was possible to *estimate the relative weight of each urban form attribute, as well as the combined influence of urban form on energy demand* (presented in Figure 59 from Chapter 4, and Figure 95 from Chapter 5).

As expected, the overall effect of urban form varies between the two case studies. This may happen, for instance, due to a more prominent influence of other drivers of energy demand (e.g. behavioural or economic). Nevertheless, it is fair to say that urban form has a significant impact in determining the overall variability of the energy needs for the three end uses considered (between 56% and 78% for the geographies at stake).

The results confirm that the energy needs for cooling are consistently those least influenced by urban form, whereas heating and mobility needs are subject to a higher influence from the physical structure of the city (see Table 22 and Table 39 from Chapters 4 and 5, concerning the city of Porto and Lisbon, respectively).

The size of the effect of each urban form variable was also estimated, resorting to the weights from ANN models. Overall, there is some degree of similarity between the two case studies (Figure 100), although some differences may be found (e.g. the relative importance of the three density indicators is not the same). Typically, the macro attributes of urban form play a dominant role. This is in line with the literature, which has been placing a greater emphasis upon this type of attributes. Specifically, density, granularity, centrality and accessibility (instead of the mix of land uses *per se*) are those that matter the most. At a lower scale, it is interesting to note the prominence of the building compactness in determining the energy needs of the built environment. In addition, although the micro scale attributes (e.g. the spatial distribution of green areas, the presence of trees, or the nature of the sidewalks) hold the smallest weights, their role should not be neglected, as their combined effect is still significant (these three attributes together have a combined weight of *ca.* 15% in both case studies).

The complexity of the phenomena inherent to energy use in cities does not allow for a ready generalization of the specific contribution of the variables from one urban context to another. Still, the model works as a case-specific tool, that can be used to determine the right weights in different cities, and therefore to build a functional model in diverse geographies.

The ANN models developed (in Chapters 4 and 5) were also used to *assess the effect of changes in the urban form regarding the energy performance of the case studies, while simultaneously* *meeting additional urban goals/ interests.* This was done by envisioning a set of urban development pathways for the two cities analysed. Each pathway corresponded to the manifestation of an urban development alternative, from a total of six alternatives (infill development – IN, consolidated development – CD, modern development – MD, multi-family housing – MFH, transit-oriented development – TOD, and green infrastructure – GI). The models were, thus, used to estimate energy demand, given the new urban form indicators resulting from the new urban configurations envisioned.

Energy-wise, most of the potential energy savings from densification are related with mobility, especially in Porto (Table 50 to Table 57). The results suggest that planning for the location and the characteristics of future urban development generally leads to a better urban energy performance than random development patterns throughout the urban territory. Thus, planning for energy-sensible urban forms may play an important role in preventing cities to get locked-in unsustainable and inefficient energy use patterns.

Nevertheless, the preference for specific development options varies for different cities, and should be considered case by case. Privileging new development in the city centre works better for Porto than for Lisbon. Nevertheless, the greatest reductions in the energy needs refer to a transit-oriented development alternative (Table 53).

It was also found that, although urban form significantly explains the variability of energy needs, its impact on the overall energy demand has a more modest (but still important) magnitude. The changes considered in the urban form, all else being equal, may decrease the primary energy use by up to 15% for mobility, and significantly less for heating and cooling, with roughly 2-3% and 1%, respectively. It is expected that having included lower scale urban elements in the analysis would have retrieved significantly higher magnitudes, notably in the case of buildings.

Additionally, acknowledging that energy is not the single factor determining urban planning choices, the analysis was extended to including additional criteria, which were merged into a composite indicator, called urban performance. The analysis moved towards identifying the dominant alternatives, according to different scores and weights. Four development alternatives were considered efficient in combining energy with urban performance, considering the two case studies (see Table 61): Transit-oriented development (TOD), Green Infrastructure (GI), Infill Development (IN) and Modern Development (MD).

TOD is expected to bring about important reductions on the travel-related energy needs, while IN, in spite of its limited implementation potential, combines significant energy savings with additional benefits on the urban performance. In its turn, GI has small contributions related to energy demand, but its urban co-benefits turn it into an attractive option. Although MD has been subject to criticism in the urban planning literature, it has been identified as a suitable development option for the city of Lisbon, mainly due to its estimated energy performance.

After the identification of sensible urban development pathways, the current international political landscape, involving urban form and energy, was reviewed (Section 7.2.). This confirmed that the concerns involving the influence of the physical structure of cities on energy demand are largely denoted in international strategies and programs. Conversely, at the local scale, where the capacity to intervene gains effective expression, a clear compromise between territorial planning and energy conservation is still lacking.

Finally, in Section 7.3 the research proceeded towards the *identification and selection of the policy mechanisms to implement such changes.* A collection of spatial planning policy mechanisms was gathered from the literature, aiming at providing local authorities with a systematic set of enabling instruments in the pursuit of energy conservation and climate change mitigation in cities. Their strengths and weaknesses have also been identified.

Although the final choice belongs to the decision-makers, it was possible to select a set of mechanisms for the implementation of the most interesting urban development alternatives (Table 65) and to recommend a narrower number of mechanisms based on the existing evidence of successful implementation and on their strengths and weaknesses (Section 7.4.1.). This allows reducing the spectrum of options available and may constitute a significant contribution to inform decision-making.

8.2. Implications and applications of this research

The growing acknowledgment of the influence of urban form on energy demand sets urban planning as a relevant field for addressing the energy conservation, the climate change, and the sustainability agendas. Firstly, the identification and compilation of the attributes of urban form with energy relevance, as well as the selection of suitable metrics to quantify them, constitutes an important analysis framework for the planning activity, towards a more thoughtful and data-driven practice.

In addition, this research proposed a methodological framework that estimates the energy demand for three relevant end uses (heating and cooling in buildings, and transport), based on a comprehensive description of the physical characteristics of the urban area under analysis. This adds to the state of the art, since the models developed are expected to have contributed to further characterizing the influence of urban form on energy demand, in a comprehensive way. The fact that it simultaneously considers the three main energy end uses, enables to uncover and account for the existing trade-offs, opening new grounds to reshape our cities. Methodologically, it also pulls further the existing approaches exploring the urban form-energy link, as it offers a ground-breaking application of a machine learning technique to the field.

Under a practical perspective, this methodology has the potential to work as a decision-support tool, which is case specific, and able to assess and guide future development choices. It provides a new mean to incorporate energy, in a quantifiable way, as a criterion in the analysis of urban projects and plans. Because it uses data that is widely available in the initial stages of urban projects, it is most relevant for early stage decision-support in urban and energy planning. Once the model for a city is developed, it can provide insights on the energy performance of different development solutions in a relatively low data and time consuming process. This may result in practical and measurable impacts on the decisions that will impact the configuration and performance of cities for a long time span.

Specifically, the methodological framework holds important implications on the identification of the most relevant urban attributes to act upon, along with where the action is expected to have the greatest benefits (given by the spatially-explicit framework). It may, thus, contribute at a strategic level to the definition of (re)development priorities, and helping informing future development choices, through the assessment of how different options of urban development will likely impact energy demand.

Potential applications include a quantified comparison of development alternatives like “enabling future development to occur in district A” or “enabling future development to occur in district B” or “random development throughout the city”. In addition, by considering different attributes, it indicates whether and where the development should privilege residential and non-residential areas, or specific development configurations such as increasing building heights instead of building new ground area.

Finally, the identification of implementation mechanisms for sensible urban development alternatives is expected to provide operational support in the pursuit of urban development pathways for improved energy performance.

The tangible application of this research is the production of case-specific knowledge on the urban form-energy link, bridging it with informed, tailored and design-efficient development strategies, ultimately contributing to achieving more sustainable urban areas.

8.3. Future research

During this research process, and in particular during the application of the methodological framework to two real case studies, some aspects were identified that have room for improvement.

In the methodological front, there may be potential to improve the prediction of the energy needs by the models developed. For instance, in the case of heating and cooling, the models were fed by a vast source of real data, the building certification database. However, because the energy demand from the building certificates is also significantly influenced by factors unrelated to urban form (e.g. building age or materials), an improved method should be designed, if possible, allowing to filter spatial trends resulting from these features. An important opportunity lies on the improvement of data availability and quality at a high-resolution scale, especially concerning the characteristics of building construction and mobility.

An updated characterization of transport patterns at a disaggregate level of analysis is still largely absent, not only for the case studies considered, but broadly for European cities, at least.

This is key information not only under the perspective of the daily management of traffic flows in cities, but also in the support of robust research focusing on such an important sector to curb the current GHG emission levels. The existence of high quality data could significantly contribute to improve the accuracy of the ANN models developed. It would also be advantageous to have the time for a more sophisticated evaluation of the urban development alternatives, resorting to an in-depth MCDA based on scores reflecting real stakeholder's preferences.

In addition, a natural research pathway would be the application of the methodological framework to new case studies, with different demographic and socio-economic backgrounds. This would enable to further understanding the patterns and the role of different drivers of energy demand across different geographies. Exploring a collection of a larger number of cities would possibly enable findings patterns and classifying different cities according to their urban form – energy relationship, i.e. understanding how the role of urban form varies according to different levels of economic development or demographic conditions.

Furthermore, it is necessary to explore the potential of application of such a methodology in the developing world. Here, data availability or reliability may represent an important bottleneck. Still, given the fact that urbanization rates in developing countries are expected to significantly increase in the next decades, it would be of major relevance to be able to provide these cities with a tool that is able to inform and assist in the future urbanization process.

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ANNEX I: NON-URBAN FORM FACTORS WITH POTENTIAL INFLUENCE ON URBAN ENERGY DEMAND

The following table presents several factors identified in the literature that, in addition to urban form, are acknowledged to influence energy demand. It is by no means extensive, but it compiles some of the factors most frequently found. Although their effect may be quite significant (especially when combined), it is out of the scope of this research to characterize their individual impact.

Table 67. Non-urban form factors with potential influence on energy demand.

Buildings	**Transports**
Climate	Orographic conditions
Behavioural/ cultural attitudes/ influences	Behavioural/ cultural attitudes/ influences
Socioeconomics – GDP/ Purchase Power/…	Socioeconomics – GDP/ Purchase Power/ …
Cost of electricity /gas/ other	Fuel cost
Technology (efficiency and carriers used)	Technology (efficiency and fuel used)
Building materials	Vehicle ownership
Window to Wall Ratio / fenestration	PT service quality (frequency, reliability…)

ANNEX II: REVIEW OF ENERGY DATABASES

The following topics present the national data sources that were consulted while seeking data for the characterization of energy demand. These were not further considered due to the retrieval of more suitable data.

INE (for the city scale):

- Electricity consumers (No.) by geographic localization and type of consumption; Annual
- Electricity consumption (kWh) by geographic location and type of consumption; Annual
- Natural Gas consumption (kWh) by geographic location and type of consumption; Annual
- Fuel sales (tonnes) by geographic location and type of consumption; Annual
- Housing units of usual residence (No.) by geographic localization, type (building) and main source of energy used for heating; Decennial (parish scale).

DGEG: Enquiry on the consumption of the Residential Sector (data only at national level and NUTS1).

ADENE: Online data on residential buildings energy certification (use of the database is subject to request and authorized use). Does not cover all buildings. Online data provides the efficiency category of the buildings certified, as well as the estimated thermal energy requirements (heating and cooling).

Municipalities' websites, only Lisbon has online vector data referring to its master plan readily available for download: Other municipalities have online tools, indicating that they have thematic cartography available, eventually shared under approved request.

Aveiro - No statistical databases; no geospatial data available for download (online visualization tool http://sigserver.cm-aveiro.pt/SMIGA-MapaInterativo/default.aspx -) + territory planning instruments

Beja – Not available at the time of consulting.

Braga - No statistical databases; no geospatial data available for download.

Bragança – No data available. Only territory planning instruments (master plan, urbanization plan and detailed plans).

Castelo Branco – No data available.

Coimbra – No statistical databases; no geospatial data available for download (online visualization tool (http://sig.cm-coimbra.pt/(S(bqzufp52fuy5sxtg04tqsieo))/Viewer.aspx?id=119) + territory planning instruments.

Évora – No statistical databases; no geospatial data available for download.

Faro – No statistical databases; no geospatial data available for download (online tool only enables to retrieve pdf files).

Guarda – No statistical databases; no geospatial data available for download.

Leiria – No statistical databases; no geospatial data available for download (online visualization tool enables to retrieve pdf files).

Lisboa – Masterplan available for download in vector format (http://www.cm-lisboa.pt/viver/urbanismo/planeamento-urbano/plano-diretor-municipal).

Portalegre – No statistical databases; no geospatial data available for download.

Porto[59] – No statistical databases; no geospatial data available for download, but online visualization tool available (http://sigweb.cm-porto.pt/mipwebportal/) + local plans available in pdf format.

Santarém – No statistical databases; no geospatial data available for download (online visualization tool didn't work)

Setúbal – No statistical databases; no geospatial data available for download (online visualization tool didn't work – http://sigsetubal.peninsuladigital.com.pt/igo_durb/)

Viana do Castelo - No statistical databases; no geospatial data available for download

Vila Real – No data available online for the characterization of the municipality. Only detailed plans available.

Viseu – No statistical databases; no geospatial data available for download (online visualization tool).

[59] For Porto there is a complementary document, which may provide valuable information (disaggregated to the parish scale): The survey on the energy consumption habits of Porto residents (AdE Porto /Univ. Católica) provides information on average daily electricity and gas consumption per building typology, some data on distances travelled, and modal share.

ANNEX III: ILUSTRATION OF SOME REFERENCED AREAS OF THE CASE STUDIES

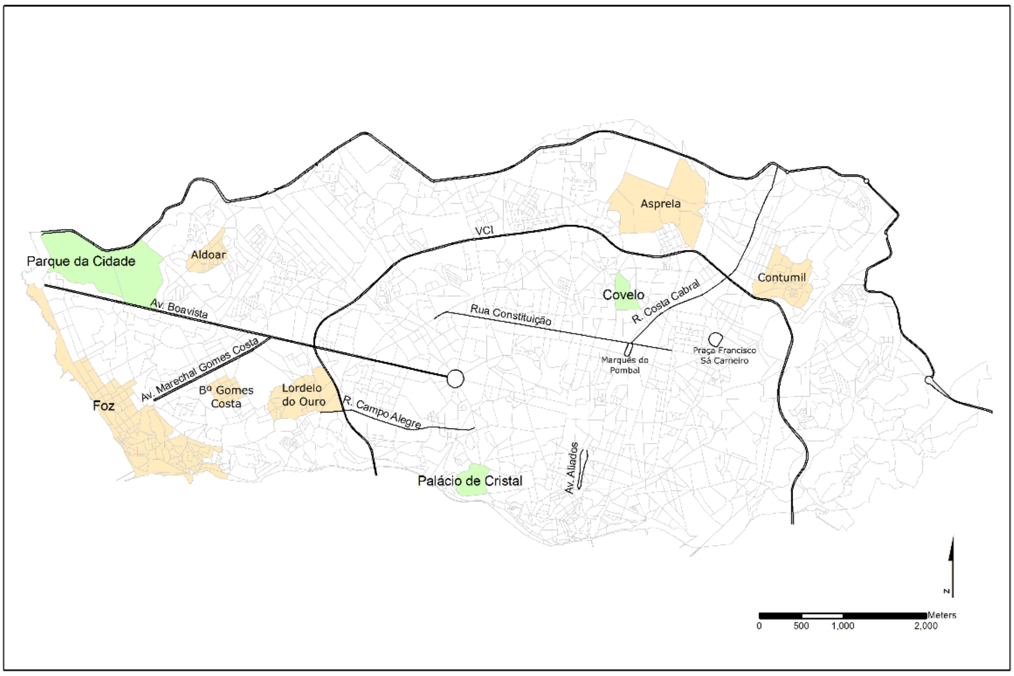

Figure 141 . Areas of the Porto case study referenced during the spatial analysis

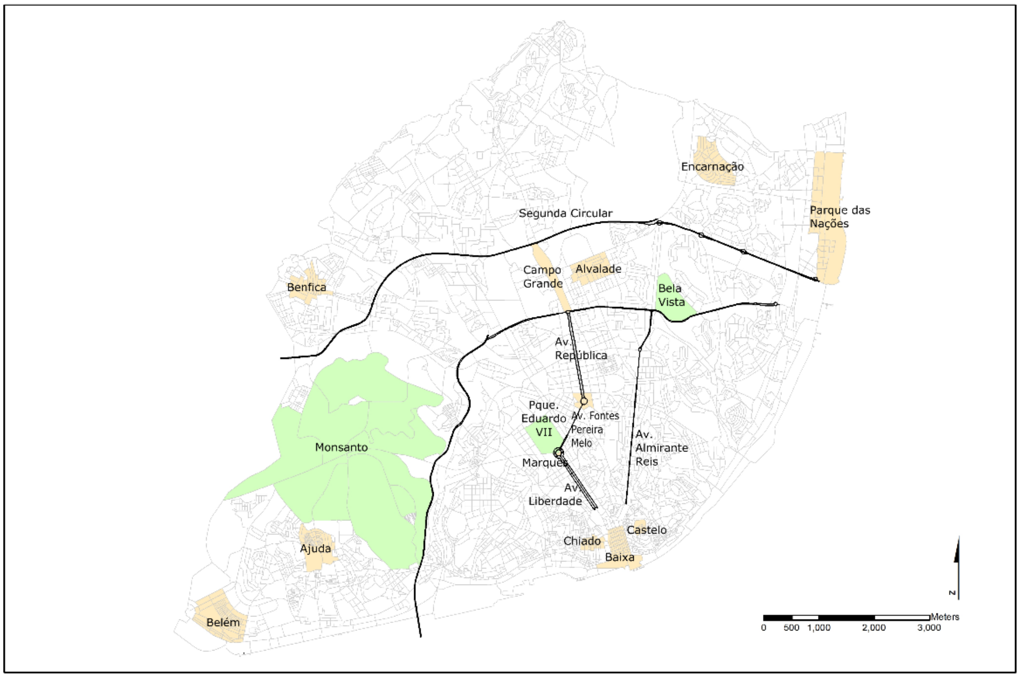

Figure 142. Areas of the Lisbon case study referenced during the spatial analysis

ANNEX IV: CONVERSION FACTORS

Table 68. Conversion factors considered

Conversion	(space) Heating	(space) Cooling	Mobility (gasoline)	Mobility (diesel)
$E_u \rightarrow E_f$	1.34	0.33	-	-
$E_f \rightarrow E_p$	1.26	1.84	1.06	1.06
GWh $E_p \rightarrow tCO_{2eq}$	104.1*	189.9*	236.4	252.7

* Accounts for the energy mix supplying the end use considered.

Table 69. Assumptions for the conversion of vkm into final energy

Fuel	Efficiency (l/100km)	Energy content (GWh/l)	% pkm
Gasoline	10.8	9.10556E-06	0.355
Diesel	8.59	9.84533E-06	0.645

ANNEX V: WORD CLOUDS OF SELECTED STRATEGIC DOCUMENTS

Figure 143. Word Cloud for the EU 2020 strategy

It is interesting to note that although the EU 2020 argues for a smart, sustainable and inclusive growth, the words that clearly stand out from this strategy are of a dominant economic connotation: “crisis”, “growth”, “recovery”, “economic”, “economies” and “economy”.

Figure 144. Word Cloud for the Energy 2020 strategy

Although the Energy 2020 strongly focuses on an efficient use of energy, one cannot find the words “cities” or “urban” in this cloud (Figure 144). This suggests that cities and urban areas are still largely detached from broader strategic visions on energy. Still, two specific sectors are included: “transport” and “industry”.

Figure 145. Word cloud for the energy efficiency plan (EC, 2011)

The energy efficiency plan (Figure 145), however, refers to cities and focuses particularly on the two key urban sectors explored in this research (buildings and transport).

Figure 146. Word cloud for the thematic strategy on the urban environment (EC, 2004).

Nevertheless, only in the programs concerned with the urban environment, the words “planning” and “land use” acquire enough significant expression to be shown in the word cloud. Although “energy” is absent from this word sample, climate issues are present in the existing debate on the urban environment.

Figure 147. Word cloud for the priority objective 8 (sustainable cities) of the Environment Action Programme to 2020 (EC - European Commission, 2013b)

Finally, when considering individually the priority objective 8 on sustainable cities, from the Environment Action Programme to 2020, not only territorial planning becomes an evident concern, as also a particular term linked to urban form ("densely") appears for the first time in the strategies analysed. Energy is one of the most prominent environmental components (along with water, waste, and food).