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Definition of reference buildings to determine the effect of energy renovation measures at a neighbourhood scale. Application to a study case in Braga

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Master's Dissertation
International Master in Sustainable Built Environment

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DIREITOS DE AUTOR E CONDIÇÕES DE UTILIZAÇÃO DO TRABALHO POR TERCEIROS

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

RESUMO

O setor dos edifícios é um dos principais responsáveis pelo consumo de energia e emissão de gases com efeito estufa nas cidades e, ao mesmo tempo, possui uma das maiores poupanças rentáveis de energia e maior potencial na redução das emissões. Nesse sentido, os projetos de renovação à escala do bairro, em vez de à escala do edifício, apresentam vários benefícios que permitem obter soluções mais rentáveis e eficientes.

Neste contexto, o trabalho de dissertação procurou desenvolver uma metodologia para definir edifícios de referência que permitam avaliar soluções de reabilitação energética à escala do grupo de edifícios para um bairro de habitação social em Portugal. A precisão do método foi avaliada comparando o desempenho energético do bairro, usando em um caso apenas os edifícios de referência, enquanto no outro os edifícios existentes.

Para a definição dos edifícios de referência, foi utilizada uma análise de cluster - que é uma técnica de análise estatística multivariada que agrupa casos com características muito semelhantes num cluster. Para a análise do desempenho energético, foram utilizadas simulações numéricas de energia. Foi realizada uma análise paramétrica considerando treze medidas de reabilitação energética na envolvente do edifício. A metodologia foi aplicada a um caso de estudo num bairro localizado em Braga, designado como "Bairro das Andorinhas".

Os resultados mostram pequenas diferenças de variação na análise comparativa à escala do bairro para as necessidades de aquecimento e arrefecimento, atingindo variações máximas de 4,9% e 3,4%, respetivamente. A análise de cada cluster demonstrou que as necessidades de aquecimento apresentaram, em geral, diferenças maiores que as necessidades de arrefecimento, em termos de variação entre os cálculos com os edifícios existentes e os edifícios de referência. Além disso, a variação máxima para o cluster orientado em direção este-oeste foi encontrada nas medidas de reabilitação da parede, enquanto nos clusters orientados em direção Norte-Sul foram encontradas no telhado e nas janelas.

Finalmente, o uso de edifícios de referência parece ser uma abordagem viável para avaliar medidas de reabilitação energética à escala do bairro, devido ao nível de precisão da metodologia. Além disso, a aplicação da análise de cluster na obtenção de edifícios de referência parece ser uma técnica adequada para definir esses tipos de edifícios.

Palavras-chave: análise de cluster, simulação dinâmica, Desempenho Energético de bairro, Escala de bairro, edifícios de referência.

ABSTRACT

The building sector is one of the major contributors to energy demand and greenhouse gases emissions within cities and, at the same time, it has one of the largest cost-effective energy saving and emissions reduction potential. In this regard, renovation projects at a neighbourhood scale instead of building level are believed to present several benefits that allow getting more profitable and efficient solutions.

In this context, the dissertation work sought to develop a methodology to define reference buildings that allows evaluating energy saving measures at a neighbourhood scale for a social housing context in Portugal. The accuracy of the method was assessed by comparing the energy performance of the neighbourhood, using in one case just the reference buildings while in the other the existing buildings.

For the definition of the reference buildings, a cluster analysis - which is a multivariate statistical analysis technique that groups cases with very similar characteristics into a cluster – was used. For the energy performance analysis, numerical energy simulations were used. A parametric analysis considering thirteen different energy renovation measures on the building envelope was carried out. The methodology was applied to a case study on a neighbourhood located in Braga, generally designated as "Bairro das Andorinhas".

The results showed small variation differences in the comparison analysis at a neighbourhood level for both heating and cooling energy demand, reaching maximum variations of 4.9% and 3.4% respectively. The examination of each cluster demonstrated that the heating demand had, in general, a much larger gap than the cooling demand in terms of variation between detailed calculations of the existing buildings and the reference buildings. In addition, the maximum variation for the cluster oriented East-West was found on the wall intervention measures while in the clusters oriented North-South was on the roof and windows.

Finally, the use of reference buildings seems to be a viable approach to evaluate energy saving measures at a neighbourhood scale due to the level of accuracy level of the method. Moreover, the application of cluster analysis on getting reference buildings appears to be a suitable technique to define these types of buildings.

Keywords: Cluster Analysis, Dynamic Simulation, Neighbourhood Energy Performance, Neighbourhood Scale, Reference Building.

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GLOSSARY OF ACRONYMS

ADENE – Portuguese Energy Agency

CHP – Combined Heat and Power

COP – Coefficient of Performance

DHW – Domestic Hot Water

GIS – Geographic Information System

EER – Energy Efficiency Ratio

EPBD – Energy Performance of Buildings Directive

EPS – Expanded Polystyrene Insulation

HVAC – Heating, Ventilation and Air Conditioning

IEA-EBC – International Energy Agency - Energy in Buildings and Communities Programme

nZEB – nearly Zero Energy Building

nZED – nearly Zero Energy District

nZEC – nearly Zero Energy City

PV – Photovoltaic

REH – Portuguese Regulation of Energy Performance of Residential Buildings

RES – Renewable Energy Sources

UHI – Urban Heat Island

WWR – Wall Window Ratio

ZEC – Zero Energy Community

CHAPTER 1. INTRODUCTION

The aim of this chapter is to contextualise and present a background of the dissertation topic, identifying the main problems that have carried out the necessity to develop this study. Furthermore, the objectives to achieve at the end of this work, as well as the dissertation structure are set out in in this chapter.

1.1 INTRODUCTION

Studies indicate that the urban and built environment in contemporary cities contribute substantially to climate change (Koutra, Becue, Gallas, & Ioakimidis, 2018).

Currently, cities are home to more than half of the world population and by 2050 the projections indicate the world population will be 30% larger**,** and that 68% of it will be urban (Villa-Arrieta & Sumper, 2019). As a result, urban areas have become the largest consumers of energy and associated greenhouse gas emissions. One of the major contributors to energy demand and CO_2 emissions within cities is the building sector which accounts for approximately 40% of the energy consumption and 36% of CO_2 emissions (Villa-Arrieta & Sumper, 2019; García-Fuentes, Vasallo, García-Pajares, Pujols, & Meiss, 2014; Marique & Reiter, 2014; Aghamolaei, Shamsi, Tahsildoost, & O'Donnell, 2018).

To avoid a further increase of these values, the European Union decided to issue several Directives in order to encourage the reduction of energy consumption and to promote the use of renewable energy sources (Becchio, Bottero, Corgnati, & Dell'Anna, 2017). Specifically, the recast of the European Energy Performance of Buildings (Directive 2010/31/EU) promotes the improvement of buildings energy performance within the European Union, and introduces a new standard, the nearly Zero Energy Building (nZEB). This type of building has a very high energy performance and the nearly zero or very low amount of energy required should be covered to a very significant extent by renewable sources produced on-site or nearby (EPBD, 2010).

The role of cities is widely recognised as key in reducing emissions and energy consumption. The building sector has a great potential to achieve significant reductions in emissions (Allegrini et al., 2015), and also has one of the largest cost-effective energy saving potentials (Becchio et al., 2017). In this path, buildings nZEB have been widely studied (Amaral, Rodrigues, Rodrigues Gaspar, & Gomes, 2018). Nevertheless, the building scale does not take into account parameters that affect their performance at an urban scale nor develop or take advantages of specific opportunities of district-level or neighbourhood-level solutions.

There is, therefore, an increasing interest in assessing the contribution of larger territorial areas, as districts or neighbourhoods, in their roles in achieving the principles of sustainability (Koutra et al., 2018). Nonetheless, the transformation of existing buildings into low-emission and low-energy buildings is particularly challenging in cities, where many buildings continue to rely too much on heat supply by fossil fuels (IEA-EBC, 2019). Hence, there is a necessity of developing new methodologies to address projects for accelerating the urban renovation towards nearly Zero Energy Districts nZED (García-Fuentes et al., 2014).

In this context, the International Energy Agency through the Energy in Buildings and Communities Programme (IEA-EBC) carried out a project – Annex 75 - that aims to investigate cost-effective strategies for reducing greenhouse gas emissions and energy use in buildings in cities at district level, combining both energy efficiency measures and renewable energy measures (IEA-EBC, 2019). The work proposed in this document is framed in the development of the Annex 75 research project and it aims to develop a method that allows using reference buildings to determine the energy performance of buildings at a neighbourhood level and consequently evaluate the impact of different renovation measures.

Problem Identification

Urban environments have grown at a remarkable rate and the world has experienced a major population shift from rural to urban areas (Aghamolaei et al., 2018). Currently, almost three-quarters of the EU population live in urban areas and the share of the urban population in Europe is projected to rise to just over 80% by 2050. Furthermore, the United Nations estimates that by 2030, city-dwellers worldwide will increase at a rate of 2 million per week. This unprecedented growth will have consequences for the environment and the quality of life of billions of persons (Allegrini et al., 2015).

This high rate of urbanization has increased the floor space for both residential and commercial purposes, which has imposed enormous pressure on the existing sources of energy. Cities account for approximately 75% and 80% of world's energy consumption and greenhouse gas emissions respectively, even though they occupy only 2% of the total world's surface (Aghamolaei et al., 2018), and are considered as crucial for effectively abating energy consumptions (Ferrari, Zagarella, Caputo, & D'Amico, 2019).

In particular, the building sector accounts for approximately 40% of the energy consumption and 36% of CO_2 emissions (García-Fuentes et al., 2014). The top four end uses are space heating, space cooling, water heating, and lighting accounting for close to 70% of site energy consumption (Harish & Kumar, 2016).

To reduce this trend, the European Union (EU) has defined energy policy targets establishing ambitious commitments to reduce greenhouse gas emissions further by at least 40 % by 2030 and 80-95% by 2050 when compared to 1990 levels, to increase the share of renewable energy consumed, to ensure a highly energy efficient and decarbonised national building stock and to facilitate the cost-effective transformation of existing buildings into nearly Zero Energy Buildings (EPBD, 2018).

In order to achieve the long-term carbon emissions targets, acting only on new buildings is not enough. In general, the European existing building stock is replaced very slowly and presents very low energy performance levels (Almeida & Ferreira, 2017). A very small part of the existing building stock is renovated every year due to technical and societal barriers, in addition to the economic barriers including fuel poverty (Eleftheriou et al., 2017). In particular, for the period 2012-2016 the annual weighted energy renovation rate was estimated close to 1% within the European Union while other estimations of the European Commission shows a rate between 0.4-1.2% depending on the Member States (Esser, Dunne, Meeusen, Quaschning, & Denis, 2019). Therefore, the challenge of achieving energy efficiency targets in Europe remains for existing buildings, which is an urgent problem to tackle.

Regarding the energy efficiency in the built environment, although there are broad concerns a limited number of nZEB are actually being properly constructed and/or retrofitted. In particular, there are distinctive challenges that have to be addressed in southern European countries. In Eleftheriou et al. (2017) is stated that there are significant differences in the progress and implementation of nZEB across the 28 European Member State. In the northern Europe, in general, they managed to develop effective technologies of nZEB corresponding to their heating dominated climates. However, southern European countries are still trying to find the most adequate solutions taking into account the local climate and local cultural, social, technical and economic context. This work concluded that the most Southern European countries are poorly prepared for nZEB implementation and especially to the challenge/opportunity of retrofitting existing buildings. In addition, there are strong barriers for nZEB in the residential sector that play a significant role in the housing sector (Eleftheriou et al., 2017). Some of those barriers are the underdeveloped market of nZEB, the lack of understanding of nZEB design due to the insufficient funding of human infrastructure and the scarcity of local governance and a national strategy to create an infrastructure for nZEB implementation. Addressing the nZEB concept at a larger scale - district or neighbourhood - can help unlock those obstacles by attracting more investments due to the size of the interventions which, in turn, may have a positive impact over all stakeholders involved.

In Portugal, buildings represent the third major energy consumption sector with a share of 29% in 2016. The building segment is in the third place of final consumption sector surpassed by transport and industry sector (ADENE, 2018). Furthermore, over the last 10 years (2006-2016), there was a 70% decrease in terms of renovation interventions in residential buildings, while completed dwellings in new housing constructions fell by 89% (ADENE, 2018). Thus, there is still a wide margin to improve energy efficiency in buildings. This is particularly important since studies using simulations on typical building envelope solutions and construction materials in Portugal showed long periods of thermal discomfort for the heating season as well as long periods of overheating during summer (Eleftheriou et al., 2017).

Investments in renovation interventions, and in particular in the residential segment, are also an effective means to alleviate energy poverty, which is a key issue in Portugal (European Commission, 2019). According to the European Union Statistics on Income and Living Conditions energy poverty indicator "inability to keep the home adequately warm", 20.4% of the population in Portugal was energy poor (European Commission, 2019). According to Simoes, et al. (2016), on average, 22% of the inhabitants in Portugal are potentially fuel poor regarding their dwellings' space heating and 29% regarding space cooling with a large variation across the country. Portugal is consistently identified as the country with the highest number of excess winter mortality in Europe (Eleftheriou et al., 2017).

On the other hand, as a consequence of the first two energy crises in 1973 and 1978, Europe intensified the effort to become gradually independent of fossil fuels (Koutra et al., 2018). However, Portugal is a country with scarce fossil energy resources and largely dependent on foreign countries for energy production, reaching a value of 79.9%, in 2017[1]. Therefore, this high dependency along to the substantial economic and environmental weight could be reduced significantly by the transition of the Portugal construction sector to energy efficient and nearly Zero Energy Buildings.

The context delineated in this section reinforces the need to encourage the building energy renovation, particularly in the residential sector, by developing strategies and methods that address the energy-related issues from a neighbourhood scale, allowing for integration of both energy efficiency and renewable energy on-site measures and taking into account potential economic and technical advantages.

1.2 OBJECTIVES

General objectives

The main objective of this research is to elaborate a methodology for the definition of reference buildings that accurately characterise neighbourhoods, as a mechanism to evaluate the effect of energy saving renovation measures to achieve the nZEB level.

Specific objectives

In order to reach the main goal of this work the specific objectives are the following:

- To find reference buildings at a neighbourhood scale, using a social housing project located in Braga as a case study, by applying a cluster analysis technique.
- To assess the accuracy of using of reference buildings for the evaluation of the energy performance of neighbourhoods by comparing numerical calculation results of both reference buildings and all buildings in the neighbourhood.
- To evaluate variation levels of different energy saving measures on three buildings elements applying the above procedure.

1.3 DISSERTATION STRUCTURE

This document is structured in six sections. In the first chapter the identification of the problem along with the objectives and the dissertation structure is set out. In Chapter 2, the conceptual framework and the state of the art found in the literature regarding the topic studied are elaborated. The literature review performed includes not only general

[1] REA State of the Environment Portal, Portugal. Energy Production and Consumption. (https://rea.apambiente.pt/content/energy-production-and-consumption?language=en)

aspects regarding energy performance but also the importance of addressing this at a neighbourhood level as well as the application of methods and tools at this scale. In the Chapters 3 and 4, the methodology used and the characterisation of the case study are explained. The methodology combines different techniques for each step: a statistical technique to define reference buildings and numeric energy simulations to obtain the buildings energy demand. In Section 5 the results are presented. Conclusions of this study are elaborated in chapter 6.

CHAPTER 2. STATE OF THE ART

In this chapter, a literature review concerning subjects related to the topic of the work is reported. The subjects include related concepts, approaches and tools associated to the energy performance at both building and district/neighbourhood level.

2.1 ADDRESSING ENERGY EFFICIENCY IN BUILDINGS

New policies and measures have been introduced to promote energy savings and CO_2 emission reductions over the last decade. In this context, the European effort is observed in the European Energy Performance of Buildings Directive recast (EPBD, 2010) which introduced the concept of nearly Zero Energy Building (nZEB). The nZEB is defined as "a building that has a very high energy performance (…) the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". The nearly zero energy concept is related to the reduction of the energy demand to almost zero, coupled to the energy supply from renewable sources (EPBD, 2010). The necessary measures to ensure the minimum energy performance requirements are set with a view to achieving cost-optimal levels, which should be calculated in accordance with the comparative methodology in European Commission (2012).

According to (Amaral et al., 2018) the elements that comprise the design of a nZEB are related to the integration of passive design and active systems:

a) Passive measures, such as building orientation or an efficient envelope including glazing areas;
b) Efficient lighting systems used complementary to daylight;
c) Efficient heating and cooling equipment;
d) Efficient ventilation;
e) Renewable technologies;
f) Building energy management systems, within a context of efficient technologies and rational use of energy.

The Portuguese regulation related to the Buildings Energy Performance has been adapted under the EPBD (2010) recast and modified over time to update its content including the definition of nZEB. According to the last version of this concept, an nZEB is defined as: a building that has a very high energy performance in which the nearly zero or very low amount of energy required should be covered to a very significant extent from renewable energy produced on-site (whenever possible) and/or adjacent to the building. The nZEBs have components compatible with the upper levels (most efficient) of the cost-optimal evaluations (Lei n°52/2018).

2.1.1 Methodology for a Cost-Optimal combination of energy efficiency and renewable energy measures

The cost-optimal methodology was introduced in the European Directive 2010/31/EU and it allows to assess combinations of energy efficiency measures and renewable energy sources. In the context of energy renovation, it is possible to compare different renovation scenarios under various macroeconomic situations with regard to cost-effective strategies and energy and environmental savings in relation to *´reference buildings´*. The method involves 5 main steps: the calculation of the energy performance of the building in the reference case, which is established according to local regulations; the definition of a set of energy efficiency renovation measures in relation to the building needs; the simulation of the energy performance of each renovation and the estimation of the global costs for each renovation scenario, which include investment costs, maintenance, energy costs, replacement and residual value.

A graphic representation of the application of the methodology is shown in Figure 1 in which the cost-optimal level can be found in the lower part of the curve that reports global costs (€/m^2) and primary energy consumption (kWh/m^2.y). The limit of cost-effectiveness is derived from a technical and economic perspective in relation to the reference case.

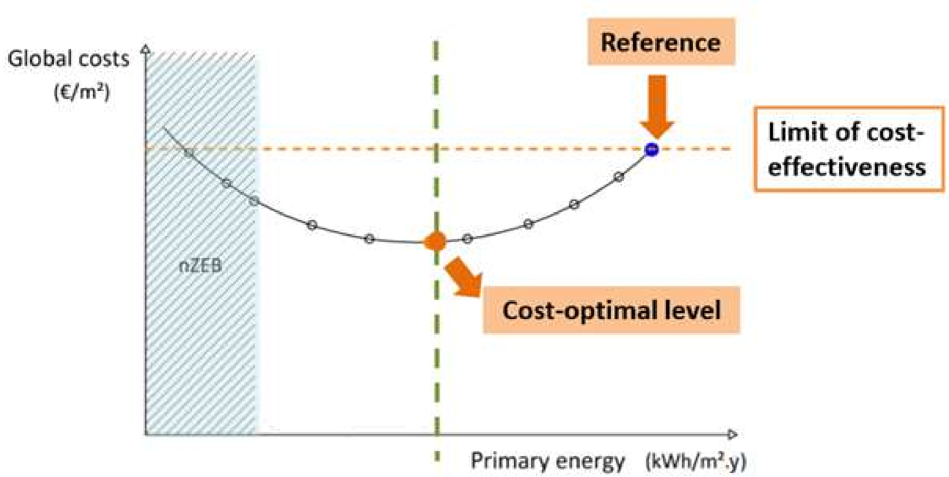


Figure 1*:* Cost-optimal level scheme.

2.1.2 The need for Reference Buildings

According to the commission delegated regulation No 244/2012 member states are required to define "reference buildings" for calculating cost-optimal levels that represent typical and average building stock in each member state in order to obtain general results consistent with the characteristics of the analysed building stock.

Currently, there is no standard for defining a reference building. In the annexe III of (EPBD, 2010) a *Reference Building* (RB) is defined as ''buildings that are characterized by and representative of their functionality and geographic location, including indoor and outdoor climate conditions''. In addition, it is a useful tool for understanding the thermal energy performance of an entire built stock and evaluating energy saving measures of an entire building stock. Thus, reference buildings have become a crucial topic for studies involving thermal and energy performance of buildings stock and quantifying the potential of effective refurbishment measures at a national or regional level (Schaefer & Ghisi, 2016). Moreover, for reducing the computational effort of physic models, the clustering of a building stock in a series of reference buildings is a well-established approach that allows maintaining an acceptable approximation of the energy evaluations (Ferrari et al., 2019).

2.2 THE IMPORTANCE OF DISTRICT AND NEIGHBOURHOOD LEVEL

There is no agreement regarding an exact definition for concepts such as district or neighbourhood. The form as both concepts are used in literature appears to be related with culture and urban morphology aspects. In Choguill (2008) are some definitions such as 'a geographically localised community located within a larger city or suburb' or 'a separately identifiable area within a community retaining some quality or character which distinguishes it from other areas' or 'an area where the residents are drawn and held together by common and beneficial interests'. Hallman defines a neighbourhood as combinations of geographical boundaries, ethnic or cultural characteristics of the inhabitants, psychological unity among people who feel that they belong together, or concentrated use of an area's facilities for shopping, leisure and learning (in Aghamolaei et al., 2018).

To adjust the nearly zero energy principles to the urban context, the concept of "nearly Zero Energy District" (nZED) was introduced to assess its potential impacts and feasibility

(Amaral et al., 2018). Some definitions found in the literature related to this concept are described in the following paragraph.

The National Renewable Energy Laboratory of the U.S. Department of Energy (NREL) defined zero net energy community (ZEC) as “one that has greatly reduced energy demand through efficiency gain such that the balance of energy for vehicles, thermal, and electrical energy within the community is met by renewable energy” (Marique & Reiter, 2014). They highlight that “community scenarios could link transportation, home and the electric grid as well as enable large quantities of renewable power onto the grid” (Marique & Reiter, 2014). In Villa-Arrieta & Sumper (2019) is defined nearly Zero Energy Cities (nZEC) as “cities made up of nearly Zero Energy Buildings (nZEB) and other installations of distributed generation to cover their energy demand by use of local renewable resources to the detriment of external resources”. In Koutra et al. (2018) is defined ZEC (Zero Energy Community) as ‘the community with reduced energy requirements (covered by renewable resources) by increasing energy efficiency’ and as the ‘community with greatly reduced energy requirements’ and includes energy not only for residential buildings but also for other infrastructure.

Although building assessment is considered as an essential stage in assessing the energy performance of built environment, focusing solely on such assessments may lead to unreliable results since the influence of urban surroundings on buildings´ energy performance, as well as the interdependency amongst them are not taking into account (Aghamolaei et al., 2018; Amaral et al., 2018). It is no longer sufficient to simulate building energy use assuming isolation from the microclimate and energy system in which they operate, or to model an urban energy system without consideration of the buildings that it serves (Allegrini et al., 2015).

The review of past literature demonstrates that although a limited number of studies exist at neighbourhood or district scale, the growing interest in this domain has been significant (Aghamolaei et al., 2018). Actually, district scale approaches are already emphasized in policy actions stated in the last Energy Performance of Buildings Directive (EPBD, 2018): “The Commission shall examine in what manner Member States could apply integrated district or neighbourhood approaches in building and energy efficiency policy, while ensuring that each building meets the minimum energy performance requirements, for example by means of overall renovation schemes applying to a number of buildings in a spatial context instead of a single building”.

According to Amaral et al.(2018), moving from building to city scale increases the complexity by involving more stakeholders and interdependencies, which act as barriers to the implementation and dissemination of nearly zero energy principles. So an intermediate scale, such as district, appears to respond to this complexity. In accordance to Fonseca and Shlueter (2015), it is an adequate scale to go beyond the limits of the single building without losing its control and capable to address tangible solutions (in Amaral et al., 2018). Therefore, neighbourhood/district level is an appropriate scale since it incorporates all the needed components such as transportation system, form and geometry metrics of buildings and district patterns, and provide means for the verification of results (Aghamolaei et al., 2018).

For Koutra et al. (2018), zero energy projects are more worthwhile and efficient on a district scale to provide energy techniques for renewable systems that are not available in individual buildings. Moreover, the existing mismatch between demand and generation can be better managed. In fact, the operation of different local energy resources allow more flexibility to adjust demand and supply through the help of energy storage, for example. Also, the energy production and distribution can be conceived together, reducing losses and contributing to cost-effective interventions (Amaral et al., 2018).

2.2.1 Advantages and challenges of addressing renovations at neighbourhood scale

Working at district level has various benefits that include economic, social and environmental aspects of sustainability concept (Haapio, 2012; Hachem, 2016; Koch et al., 2012; cited in Aghamolaei et al., 2018). Some of them are detailed in the next paragraphs. From a social viewpoint, the district scale enhances community participation in neighbourhood planning (Komeily, Srinivasan, & Rinker, 2015; Lippard, 1997; Rey et al., 2013; Sharifi & Murayama, 2013; cited in Aghamolaei et al., 2018). Likewise, an intermediate scale provides opportunity for energy planning, since it facilitates the integration of engineering and social science domains (Aghamolaei et al., 2018). For instance, the energy performance analysis and planning can be modified through social principles such as human behaviour, policy decision making and financial incentives which are often not available in planning for individual buildings (Aghamolaei et al., 2018).

From a technical point of view, it is possible to improve efficiencies through the implementation of centralized heating or cooling systems, the exploitation of different slopes and tiles for solar technologies or the utilization of common and public spaces for the installation of Renewable Energy Sources (RES) technologies to cover the demand (Miguel, Mendes, & Madeira, 2018). Regarding Energy Flexibility (which is the ability of a building to manage its energy demand and generation according to local climate conditions, user needs, and energy network requirements), the strategies for a successful implementation depends on the amount of energy that can be shifted (Jensen et al., 2017). This quantity from a single building is often very small, thus, a larger scale is needed to aggregate many buildings that pool the energy flexibility.

In the economic sphere, the refurbishment at a larger scale such as a district scale or neighbourhood scale, can contain several benefits compared to mere building renovations, such as reduced costs due to smaller unit costs (Paiho, Ketomäki, Kannari, Häkkinen, & Shemeikka, 2019). In addition, interventions at this scale contribute to an improvement of new shared-risk models through the combination of financial entities, construction companies or other possible public or private investors being in charge of the initial investment needed, and establishing medium or long-term contracts with the owners (García-Fuentes et al., 2014). In particular, it provides municipalities better opportunities to implement energy and sustainability strategies (Paiho et al., 2019).

On the other hand, working at district scale may be more complex to work with, since it involves some difficulties due to the existence of various sub-systems and their interdependencies that affects the overall energy performance. Financial context, technological aspects, society, policy, legal frameworks and on-site conditions, such as existing buildings, infrastructure and landscape, can create constraints as well as opportunities for planning. The most important constraints include financial limitations, implementation of theories and plans, different user patterns, and finally, multiple goals and priorities, which may result in conflicting interests (Aghamolaei et al., 2018).

2.3 FACTORS INFLUENCING NEIGHBOURHOOD ENERGY PERFORMANCE

According to Amaral et al. (2018), the key factors that influence nZED energy behaviour are: for energy consumption - passive design, active systems, urban climate and urban morphology; for energy production - urban climate and morphology as well as energy distribution and production; and the consumption patterns, as Figure 2 shows. Likewise, this work defines the main determinants at each scale (Figure 3). For building alone, there are: for energy consumption - passive design, active system, urban climate and urban morphology; for public space energy consumption - lighting, infrastructure, landscape and public uses; and for district energy production - consumption patterns, energy production and energy distribution.

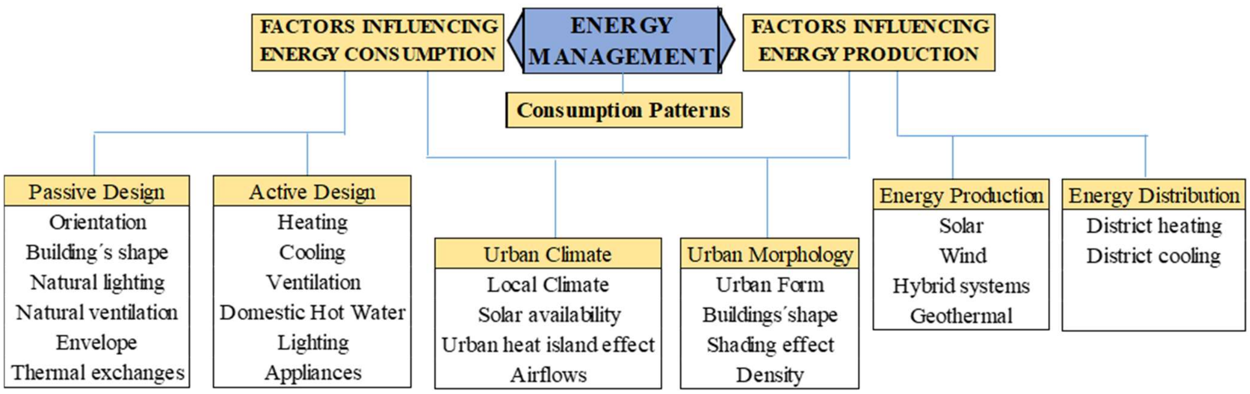


Figure 2: nZED energy performance factors (source: *Amaral et al. (2018)*).

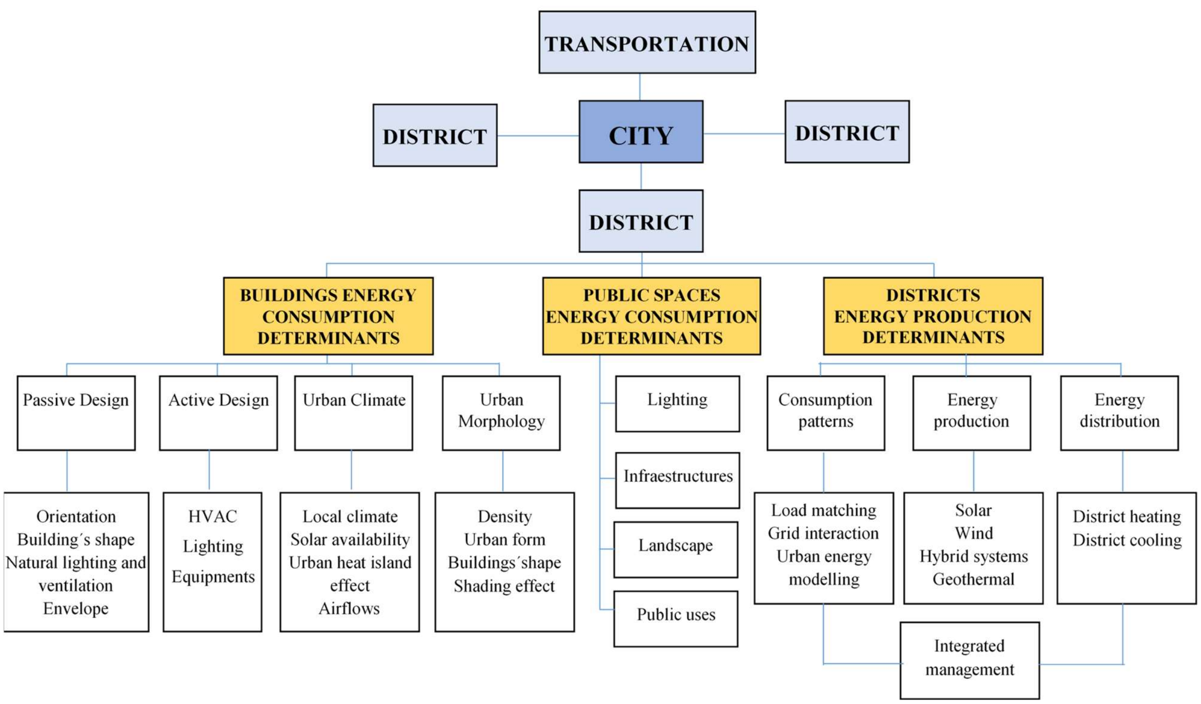


Figure 3: Main energy determinants in each scale (source: *Amaral et al. (2018)*).

2.3.1 Energy Consumption

Buildings play an important role in urban energy systems regarding both the demand and supply of energy (Allegrini et al., 2015). An nZED is not a sum of nZEB's of a district; it is considered as a group of buildings with different consumptions and their respective public surroundings, whose overall balance must reach almost zero (Amaral et al., 2018). Nevertheless, buildings remain the largest consumers of the total amount of energy demand, thus the main effort still resides in decreasing individual buildings' loads, and for that, the same energy efficiency strategies proposed for nZEB should be met at the district scale as well (Amaral et al., 2018).

According to Table 1 in ADENE (2018), over the years, the energy performance requirements on buildings in Portugal have improved following the main legislative EU instruments that promote the energy performance of buildings and renovation.

Table 1: Energy performance indicators and corresponding requirements *(source: (ADENE, 2018))*

			Existing				New	
			Before EPBD (before 2006)		EPBD 2006-2013		EPBD recast after 2013	
			Average	Minimum	Average	Minimum	Average	Minimum
Residential	Heating [kWh/m^2.year]	Useful energy	94	a)	45	b)	45	c)
	Cooling [kWh/m^2.year]	Useful energy	15	14	12	13	10	10
	DHW [kWh/m^2.year]	Useful energy	0	-	0	d)	0	d)
	Total [kWh/m^2.year]	Primary Energy	259	e)	87	f)	103	g)

a) Varies between 33 - 56 kWh/m^2.year (1st and 3rd quartile)
b) Varies between 38 - 66 kWh/m^2.year (1st and 3rd quartile)
c) Varies between 46 - 75 kWh/m^2.year (1st and 3rd quartile)
d) Minimum solar energy contribution for DHW
e) Varies between 105 - 182 kWh/m^2.year (1st and 3rd quartile)
f) Varies between 88 - 177 kWh/m^2.year (1st and 3rd quartile)
g) Varies between 113 - 220 kWh/m^2.year (1st and 3rd quartile)

2.3.1.1 Passive Design

Passive Design is the design that takes advantages of the climate to maintain a comfortable temperature range in the dwellings. Passive design uses layout, fabric and form to reduce or remove mechanical cooling, heating, ventilation and lighting demand. Some examples of passive measures include optimising spatial planning and orientation to control solar gains and maximise daylighting, manipulating the building form and fabric to facilitate natural ventilation strategies and making effective use of thermal mass to help reduce peak internal temperatures.

The proper design and selection of a building envelope and its components are an efficient means to reduce both the space heating and cooling loads. Although the passive measures are applied at building level, a district intervention affords cost reduction in both project and execution phases through economies of scale (García-Fuentes et al., 2014).

In Aguacil et al. (2017) is stated that the International Energy Agency estimates the potential energy savings for 2050 in about 1509 million tonnes of oil equivalent of which 50–75% may be reached by considering only the improvement of the building envelope. It, therefore, seems clear that the residential building stock offers high potential for energy efficiency gains.

Aiming at 'nearly zero energy heating' targets to achieve the optimum savings is technically feasible in South Europe with higher summer temperatures and solar radiation by reducing the envelope conductivity and infiltration and selecting optimal glazing and window openings which may decrease significantly heating energy demand (Eleftheriou et al., 2017). The same author states that in the case of existing buildings the transition to nZEB introduces additional constraints for the control of overheating risks, thus nZEB need to be address properly for both heating and cooling seasons.

Thermal insulation is known to play a critical role in saving energy by reducing the rate of heat transfer. Determining the amount of insulation material required in walls is a key factor. Thermal insulation is one of the most valuable tools in achieving energy conservation in buildings. A proper amount of thermal insulation in the building envelope helps to reduce the cooling and heating energy demands of a building and its associated CO_2 and SO_2 emissions into the atmosphere (Kaynakli, 2012).

In Omranya et al (2016) presented a comprehensive review of passive wall systems for improving the energy efficiency in buildings. They were divided in two categories: 1) Passive wall system; Trombe walls, Autoclaved Aerated Concrete (AAC) walls, Double skin façades (DSF), Application of Phase Change Materials (PCM), Green walls/systems and Innovative wall system solutions; and 2) Future trends of building façade, such as Intelligent façades, Kinetic façades, Biophilic design and Climate adaptive building shells.

For measures regarding the roof is also possible to detail diverse types (Sadineni et al, 2011): masonry roof, lightweight roof, Ventilated and micro-ventilated roofs, Vaulted and domed roofs, Solar-reflective/cool roofs, Green roofs, Photovoltaic roofs and the Thermal roof insulation systems.

A deep review on fenestrations was carried out in Petter et al. (2012) where different types of glazing are described; Multilayer glazing, suspended films, vacuum glazing, low-emissivity coatings, smart windows, solar cell glazing, self-cleaning glazing, aerogels, glazing cavity gas fills; spacers, made of foam, thermoplastic and metal-based; and frames, made from wood, aluminium, polyvinylchloride (PVC).

Over the years, the minimum requirements evolution for building envelope and ventilation in Portugal have improved significantly due to the growing need for energy reduction. Regarding the building envelope, Table 2 and Table 3 show the current reference maximum values of envelope U-value and window solar gain factor by climate zone in Portugal (Figure 4). In relation to the ventilation, the current standard should not be less than 0.4 air changes per hour.

Table 2: Reference and m*a*ximum U-Value by climate zone in Portugal.

Envelope U-value [W/(m^2.°C)]		**I1**	**I2**	**I3**
Envelope elements and elements separating useful and non-useful areas (elevator shaft, common circulation areas) with btr <0.7 (thermal conditions similar to outdoors)	Opaque vertical elements	0.50	0.40	0.35
	Opaque horizontal elements	0.40	0.35	0.30
Construction elements between buildings and non-useful areas (elevator shafts, common circulation areas) with btr ≤0.70 (thermal conditions similar to indoors)	Opaque vertical elements	0.80	0.70	0.60
	Opaque horizontal elements	0.60	0.60	0.50
Windows (Uw) (doors and windows)		2.80	2.40	2.20
Elements in contact with the ground		0.50		

Table 3: Maximum window solar gain factor by climate zone in Portugal.

$g_{Tmáx}$	**Climatic Zone**		
Thermal inertia	**V1**	**V2**	**V3**
Low	0.15	0.10	0.10
Medium	0.56	0.56	0.50
High	0.56	0.56	0.50

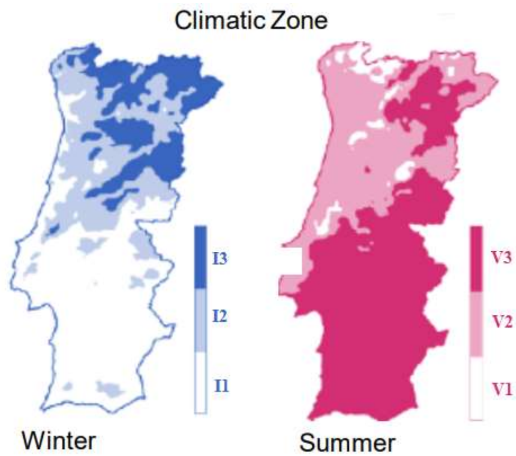


Figure 4: Portugal Climatic Zone.

2.3.1.2 Active Design

An active design refers to the use of the technical systems for heating, cooling, domestic hot water, ventilation and energy generation.

In general, to maintain thermal comfort, a certain amount of energy demand to be added or removed (heating/cooling) to or from the building indoor space. The amount of energy is mainly dependent on outdoor weather conditions such as outside air temperature, relative humidity, wind characteristics and on indoor conditions of occupancy, heat and moisture flow through the walls and interiors, etc. Such energy acts as load on the heating, ventilation and air-conditioning (HVAC) system (for heat and moisture) installed to condition the building space. That energy load is the rate (heat gain rate) at which energy is being added (heating) or removed (cooling) to or from the building space in order to maintain the space temperature at the desired levels (Harish & Kumar, 2016).

For García-Fuentes et al. (2014), an active system can be implemented from a district perspective achieving higher energy efficiency in order to meet the nZED objectives.

According to ADENE (2018), in Portugal, there are requirements to be fulfilled regarding technical systems, which have been increasingly more demanding as new regulations came into force. Table 4 presents a brief resume of the evolution in requirements for technical systems.

Table 4: Minimum requirements for technical system (source: *ADENE (2018)*)

<table>
<tr><th rowspan="2">Building type</th><th rowspan="2" colspan="2">Technical System</th><th colspan="3">Requirement evolution</th><th rowspan="2">Standard</th></tr>
<tr><th>Before 2013</th><th>2013-2015</th><th>After 2016</th></tr>
<tr><td rowspan="6">Residential and non-residential buildings</td><td rowspan="3">Heat pumps</td><td>Cooling</td><td rowspan="7">None</td><td rowspan="2">Eurovent Label C (Example: Chiller COP ≥2.8; EER ≥2.7)</td><td rowspan="2">Eurovent Label B (Example: Chiller COP ≥3.0; EER ≥2.9)</td><td>EN 14511</td></tr>
<tr><td>Heating</td><td>EN 14825</td></tr>
<tr><td>DHW</td><td colspan="2">COP ≥2.3</td><td>EN 16147</td></tr>
<tr><td colspan="2">Boilers</td><td>Minimum nominal efficiency 86%</td><td>Minimum nominal efficiency 92%</td><td rowspan="3">-</td></tr>
<tr><td rowspan="2">DHW Gas heater</td><td>Power ≤10 kW</td><td colspan="2">Efficiency ≥ 82%</td></tr>
<tr><td>Power >10 kW</td><td colspan="2">Efficiency ≥ 84%</td></tr>
<tr><td>Residential</td><td colspan="2">Domestic Electric Storage Water Heaters</td><td colspan="2">Maximum stand-by heat loss</td><td>EN 60379</td></tr>
</table>

2.3.1.3 Urban climate

The energy demand for heating, cooling and lighting of buildings is strongly dependent on the local microclimate at the specific building location (Allegrini et al., 2015). Furthermore, the growth of urban areas and the complexity of urban morphology have provided the development of urban microclimate with special attention to airflows and wind speed, outdoor temperature and solar radiation; these all together contributes to *the Urban Heat Island* (UHI) effect (Amaral et al., 2018). The local microclimate in urban areas differs from rural areas. For example, the air temperatures are higher due to the urban heat island effect, local wind speeds are lower due to wind sheltering by buildings and the solar and longwave radiation is influenced by shadowing effects and reflections from neighbouring buildings (Allegrini et al., 2015).

This strong interaction between the local microclimate and the effect of neighbouring buildings should be taken into account when conducting energy simulations, modelling both in a coupled way rather than the microclimate being a predetermined boundary condition, as is mostly the case (Allegrini et al., 2015). In Palme et al. (2017) was found that incorporating the UHI effect in the buildings´ performance simulation can result in an increase of energy demand for cooling from 15% to 200% in south American coastal cities, hence temperature has an influence over on energy consumption associated with buildings´ cooling (Amaral et al., 2018).

A microclimate model typically consists of three sub-models: radiation models for solar and longwave radiation, flow models to determine wind speed, convective heat transfer at building facades and air temperatures, and building or city energy models to determine surface temperatures and energy demands. Researchers have recently been exploring methods of how to model local microclimatic phenomena within cities such as the urban heat island effect, local wind patterns and linking climate change predictions to current day to study the implications over urban building energy modelling (Reinhart & Cerezo, 2016).

2.3.1.4 Urban morphology

Urban morphology refers to the form of human settlement special structure and street pattern, building typology and the relation between them. Urban configurations will affect energy consumption, in buildings and public spaces, and they will influence the energy generation at urban level, especially solar due to different buildings´ forms height and densities and the consequent shading patterns (Amaral et al., 2018).

The building form is the most passive design aspect at a district scale which will influence the effect over surrounding buildings, for instance the shading effects. In this regard, high surface- volume ratio can increase heat gains in warmer climates and in colder regions larger surfaces are more exposed to thermal losses and therefore heating consumption, so the optimal form should be the minimal external surfaces (Amaral et al., 2018). Urban morphology and building typology are considered as crucial parameters to evaluate the energy performance of the built environment (Miguel et al., 2018).

The density is important in nZED analysis due to the influence of shading effect, which affects energy consumption or even natural lighting (Amaral et al., 2018). Studies show that density is the most influential parameter regarding solar potential/availability in building stocks (Amaral et al., 2018). Some studies state that high densities decrease energy consumption associated to mobility and others say denser urban block have lesser solar potential (Amaral et al., 2018). In warm climates, this effect may decrease the cooling needs but can block sunlight in colder climates.

District configurations can compensate the increased energy consumption by more generation and improve the demand pattern in peak times. In addition, compactness of building and density have a positive impact on the energy performance of districts but urban sprawl and suburban districts can lead to significant energy consumption in both buildings and transportation sector (Aghamolaei et al., 2018).

2.3.2 Energy Production

2.3.2.1 Energy production (on-site)

The integration of micro grids and local energy resources is considered to be a required step to enhance the energy performance of districts. The electric grid can provide energy to the district when on-site renewable generation is lower than the demand side and if greater, the on-site production can be sent to the grid or stored (Aghamolaei et al., 2018).

2.3.2.1.1 Renewable Energy

The production of energy using renewable sources reduces the need to import fossil fuels, such as coal and natural gas, making the country less dependent on foreign energy and reducing greenhouse gas emissions. Electricity is becoming a cleaner form of energy, since a massive increase of renewable energies, namely wind and solar, has been observed in EU in the last decade, leading to a progressively lower carbon content electricity.

Districts as integrated systems link transportation, home and the electric grid as well as enable large quantities of renewable power onto the grid (Aghamolaei et al., 2018). The advantages of local renewable energy generation include integration with existing building structures and reduction of grid transmission losses and grid congestion issues (Allegrini et al., 2015).

According to Allegrini et al. (2015) the solar, wind and bioenergy have the scale that allow successful integration with buildings, and hydropower, marine and high-temperature geothermal renewables are usually constructed at large scale (they are usually considered in the context of national or regional energy system). Determining the potential and calculating the performance of renewables in an urban environment is important for the design of future urban areas and the renovation of existing districts and neighbourhoods.

2.3.2.1.2 Solar

Solar technologies offer great potential for urban energy generation due to the availability of surfaces on buildings as well as the maturity of the technologies (Allegrini et al., 2015). In this regard, Portugal has the best yearly solar irradiance in Europe after Cyprus, particularly in the Alentejo region, in the southern part of the territory, and it is expected that solar energy will play an important role in decentralised power production (Miguel et al., 2018).

To calculate the energy that can be generated by solar technologies in the urban environment, two main elements must be considered: the *urban solar availability*, i.e. the total incident irradiation on building roofs and facades, and the *utilisation factor* that assesses the area suitable for installation as well as technical characteristics. On the other hand, urban morphologies impose difficulties on modelling of solar radiation compared to open areas due to complex shading patterns caused by different building heights, built densities and varying roof slopes (Allegrini et al., 2015).

According to the Portuguese legislation related to thermal solar panels, there is a minimum solar energy contribution for domestic hot water with a reference value equal to 0.65 m^2/occupant that should be applied under certain conditions defined in energy regulations in both new constructions and major renovations (REH, 2013).

2.3.2.1.3 Photovoltaic

In Villa-Arrieta & Sumper (2019) was presented a model of energy-economic evaluation of the cities self-sufficiency with the aim to analyse the investment in photovoltaic self-consumption of buildings to promote the creation of prosumers[2] communities within the cities. The model was applied in Barcelona city using PV generation capacity of around 35% of the Barcelona´s rooftop, energy efficiency measures and photovoltaic self-consumption in 17% of the residential buildings with the capacity of export to the grid. The results indicated that photovoltaic self-consumption and thus the existence of communities of nearly zero energy buildings sharing energy as Prosumers helps reduce primary energy consumption and CO_2 emissions. The investment required to generate those savings is 1.25 and 1.32 times the energy cost of the city over a period of 37 years.

[2] The term "Prosumer" has been adopted since, in theory, each costumer can operate as a "consumer" and "producer" of thermal energy towards the network (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019).

Photovoltaic sector in Portugal is mainly driven by small installations, since 2014 significant cuts were made in the feed-in tariff (FIT) previously implemented, aiming to bring micro and mini generation FIT prices down to the market. The main incentive is now given to the self-consumption regime by the elimination of almost any bureaucracy to allow its installation (Eleftheriou et al., 2017). The Portuguese government aims to improve the guidelines issued in 2014 through the new legislation, the *Decreto-Lei 162/2019,* that came into force in 2020 by providing a clearer and more favourable framework for renewable energy self-consumption, energy storage and energy communities.

2.3.2.1.4 Wind

Even though wind energy is seen mainly as a national-scale energy resource, building-mounted wind turbines are also considered for micro-generation applications (Allegrini et al., 2015). However, there are some arguments regarding the modelling of urban wind speed as well as urban power production for urban environments, where accurate wind flows, including turbulent fluctuation, are extremely difficult to predict (Allegrini et al., 2015).

The most established renewable energy sources (RES) for electricity production in Portugal are hydro and wind, both account for over 90% of the installed capacity. Besides, Portugal has been a pioneering country regarding the adoption and massive diffusion of wind power parks across its territory (Miguel et al., 2018).

2.3.2.1.5 Biomass

The biomass exploitation takes advantage of the agricultural, forest, and manure residues and in extent, urban and industrial wastes, which under controlled burning conditions, can generate heat and electricity, with limited environmental impacts. Therefore, Biomass can significantly contribute in the energy supply system. According to Sartor, Quoilin, & Dewallef (2014), Biomass combined heat and power (CHP) plants connected to district heating (DH) networks are recognized as a very good opportunity to increase the share of renewable sources into energy systems.

The most common biomass resources available in Portugal are wood residues, animal waste, and municipal solid waste (Miguel et al., 2018).

2.3.2.2 Energy distribution

To facilitate heating and cooling throughout a building, the energy required for these functions is distributed from one or more central points. In a district/neighbourhood level, heating and cooling district play a distinct role by interconnecting the energy production to many customers, in a centralised way, through means of hot/cool water or steam networks to serve room space heating and cooling.

According to Lake, Rezaie, & Beyerlein (2017) district energy systems have higher efficiency when compared with individual heating and cooling systems. District heating and cooling energy systems are often more environmentally beneficial and financially reasonable when limited retrofit is required and are cost effective for more populated areas rather than rural areas. Several district networks are already in operation in different cities in Europe, however in Portugal there is only one network currently in operation in Lisbon (Popovski, Fleiter, Santos, Leal, & Fernandes, 2018) and it has not been replicated so far.

In Lake et al., (2017) also are described some advantages of district heating and cooling energy systems:

a) Linked to a decrease in CO_2 emissions resulting from implementation of polygeneration energy conversion technologies.
b) Combined heating and cooling is depicted to be more efficient user of energy resources.
c) Results of the effects of district heating on breathing rates indicate improvements in the health of the nearby population.
d) Potential to store heat in buildings for short-term thermal energy storage.
e) District heating is competitive in high heat density city districts.

The Table 5 shows the different generation for district energy along time related to the type of heat production and energy source.

Table 5: Production and energy sources for district energy (source: Lake et al. (2017)).

	1st Generation	2nd Generation	3rd Generation	4th Generation
Peak Technology Period	1880-1930	1930-1980	1980-2020	2020-2050
Heat Production	Steam Boilers	CHP and heat-only boilers	Large-scale CHP	Heat Recycling
Energy Source	Coal	Coal and Oil	Biomass, waste and fossil fuels	Renewable sources

a) First generation

The primary transport fluid for heat for district heating systems until the 1930s was steam; this system uses pipes in concrete ducts with steam traps and compensators, but steam at high temperatures generates large amounts of heat losses and poses a risk from steam explosions. These first systems were often used in apartment buildings to reduce the risk of boiler explosions.

b) Second Generation

District energy transport systems used pressurized hot water using water pipes in concrete, shell-and-tube heat exchangers and large valves. These systems showed inability to provide control for the heat demand but showed improvement in fuel savings.

c) Third generation

District energy transport systems was developed; using pressurized water but at lower temperatures than the previous generation and often referred to as the "Scandinavian district heating technology" these systems featured prefabricated buried pipes, and compact substations and is the current system in use throughout the developed world.

2.3.2.2.1 District Heating

The fundamental idea of district heating is to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place (Sven Werner, 2017)

District heating is the interconnection of various heat sources to customers by means of hot water or steam networks to serve room space heating and usually domestic hot water as well. District heating enables the use of a variety of heat sources that are often wasted, as well as renewable heat. The future standard of district heating is referred to as fourth-generation system, which operates at lower temperature, resulting in reduced heat loss compared to previous generations, and they make feasible to connect to areas with low energy density. The systems can use diverse sources of heat, including low-grade waste heat, and can allow consumers to supply heat as well. Through heat storage, smart systems and flexible supply, these systems are an inexpensive solution for creating the flexibility required to integrate high levels of variable renewable energy into the electricity grid (UNEP, 2015).

2.3.2.2.2 District cooling

District cooling systems supply cold water through pipes in combination with cold storage. Cold water can be produced from waste heat (ie. Power generation or industry) through the use of steam turbine-driven or absorption chillers; from free cooling sources such as lakes, rivers and seas; and via electric chillers. District cooling can be more than twice as efficient as traditional decentralized chillers such as air-conditioning units and can reduce electricity use significantly during peak demand period through reduced power consumption and the use of thermal storage (UNEP, 2015).

2.3.3 Consumption Patterns

Consumption patterns refer to occupants´ interaction with building systems in order to control the indoor environment for health, and to obtain thermal, visual and acoustic comfort inside buildings (Delzendeh, Wu, Lee, & Zhou, 2017).

There is an alarming gap between the predicted and actual energy consumption of buildings and the analysis of the impact of occupants' behaviour is considered to be largely overlooked in energy studies. In energy simulation tools is normally only considered through means of fixed and scheduled patterns of behaviour. The vast majority of research on occupants' energy behaviour focuses on single buildings and there are only a few studies that investigate the urban scale impacts (Delzendeh et al., 2017).

The total energy consumption of buildings are not only influenced by the metabolic heat produced by occupants passively but also by their active energy use. Occupants interact with control systems and building elements to reach their own personal desired level of comfort in different ways: use of building openings, use of lighting and controlling solar shading, use of HVAC systems, use of hot water and electrical appliances as it shows the Figure 5.

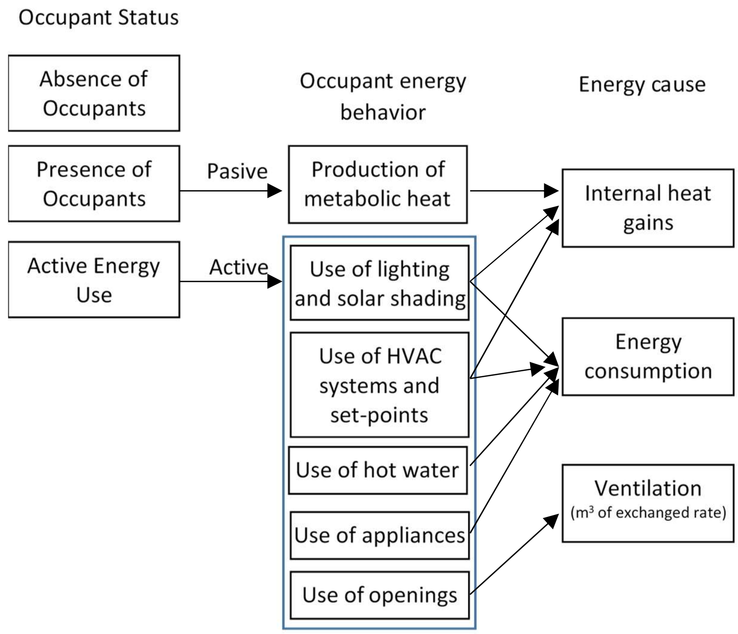


Figure 5*:* Effects of Occupants´ activities types on building energy performance (source: Delzendeh, Wu, Lee, & Zhou (2017)).

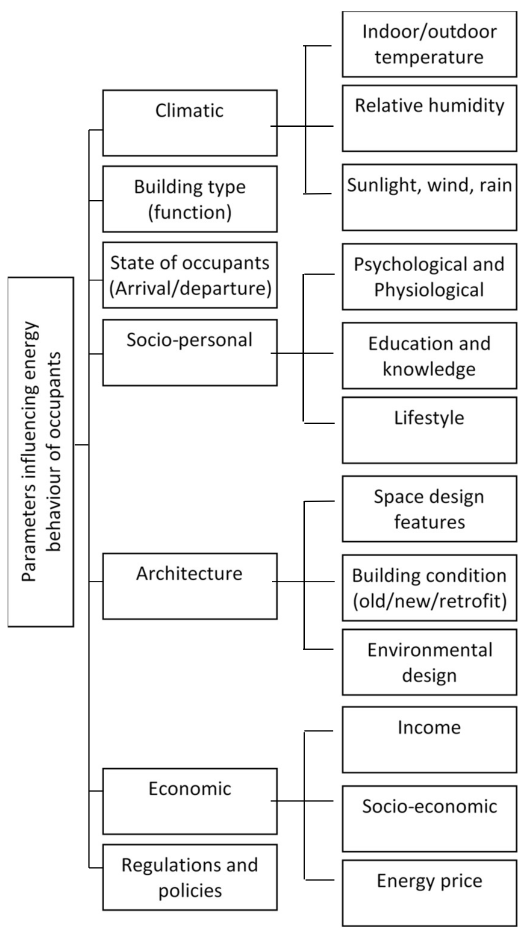


Figure 6*:* Factors influencing energy behaviour of occupants performance (source: Delzendeh, Wu, Lee, & Zhou (2017)).

HVAC systems, electrical devices and lighting that enable users to manage their own thermal and visual comfort, are the key sources of energy consumption in buildings and changes in using these systems can cause significant variations in the total energy consumption in buildings (Delzendeh et al., 2017).

The Figure 6 indicates the factors that influence the energy behaviour of occupants (Delzendeh et al., 2017): *Climatic* parameters; that are important influencing occupants' interactions with building systems to acquire thermal comfort. *Building type,* which helps to determine the type of activity, clothing type, production of metabolic heat, together with the occupants' specific needs and expectations and their possible degree of interactions with building systems. *Social and personal parameters*, such as users' awareness, education, gender, play a substantial role in occupants' comfort and energy attitude. *Energy regulations and economical parameters,* such as energy price and employment. In this context, studies show that when occupants are directly responsible for pay energy bills they act more energy frugal, energy costs is the main reason for avoiding the use of mechanical fans and accepting some level of discomfort (Delzendeh et al., 2017). However, another study showed that in harsh climatic conditions, low-income occupants consumed more electricity for cooling in comparison to other households due to the inadequate thermal insulation of the buildings. A number of studies have revealed that occupants tended to adjust building systems and appliances more at arrival than at departure of a building. *Architecture and interior design features* can influence occupant behaviour in differing ways, including visual quality of building openings, the architecture circulation and colours, material and compositions of interior spaces which may change occupants' thermal perception.

2.4 METHODS AND TOOLS USED AT DISTRICT AND NEIGHBOURHOOD SCALE

Significant progress has recently been made towards the development of simulation workflows to estimate overall operational building energy use across neighbourhoods (Reinhart & Cerezo, 2016).

In Reinhart & Cerezo (2016) reviewed the data input at an urban building energy modelling. For geometry data consisted of building envelope shapes and windows open ratios as well as terrain data, the information can be extracted from datasets or generated from scratch. Over the past decades, city-wide Geographic Information System (GIS) databases are increasingly accessible to the general public that can be used to generate extruded or 2.5D massing models of whole cities. For the non-geometry building properties; such as infiltration, equipment loads and occupant behaviour; construction assembly and HVAC systems at an urban scale the collection data at individual building level is impractical due to the enormous modelling effort. It is, therefore, necessary to abstract a building stock into "reference building". The reference building approach has been extensively used in the context of national bottom-up building stock model to understand the aggregated impact of energy efficiency policies.

Regarding thermal modelling, Reinhart & Cerezo (2016) reviewed the workflows at urban level which differs in the type (steady-state or dynamic) and detail of thermal model used (single or multiple zone) as well as the effect of surrounding buildings (the shading between buildings, wind speed). The simplest case consists of single zone and steady-state heat balance models of each building archetype. Same as single zone models, multi-zone models can either be generated for archetypes buildings only or for each building individually so that solar shading can be considered as well. However, while building a multi-zone model for select archetypes is still feasible manually, this process has to be automated if applied to all buildings. In dense urban setting being able to model local wind speed and longwave radiation exchange between buildings in addition to direct shading can become relevant to quantify the impact of urban microclimate which has been applied using computer fluid dynamic (CFD) models (Reinhart & Cerezo, 2016).

2.4.1 Representativeness of Buildings

In the guidelines of the EPBD (2010), three methodologies are suggested for the determination of reference buildings from data collected:

d) Example Reference Building

   Used when there is no available data so the information is gotten from literature such as manuals, standards, etc., or from the knowledge of experts in the field. Therefore, the RB is a non-real building that is supposed to have the most likely features of the building stock.

e) Real Reference Building

   Based on on-site surveys and it results from a selection of existing buildings in the sample to represent its cluster. The building type shows characteristics similar to the mean geometrical and construction features of the statistical sample.

f) Theoretical Reference Building.

Based on statistical analysis and is developed from the combination of the most representative features of its cluster. The model is not a real building but a virtual one with statistical characteristics.

Different criteria have been adopted by the scientific community for defining samples for RB characterization. In the TABULA project, which was a three-year project (2009-2012) within the European programme that aimed at creating a harmonised structure for European building typologies, the buildings classification was according to: the location and, thus, climate zone; year of construction, related to constructive principals and materials; and type and shape of the buildings (Ballarini, Corgnati, & Corrado, 2014).

2.4.1.1 Reference Buildings for the District Level

Monteiro, Pina, Cerezo, Reinhart, & Ferrão (2017) presented a methodology to define archetypes for urban building energy modelling, as shown in Figure 7. The methodology consists of a hierarchical tree, establishing different tiers of detail based on selected parameters; in this case 5 levels were applied: Main Use (Residential), Construction period, Size-class (single or multi-family), Roof type (flat or slope) and Neighbouring (isolated or contiguous unit). For each tier, the buildings in the study area were assigned to the corresponding archetype and the share of total built area associated with each archetype were estimated, determining its representativeness. For collecting and processing the whole data, a GIS database was used. For characterising the building, ***average values*** were calculated for relevant geometric inputs; in this study were considered 7 variables: length, width, height, orientation, floor number, dwelling number and WWR (wall window ratio). The results showed significant discrepancies in the energy demand among different tiers which accordingly to the authors this is due to the variability of the parameters used and its representativeness.

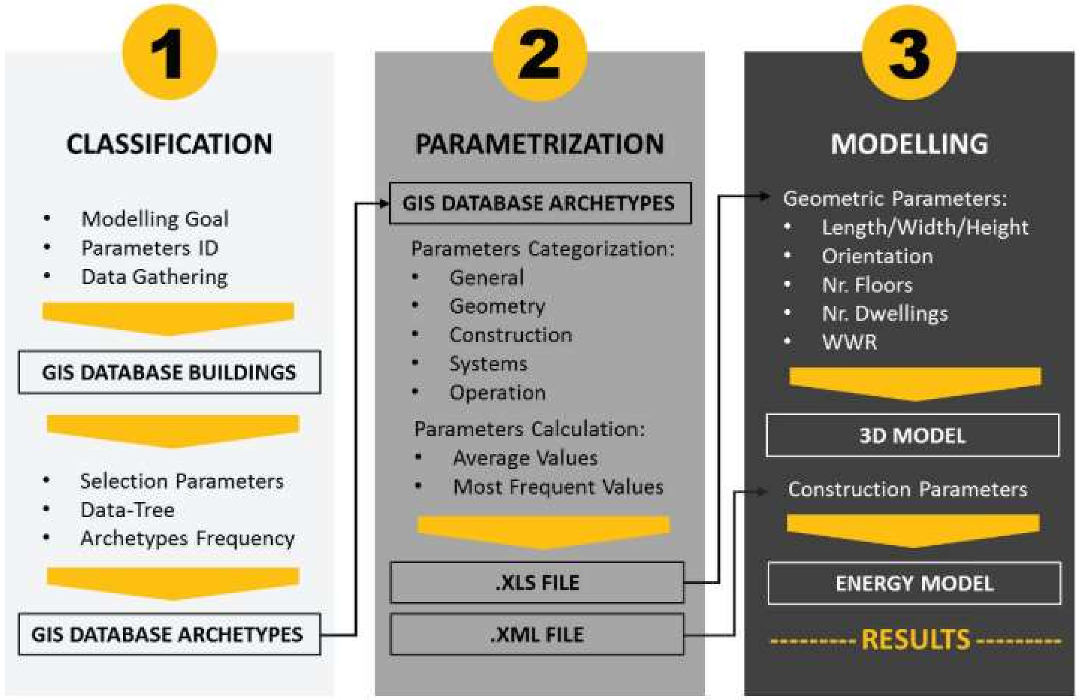


Figure 7: Methodology to define Archetypes for Urban Building Energy Modelling (Monteiro et al., 2017).

Ghiassi & Mahdavi (2016) developed an automated sampling process to obtain archetypes for Urban Building Energy Modelling by applying Multivariate Cluster Analysis Method to available large scale data to arrive at a set of buildings that represented the energy performance diversity of the investigated area. For characterising the buildings, a set of numerical variables that represented the geometric, semantic, operational and contextual aspect of the building were defined (net volume, thermal compactness, effective floor height, envelope U-Value, glazing ratio, daily internal gains). For the collection data a GIS database and available data was analysed and processed. The samples or archetypes were then subjected to simulations. The results of these were up-scaled to the entire building assembly. In Figure 8 is shown the methodology.

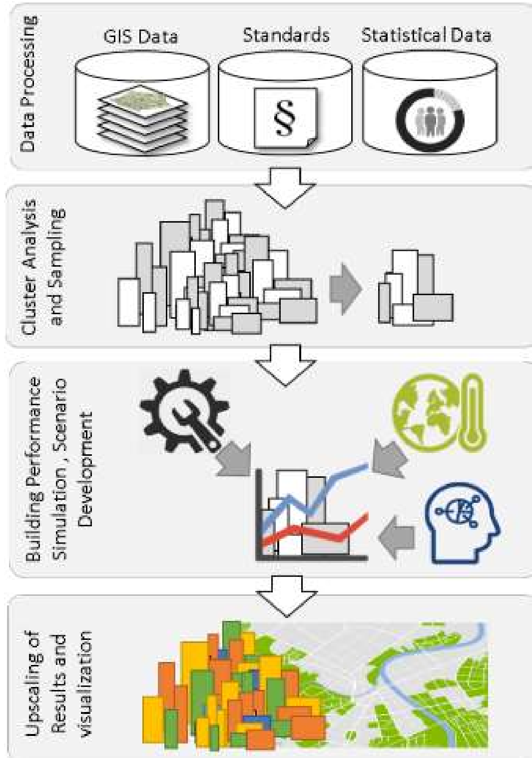


Figure 8: Methodology to define Archetypes for Urban Energy Modelling (Ghiassi & Mahdavi, 2016)

Li et al. (2018) presented a method for developing typical residential reference buildings at district level by means of widely and freely available satellite images. Furthermore, an information database of buildings shapes was created and a clustering analysis of geometrical features was performed to define the number of reference buildings for energy performance of the district. The method was tested through a case study in a Chinese district by comparing the energy consumption from clustered reference buildings and building-by-building simulations and the results showed very small differences in the estimated stock energy consumption.

Clustering has been widely used in the building energy research for different purposes including building archetype development. Li et al. (2018) described some examples of this application making this technique suitable for it.

2.4.1.1.1 Cluster Analysis

Cluster analysis is a multivariate analysis technique which aims to group objects from a sample of a set of measured variables into a number of different clusters so that objects

within the same cluster have very similar features (high internal homogeneity), while objects from different clusters have low similarity (high external heterogeneity).
There are two main methods: hierarchical and non-hierarchical cluster analysis.

a) Hierarchical Cluster analysis

Hierarchical clustering combines cases into homogeneous clusters by merging them together one at a time in a series of sequential steps. At each step, two objects are grouped according to the measure of similarity between them and the rules of the selected partition algorithm, forming a new cluster. This technique allows the construction of a diagram called dendrogram, which indicates, as shown in Figure 9, in *x* axis the similarity level obtained at each new joint and in the *y* axis the different cases.
Objects that are more similar to each other are joined early in the process, while less similar objects are joined only at the end of the process. As Figure 9 depicts, an example in which is observed that the AB cluster was formed early in the process, suggesting that the objects A and B are very similar, while the CDE cluster was formed with a lower similarity level, indicating that the objects of this cluster have less similar characteristics.

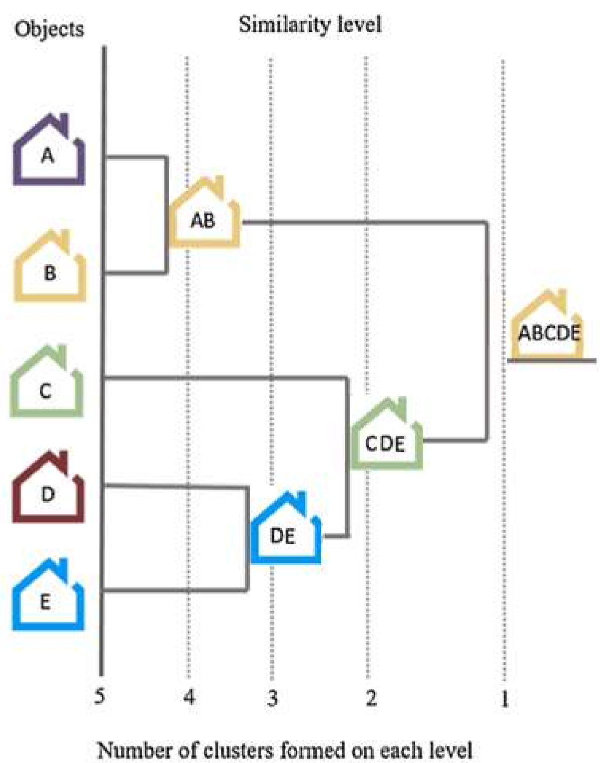


Figure 9*:* Dendrogram construction process (source: Schaefer & Ghisi, 2016).

b) Nonhierarchical techniques (e.g., k-means clustering)

In a non-hierarchical technique, the clustering process happens interactively, an initial set of cluster means must be established and then assign each case to the closest cluster mean. From seed points, the objects are distributed into clusters simultaneously and, at the end of the partition, some objects are relocated to other clusters, until no object resembles more to other cluster than the one in which it is allocated.

This method requires the researcher to establish a priori the number of clusters in the final solution. If there is uncertainty about the total number of clusters in the dataset, the analysis must be re-run for each possible solution. In this situation, **hierarchical clustering is preferred** as it allows to compare the clustering result with an increasing number of clusters; no decision about the final number of clusters needs to be made a priori.

2.4.2 Energy Performance assessment

Energy performance evaluation of buildings has experienced a major boost over the past decades as advanced techniques and methodologies are being developed (Aghamolaei et al., 2018). Kavgic et al. (2010) pointed out two fundamental classes of modelling methods to predict and analyse various aspects of the overall building stock energy use performance and associated CO_2 emissions: the top-down and bottom-up approaches:

2.4.2.1 Top-down approach

This approach works at an aggregated level and considers the overall energy consumption of the residential sector, typically aimed at fitting a historical time series of national energy consumption or CO_2 emissions data. The econometric top-down models are primarily based on energy use in relationship to variables such as income, fuel prices, and gross domestic product to express the connection between the energy sector and economic output. It is used to identify factors defining changes in energy consumption trends on the long-term.

According to Kavgic et al. (2010) this approach often lack details on current and future technological options as they place the emphasis on the macroeconomic trends and relationships observed in the past, rather than on the individual physical factors in buildings that can influence energy demand.

2.4.2.2 Bottom-up approach

The bottom-up models are built up from data on a hierarchy of disaggregated components that are combined according to some estimate for their individual impact on energy usage. This approach accounts for models considering small samples with similar characteristics that later can be used to extrapolate the results and needs extensive databases of empirical data to support the description of each component.

There are two distinct approaches applied in the bottom- up models, building physics and statistical based methods, to determine the energy consumption of specified end-uses.

2.4.2.2.1 Building physics

Building physics-based modelling techniques generally include the consideration of a sample of houses representative of the national housing stock and utilization of a building energy calculation method to estimate the delivered energy consumption.

The approaches for building physics can be *steady-state* or *dynamic*. A steady-state model performs a mass and energy balance of a steady state process independent of time, therefore it is unable to address temporal changes in demand. On the other hand, a dynamic simulation is an extension of steady-state process simulation whereby time dependence is built into the models via derivative terms, i.e. accumulation of mass and energy. Dynamic models are certainly more complex than steady-state ones, but they become so much more effective and preferable as the phenomenon under consideration shows significant variations over time (Vincenzo & Enrico, 2019).

The required data input is composed of quantitative data on physically measurable variables, such as the efficiency of space heating systems and their characteristics, information on the areas of the different dwelling elements (walls, roof, floor, windows, doors) along with their thermal characteristics (U-values), internal temperatures and heating patterns, ventilation rates, energy consumption of appliances, number of occupants, external temperatures, etc.

In Europe, bottom-up building physics stock models are seen as useful tools to provide policymakers with estimates for the effectiveness of policies and can help to identify technological measures that end-use efficiencies A level of building physics stock model's complexity is determined by their core calculation engines.

2.4.2.2.2 Statistical models

Most of the bottom-up statistical models are based on regression techniques and uses historical data on energy consumption to identify the source of the energy consumption from particular end-uses. Compared to the physics model do not require physical information about the building or systems and it includes Multiple Linear Regression or Conditional Demand Analysis, Genetic Algorithm, Artificial Neural Network, and Support Vector Machine.

2.4.2.2.3 Hybrid models

There is a third approach that consists in the development of hybrid models that combines the two types previously described. This is the case when building physics-based models rely on statistics for much of their empirical data, for instance average hot water demand per person. Some of the more sophisticated models combine, in a more fundamental way, components where both building physics and statistical approaches have been applied.

According to Fumo (2014) the accuracy of any approach depends on the information that is available for the purpose of the approach. In this way, statistical approaches need measured data but not buildings characteristics, while the building physics approach needs building characteristics but not data. Therefore, the best approach depends on what type of information is available and in what magnitude.

Aghamolaei et al. (2018) presented energy performance methods applied at a district scale:

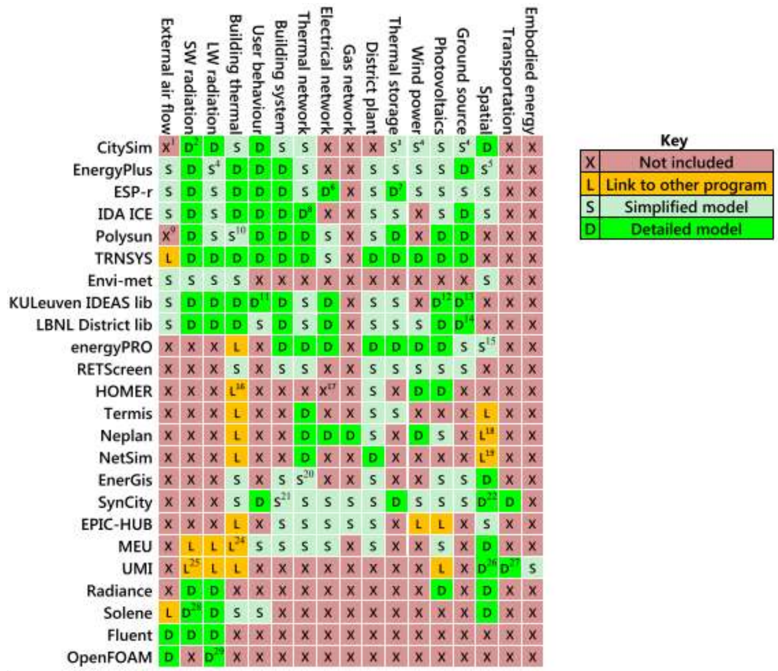
- Parametric methods: such as sensitivity analysis identifies the value of each parameter individually and in relation to others, based on the multi-objective nature of energy issue in districts, it usually exists no single optimal solution, that means when a large number of solutions are available the required evaluation and selection process is more difficult.
- Data-driven methods: this kind of approach is emerging as new tools to analyse and understand the energy performance of multiple buildings within a dense urban area (Aghamolaei et al., 2018). Data-driven machine learning models have been integrated with traditional physics-based energy simulations to enable more accurate simulation results on multiple scales (single building, community, urban). These techniques result in a more accurate and robust energy performance characterization and simulation of urban buildings.

- Optimization method: it guides the planners and managers to one or more optimised scenarios representing the fittest condition based on the priorities, goals, limitations and delimitations. Significant studies have developed multi-objective optimization algorithms for district energy systems, which deal with the diverse set of solutions based on stakeholder preferences. Multi-criteria analysis utilises mathematical methods such as Pareto analysis to obtain the most fitting solution for the optimum and feasible condition.

Problems faced by the existence of multiple and competing objectives and wide variety of solutions require special methods such as Multi-Criteria analysis or Analytic Hierarchy Process since these methods ensure a balance by assigning a proper weight to each parameter based on its priority and presents the most appropriate solution (Aghamolaei et al., 2018).

According to Amaral et al. (2018) the performance simulation techniques and design optimization are dominant amongst the tools and methods used in a district scale and can be an efficient way to obtain the best option for each case. Koutra et al. (2018) reviewed thirteen Simulation tools that deal with districts: CitySim, analyses thermo-physical properties of buildings on an urban scale; SimStadt, studies heating demands, PV potential and renewable energy supply; NEST assessment tool, assesses both environmental and socio-economic indicators; TRNSYS, simulates thermal and electrical energy systems.

Allegrini et al. (2015) reviewed models and tools that address both the demand and supply sides of energy systems, and their application to district-level design problems. It provides a matrix (see Figure 10) in which twenty tools are shown along with their capabilities in modelling sixteen topic areas of relevance to urban energy system design such as energy air flow, long and short wave radiation, building thermal, user behaviour, building system, thermal storage, wind power, photovoltaics, embodied energy, etc.



	External air flow	SW radiation	LW radiation	Building thermal	User behaviour	Building system	Thermal network	Electrical network	Gas network	District plant	Thermal storage	Wind power	Photovoltaics	Ground source	Spatial	Transportation	Embodied energy
CitySim	X[1]	D[2]	D	S	D	S	S	X	X	X	S[3]	S[4]	S	S[4]	D	X	X
EnergyPlus	S	D	S[4]	D	D	D	S	X	X	S	S	S	S	D	S[5]	X	X
ESP-r	S	D	S	D	D	D	S	D[6]	X	S	D[7]	S	S	S	S	X	X
IDA ICE	S	D	S	D	D	D	D[8]	X	X	S	S	X	S	D	S	X	X
Polysun	X[9]	D	S	S[10]	D	D	D	S	X	S	D	X	D	D	X	X	X
TRNSYS	L	D	D	D	D	D	D	S	X	D	D	D	D	D	X	X	X
Envi-met	S	S	S	S	X	X	X	X	X	X	X	X	X	X	S	X	X
KULeuven IDEAS lib	S	D	D	D	D[11]	D	S	D	X	S	S	X	D[12]	D[13]	X	X	X
LBNL District lib	S	D	D	D	S	D	S	D	X	S	S	S	D	D[14]	X	X	X
energyPRO	X	X	X	L	X	D	D	D	X	D	D	D	D	S	S[15]	X	X
RETScreen	X	X	X	S	X	S	S	X	X	S	S	S	S	S	X	X	X
HOMER	X	X	X	L[16]	X	X	X	X[17]	X	S	X	D	D	X	X	X	X
Termis	X	X	X	L	X	X	D	X	X	S	S	X	X	X	L	X	X
Neplan	X	X	X	L	X	X	D	D	D	S	X	D	S	X	L[18]	X	X
NetSim	X	X	X	L	X	X	D	X	X	D	X	X	X	X	L[19]	X	X
EnerGis	X	X	X	S	X	S	S[20]	X	X	S	X	X	S	S	D	X	X
SynCity	X	X	X	S	D	S[21]	S	S	S	S	D	S	S	S	D[22]	D	X
EPIC-HUB	X	X	X	L	X	S	S	S	S	S	X	L	L	X	S	X	X
MEU	X	L	L	L[24]	S	S	S	S	X	S	X	X	S	X	D	X	X
UMI	X	L[25]	L	L	X	X	X	X	X	X	X	X	L	X	D[26]	D[27]	S
Radiance	X	D	D	X	X	X	X	X	X	X	X	X	D	X	D	X	X
Solene	L	D[28]	D	S	S	X	X	X	X	X	X	X	X	X	D	X	X
Fluent	D	D	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X
OpenFOAM	D	X	D[29]	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 10: Software tools and packages capabilities matrix (source: *Allegrini et al. (2015)*).

The trend towards increasing use of urban-level design and analysis is in some cases surpassing the capabilities of tools that were developed for use at the building-level (Allegrini et al., 2015). One of the main challenge to move nZEB towards nZED is the definition of the boundaries for developing properly performance assessment methodologies, enlarging the scale of intervention and therefore enlarging the complexity and design constraints that influence the energy performance (Amaral et al., 2018).

Districts are composed of several subsystems where accurate and effective models need to consider the different subsystems together, the multidisciplinary and numerous effective parameters of district scale studies have resulted in the ambiguity of defining methodologies and the complexity of the calculations involved deems it mandatory to implement the most effective method for performing these calculations (Aghamolaei et al., 2018). There is a trend towards broader tools that attempt to simulate many aspects of the urban system at once and other approaches that integrate specific models that each address particular facets of the problem into one combined environment such that they can share inputs, link outputs to the inputs of other models (Allegrini et al., 2015).

Given that even individual building energy modelling predictions may significantly differ from measured results due to uncertainties, it may initially seem unlikely that an urban building energy modelling will be capable of faithfully predicting the energy use of many buildings. However, when comparing aggregated annual measured versus simulated energy use of multiple buildings, these individual model inaccuracies tend to average out, reaching acceptable error ranges for guiding decisions that affect multiple buildings (Reinhart & Cerezo, 2016).

In conclusion, the promotion on energy saving has introduced new concepts such as nearly zero energy applied to either building or district scale, and new methods like the cost-optimal methodology to reduce the energy demand to almost zero. The research on this field has shown an increasingly attention to encompass this topic from an integrated and holistic way by analysing the issue not just as an isolated matter, like a building level, but instead considering the whole district or neighbourhood with the effects of its surroundings, thus allowing to achieve more accurate results. Nowadays, the knowledge in new techniques and technology enable to follow this trend.

CHAPTER 3. METHODOLOGY

The objective of this chapter is to explain the methodology developed in this dissertation work describing each of its steps in detail and the tools used. The methodology involved two main steps, (1) Statistical Analysis for the definition of the Reference Building, which was split into three phases, and (2) Energy Performance Assessment, as depicted in Figure 11.

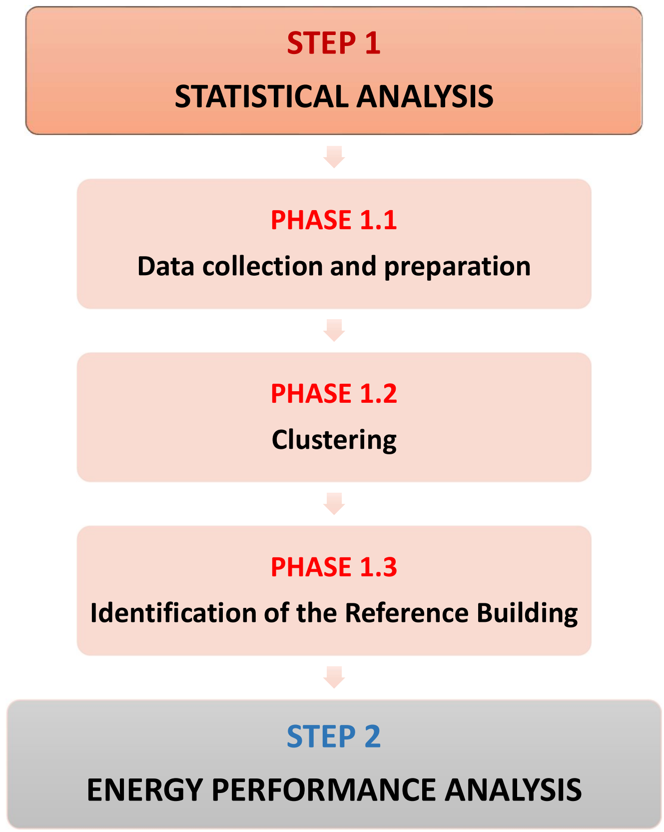


Figure 11: Methodology Scheme.

3.1 STEP 1: STATISTICAL ANALYSIS

The first step was the definition of reference buildings through a statistical Analysis technique. The Cluster Analysis was chosen in order to create groups of buildings with similar geometric features that were more influential on thermal and energy performance. This technique was picked up because of its inherent advantages, having an unsupervised machine-learning approach that automatically divides data into sub-groups, and also has been applied widely in the building energy research (Li et al., 2018).

The procedure involved three phases: the initial one was the data collection and preparation that was used later as an input to the statistic technique, the second was the application of the method of clustering itself, and the last one was the identification of the reference buildings, which included the determination of the number of clusters and the geometric characteristics definition of each one.

3.1.1 PHASE 1.1: DATA COLLECTION AND PREPARATION

In the first phase, a database of buildings geometric feature from the neighbourhood was collected, prepared and organised. This set of variables was defined based on a literature research (Brandão de Vasconcelos, Pinheiro, Manso, & Cabaço (2015), Caputo, Costa, & Ferrari (2013), Ascione, De Masi, de Rossi, Ruggiero, & Vanoli (2016), Amaral et al. (2018) and Signor, Simon, & Lamberts (2001)) on the most influential geometric parameters on the building thermal and energy performance as shown in Table 6. This dataset was analysed to avoid repeated or redundant data entries and to get a complete database to use later as an input on the clustering algorithms.

Table 6*:* Influential Building Variables on thermal performance. Source: adapted from Brandão de Vasconcelos et al. (2015), Caputo et al. (2013), Ascione et al. (2016), Amaral et al. (2018) and Signor et al. (2001).

Building Variables
Physical properties of the building (geometry and thermal properties)
Floor area
Orientation
Number of levels
Number of units
Window to wall ratio
Window area
Net volume
Floor-to-floor height
Shape of the building
Height
Size
internal load density
Roof Area/Total Area
Façade Area/Total Area
ILD – internal load density
Built form

Building Variables
Physical properties of the building (geometry and thermal properties)
Footprint Shape
Surface to volume
Heated volume
Exposed end area
Height/Floor height
Roof shape
Type of lowest floor
Air change rate (ac/h)
number of storeys
number of exposed walls
Average floor area
Use profiles (schedules, set points, user behaviour)
Occupancy
Ratio of daytime use hours to overall use hours
Daily air-change rate
Number of occupants
Urban contextual parameters (adjacencies, obstructions)
Sky View Factor

In a second stage, the above list was shortened to avoid redundant items and consider the buildings characteristics of the neighbourhood. The variables chosen were those most often used in the reviewed literature as well as obtainable from the available information. Then, the parameters applied for the cluster analysis in the case study were exposed areas, the ratio between wall and windows, floor surfaces and number of storeys of the buildings.

3.1.2 PHASE 1.2: CLUSTERING

The cluster analysis was performed using the SPSS 20.0 statistical software package. The method applied was the hierarchical clustering, which needs a set of specific parameters to run the analysis; the distance measure, the linkage method and the score standardisation. The distance measure is the distance or similarity between cases and is measured by a statistic. In a hierarchical clustering all objects start as an individual cluster, then they are all merged through a linkage method. When the parameters are not measured on the same units it is needed to transform the values applying to them a standardization method.

The linkage measure was the *between-group linkage* that is equivalent to average linkage between groups and the proximity between two clusters is the arithmetic mean of all the proximities between the cases of one and other. The distance measure used was the squared Euclidean distance as it is the most common one for continuous variables (Yim & Ramdeen, 2015). Finally, as a standardization method was used one of the two most common transformation options, the *z-score* (Yim & Ramdeen, 2015).

3.1.3 PHASE 1.3: IDENTIFICATION OF THE REFERENCE BUILDING

The final phase of the first step consisted of the identification of the number of clusters by analysing the graphical representation (dendrogram) that groups the cases according to the similarity level among them. The characteristics of each cluster were obtained by calculating a descriptive statistic of the median of each variable within every cluster, and so those geometric features represented the attributes of the reference buildings.

3.2 STEP 2: ENERGY PERFORMANCE ASSESSMENT

The step two was the application of energy performance assessment and variation analysis to both the reference buildings and the different buildings of the neighbourhood. The simulation of the buildings, included the reference typologies, was made under two scenarios; the first one considered no intervention in the buildings (i.e. initial state) while in the second were applied thirteen energy saving measures on the buildings´ envelope to run a parametric analysis. Thus, the total cases were fourteen (14).

The outputs considered for the energy performance simulation were two, the annual heating and cooling load per area (kWh/m^2.year). Therefore, each case had four (4) outputs; heating load for scenario 1 and 2, and cooling load for scenario 1 and 2. Having those results, a variation analysis was carried out considering the percentage difference between the two scenarios in order to verify the accuracy of the use of reference buildings to assess energy performance at a neighbourhood scale.

The renovation measures chosen took into consideration firstly that 50-75% of savings could be reached by passive interventions according to the International Energy Agency in Aguacil et al. (2017), and secondly the feasibility of a parametric analysis obliged to simplify and limit the number of cases to be run in each constructive element.

As part of this step a contrasting analysis was applied with the first results obtained from the dynamic simulations to evaluate the precision of these values. The seasonal quasi-

steady state method approach in the Portuguese Regulation of Energy Performance of Residential Buildings (REH, 2013) was used for this purpose.
In order to perform the energy analysis, dynamic simulations using EnergyPlus software were calculated. EnergyPlus was chosen because is one of the most robust and widespread tool used in the building energy analysis community around the world for both academic and commercial levels as well as is an open source and freely downloadable (Fumo, et al. (2010), Vincenzo & Enrico (2019)).

3.2.1 EnergyPlus

The EnergyPlus is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources. It is also an integrated simulation which means that all major parts, the building zones, air handling systems, and central plant equipment are simulated simultaneously with feedback from one to the other.
This software is based on an integrated simulation of the zone and the air-conditioning system in an iterative process. A predictor–corrector scheme estimates the thermal load of each zone and passes it to the systems simulation side, where the actual capacity of the systems, as a function of the previous time-step conditions, is determined and passed again to the zone simulation side. This serves to update and compute the actual indoor air temperature of the zone under investigation and it is performed in an iterative way until the convergence is reached.
The program computes the heat loads through the *Air Heat Balance* of the enclosure considering the simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step through the *Surface Heat Balance*.

a) Air Heat Balance

The basis for the zone and air system integration is to formulate energy and moisture balances for the zone air and solve the resulting ordinary differential equations. The formulation of the solution scheme starts with a heat balance on the zone air.
The Air Mass Balance Module deals with various mass streams such as ventilation and exhaust air, and infiltration.

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{Nsl} \dot{Q}_i + \sum_{i=1}^{Nsurfaces} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{Nzones} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys}$$

Where:

$C_z \frac{dT_z}{dt}$=energy stored in zone air
$\sum_{i=1}^{Nsl} \dot{Q}_i$=sum of the convective internal loads
$\sum_{i=1}^{Nsurfaces} h_i A_i (T_{si} - T_z)$=convective heat transfer from the zone surfaces
$\sum_{i=1}^{Nzones} \dot{m}_i C_p (T_{zi} - T_z)$=heat transfer due to interzone air mixing
$\dot{m}_{inf} C_p (T_\infty - T_z)$=heat transfer due to infiltration of outside air
$\dot{Q}_{sys}$=air systems output

b) Surface Heat Balance

The Surface Heat Balance Module simulates inside and outside surface heat balance, interconnections between heat balances and boundary conditions, conduction, convection, radiation, and mass transfer (water vapour) effects.

- **Inside Heat Balance**

The heart of the heat balance method is the internal heat balance involving the inside faces of the zone surfaces. This heat balance is generally modelled with four coupled heat transfer components:

1) Conduction through the building element
2) Convection to the air
3) Short wave radiation absorption and reflectance
4) Longwave radiant interchange.

The incident short wave radiation is from the solar radiation entering the zone through windows and emittance from internal sources such as lights. The longwave radiation interchange includes the absorption and emittance of low temperature radiation sources, such as all other zone surfaces, equipment, and people. The heat balance on the inside face can be written as follows:

$$q''_{LWX} + q''_{SW} + q''_{LWS} + q''_{ki} + q''_{sol} + q''_{conv} = 0$$

Where:

q''_{LWX} = Net longwave radiant exchange flux between surfaces in a zone or group of zones (enclosure).

q''_{SW}= Net short wave radiation flux to surface from lights.
q''_{LWS}= Longwave radiation flux from equipment in a zone or group of zones (enclosure).
q''_{ki}= Conduction flux through the wall.
q''_{sol}= Transmitted solar radiation flux absorbed at surface.
q''_{conv}= Convective heat flux to zone air.

- **Conduction through the building elements**

The heat transfer simulation through building elements is by Conduction Transfer Functions (CTFs) which are an efficient method to compute surface heat fluxes and whose form reveals that with a single, relatively simple, linear equation with constant coefficients, the conduction heat transfer through an element can be calculated. The basic form of CTFs solution is shown by the following equation:

$$q''_{ki}(t) = -Z_o T_{i,t} - \sum_{j=1}^{nz} Z_j T_{i,t-j\delta} + Y_o T_{o,t} + \sum_{j=1}^{nz} Y_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ki,t-j\delta}$$

for the inside heat flux, and

$$q''_{ko}(t) = -Y_o T_{i,t} - \sum_{j=1}^{nz} Y_j T_{i,t-j\delta} + X_o T_{o,t} + \sum_{j=1}^{nz} X_j T_{o,t-j\delta} + \sum_{j=1}^{nq} \Phi_j q''_{ko,t-j\delta}$$

for the outside heat flux (q” = q/A)

where:

X_j= Outside CTF coefficient, j = 0,1,…nz.
Y_j= Cross CTF coefficient, j = 0,1,…nz.
Z_j=Inside CTF coefficient, j = 0,1,…nz.
Φ_j=Flux CTF coefficient, j = 1,2,…nq.
T_i=Inside face temperature
T_o=Outside face temperature
q''_{ko}=Conduction heat flux on outside face
q''_{ki}= Conduction heat flux on inside face

- **Convection from Surfaces**

The surface convection load requires the most complicated calculations because a detailed energy balance is required at the inside and outside surface of each wall, floor, and roof. In addition, the transient heat conduction in the material between the surfaces must be solved as it was explained above. This solution gives the inside and outside temperatures and heat fluxes that must be known in order to calculate the convection component to the zone load for each zone surface.

The convective heat transfer from surfaces is expressed as follows:

$$q_{conv} = \sum_{i=1}^{nsurfaces} h_{c,i} A_i \left(T_a - T_{s,i}\right)$$

Where T represents temperature, a air, s surface, A area and $h_{c,i}$ the inside heat transfer coefficient which is modelled from a choice of correlations.

Inputs and considerations were assumed in the EnergyPlus programme, as shown in Table 7. In the following paragraphs some of them were explained in details:

Firstly, for the case study the comfort temperatures considered were 25°C for cooling and 18°C for heating, which is aligned with how the current Portuguese thermal and energy regulations define indoor comfort temperature. Besides, the Portuguese adaptive model of thermal comfort from the National Civil Engineering Laboratory (LNEC) gives a range of values instead of fixed ones taking into account the occupants may tolerate broader temperature ranges since their thermal perception/sensation is strongly influenced by the outdoor temperature (Fernandes et al., 2020).

Secondly, for the ventilation input, accordingly to Pinto & Peixoto de Freitas (2002) the National Laboratory of Civil Engineering (LNEC) recommends for the natural ventilation of residential buildings an average of one renewal per hour in main rooms (bedrooms and living/dining rooms) and four renewals per hour in service rooms (kitchens and bathrooms). As a simplification in the case study was considered the former value, equal to one air change per hour, for all conditioned areas, which did not consider bathrooms nor corridors.

Thirdly, for the case study, the weather file was obtained from the EnergyPlus database and picked Porto for being the closest location to the project.

Fourthly, for the internal heat gains from equipment, people occupancy and lighting a standard and constant value of 4 W/m^2 for residential buildings was used. This quantity is aligned to the Portuguese Regulation of Energy Performance of Residential Buildings and was used in order to simplify the calculations.

Finally, in order to simulate in an accurate way the heat transfer of the horizontal building surfaces in contact with the ground a tool in EnergyPlus was run which uses surface heat balance algorithms, where long and short wave radiation, conduction, and convection are considered, and a finite difference formulation to solve for the ground temperatures.

Table 7: Inputs and considerations for dynamic simulation in EnergyPlus.

Parameter	Value	Unit
Heating Setpoint	18	°C
Cooling Setpoint	25	°C
Ventilation rate	1	AirChange/hour
Internal Gains	4	W/m^2

In short, the approach proposed here for developing the methodology to define reference buildings was divided in two blocks. The first one aimed at identifying the buildings that best represented the whole neighbourhood regarding the energy performance through the application of the statistic technique *Cluster Analysis*, while the other part focused on analysing the accuracy of those reference typologies by comparing dynamic simulation results using in one case the existing buildings and the other the reference ones. This latter comparison process was also implemented on a set of renovation measures in order to extend the assessment.

CHAPTER 4. CASE STUDY CHARACTERISATION

In this chapter, the case study neighbourhood used in order to demonstrate the application of the methodology is characterized and its main features are explained, as well as the renovation measures considered.

4.1 ANDORINHAS NEIGHBOURHOOD

The Andorinhas neighbourhood is located in Braga, Portugal. It has in total 115 dwellings in 32 buildings distributed in two perpendicular directions, aligned very close to East-West and North-South orientation, as shown in Figure 12.

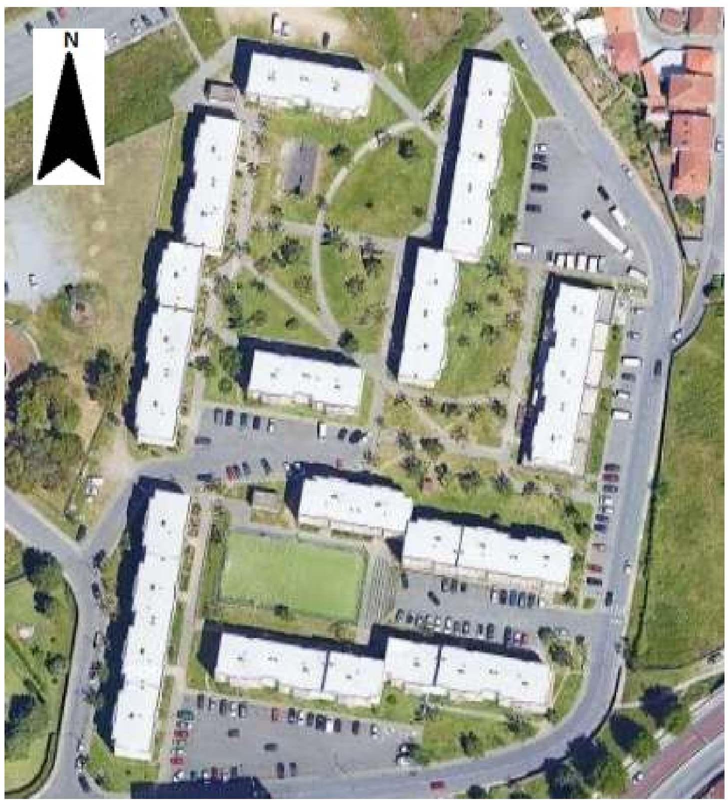


Figure 12: Satellite photo of Andorinhas Neighbourhood (source: Google Map).

The Figure 13 displays the layout and the numbering assigned to each building of the neighbourhood for later calculations.

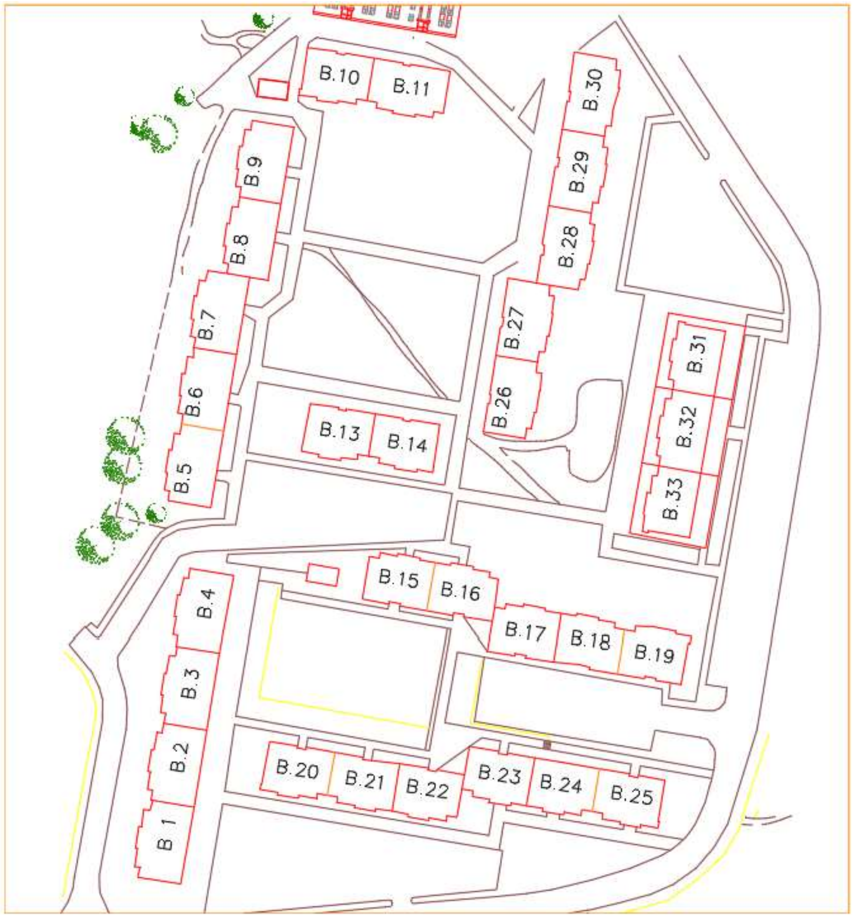


Figure 13: Andorinhas Neighbourhood Layout.

The neighbourhood has three different dwellings, categorized by T2, T3 and T4 accordingly to the number of bedrooms; 2, 3 and 4 respectively. The Figure 14 shows the architectural plans of each one and Table 8 the total area. All buildings are formed by 2 different dwellings in each floor, which may be either a combination between the typologies T2-T3 or T3-T4. The number of floors varies between 3 and 4.

Table 8: Total Area dwellings.

Dwelling type	Total Area [m^2]
T2	68
T3	82
T4	97

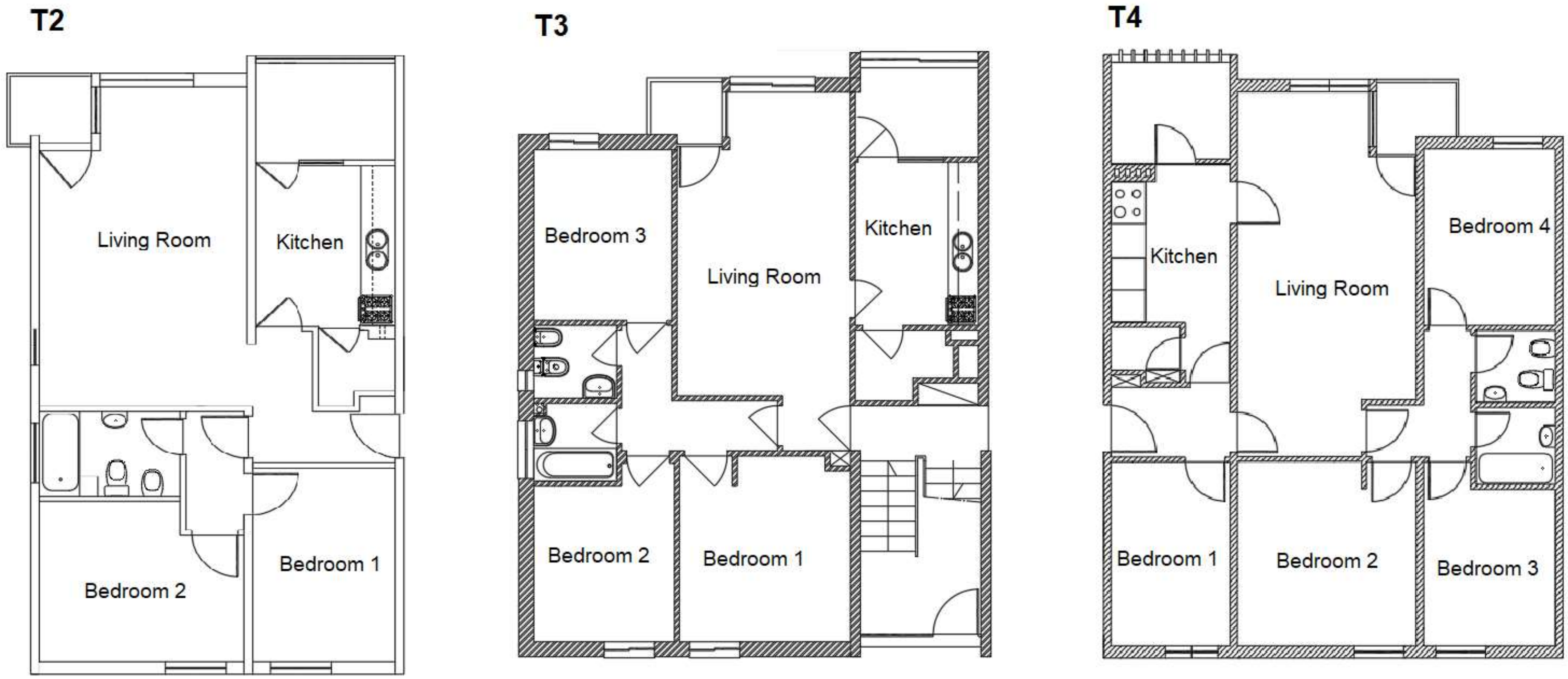


Figure 14: Dwelling typologies T2, T3 & T4 - Architecture plants.

The results in Table 9 and Table 10 indicated that 53% of buildings were orientated towards East-West and 47% to South-North, and the amount of combination types of dwellings were quite similar between the two kind, T2-T3 and T3-T4, with 51% and 49% respectively.

Furthermore, those tables showed that a bit more than three quarter (76%) of buildings orientated to the East-West had 3 floors and 24% four, and the majority of floors were composed by T3-T4 dwelling combination with 95% and just 5% were T2-T3. On the other hand, all buildings aligned to the South-North were built with 4 floors and 93% of them were comprised by T2-T3 dwelling combination and only 7% were T3-T4.

Table 9*: Floor number-Orientation Cross tabulation.*

			Floor Number		**Total**
			3	**4**	
Orientation	East-West	Count	13	4	17
		%within Orientation	76%	24%	100%
		%within Total	40.6%	12.5%	53.1%
	South-North	Count	-	15	15
		%within Orientation	0%	100%	100%
		%within Total	0%	47%	47%
Total		Count	13	19	32
		%	41%	59%	100%

Table 10*: Dwelling typology – Orientation Cross tabulation*

			Dwelling Typology		**Total**
			T2-T3	**T3-T4**	
Orientation	East-West	Count	3	52	55
		%within Orientation	5%	95%	100%
		%within Total	2.6%	45.2%	47.8%
	South-North	Count	56	4	60
		%within Orientation	93%	7%	100%
		%within Total	48.7%	3.5%	52.2%
Total		Count	59	56	115
		%	51%	49%	100%

From the construction point of view, the Andorinhas neighbourhood was built in 1983, consequently the characteristics of building materials considered in this case study were those from construction common practices used in the 80´s as described in Table 11.

Table 11*:* Characterization of building elements.

Construction element	Description	U-value [W/m².°C]
Exterior Walls	Double brick wall with air gap and coated from both sides: • Brick: 11 cm • Air gap: 4 cm • Plaster: 1 cm • Total wall: 28 cm	1.1
Interior Walls	Simple brick wall coated from both sides: • Brick: 11 cm • Plaster: 1 cm • Total wall: 13 cm	1.61
Slab	Lightened slab: wooden beam. Thickness: 20 cm	1.85
Windows	Windows with timber frame, simple glass and PVC outdoor blinds	4.3
Roof	Reinforced concrete slab 15 cm thickness and Pitched roof covered by sandwich panels composed by thermal isolation confined from both sides by steel sheets.	3.5

Regarding renovation interventions for the case study, the focus was just on passive interventions, specifically on the roof and on the exterior walls where five different insulation thicknesses were considered, plus an additional case on the wall where it was considered the injection of insulation material in the air gap between the bricks; on the windows two cases were contemplated modifying the technology of the glazing.

The insulation thicknesses and the U-value used were obtained from a study on the Portuguese building market and the 13 measures are listed in Table 12.

Table 12: Renovation measures details.

	Description	Parameter	Value	Unit
Wall				
(a)	Expanded Polystyrene Insulation (EPS) with thermal conductivity λ=0.03 W/(m.°C)	thickness	3	cm
(b)			6	
(c)			8	
(d)			12	
(e)			16	
(f)	EPS (λ=0.03 W/[m.°C]) injected into the Air Gap.		4	
Roof				
(g)	Expanded Polystyrene Insulation (EPS) with thermal conductivity λ=0.03 W/(m.°C)	thickness	3	cm
(h)			6	
(i)			8	
(j)			12	
(k)			16	
Windows				
(l)	Double Glass 4 mm thickness, 6 mm air gap	U-value	3.3	W/m².°C
(m)	Double Glass 6 mm thickness, low-emissivity exterior glass, 8 mm air gap.		2	W/m².°C

In conclusion, the Andorinhas neighbourhood is characterised by nearly half buildings oriented towards one direction, East-West, and the other to South-North. The former are composed mainly by typology combination T3-T4 and 3 stories while the latter are mostly T2-T3 and comprised by 4 floors. Double bricks with air gap on the walls, reinforced concrete on the roof, lightened slabs for the floor and simple windows form the building structure.

CHAPTER 5. RESULTS AND DISCUSSION

In this chapter the results of the study are presented and their corresponding analysis for all phases of the two main steps according to the methodology proposed and the application in the case study neighbourhood.

5.1 STEP 1: STATISTICAL ANALYSIS

PHASE 1.1 DATA COLLECTION AND PREPARATION

The variables were defined taking into account the list from Table 6 and considering the available data of the neighbourhood in study, drawn from the architectural drawings. Thus, the parameters applied were the wall length exposed, windows area, number of room, floor area, number of storeys and window/wall ratio. Additionally, in order to keep in mind the exact orientation of each building since within both groups, South-North and East-West, there were buildings positioned in two different ways (see Figure 13), the calculation was carried out dividing the analysis into the four cardinal points (**E**ast, **N**orth, **W**est and **S**outh). The average values of the parameters were grouped according to the orientation into South-North and East-West (E-W) as shown in Table 13. The complete and detailed procedure of this information is presented in appendix Table A 1.

Table 13: Average values of physical parameters for buildings oriented S-N and E-W.

Wall exposed Length [m]				Area Windows [m²]				N° room				Area floor [m²]				N° floor	WWR			
E	N	W	S	E	N	W	S	E	N	W	S	E	N	W	S		E	N	W	S
South-North																				
13.8	1.9	12.8	1.9	5.7	0.9	7.2	1.0	4.6	0.0	4.2	0.0	53.9	0.0	58.6	0.0	3.2	0.2	0.0	0.2	0.0
East-West																				
2.2	11.5	2.2	10.7	0.8	5.1	1.5	6.2	0.0	3.7	0.0	3.4	0.0	43.0	0.0	46.3	4.0	0.0	0.2	0.0	0.2

PHASE 1.2 CLUSTERING

The above database was introduced in the statistical software SPSS to run the cluster analysis and the result of the algorithm can be visualised in Figure 15 which shows the dendrogram.

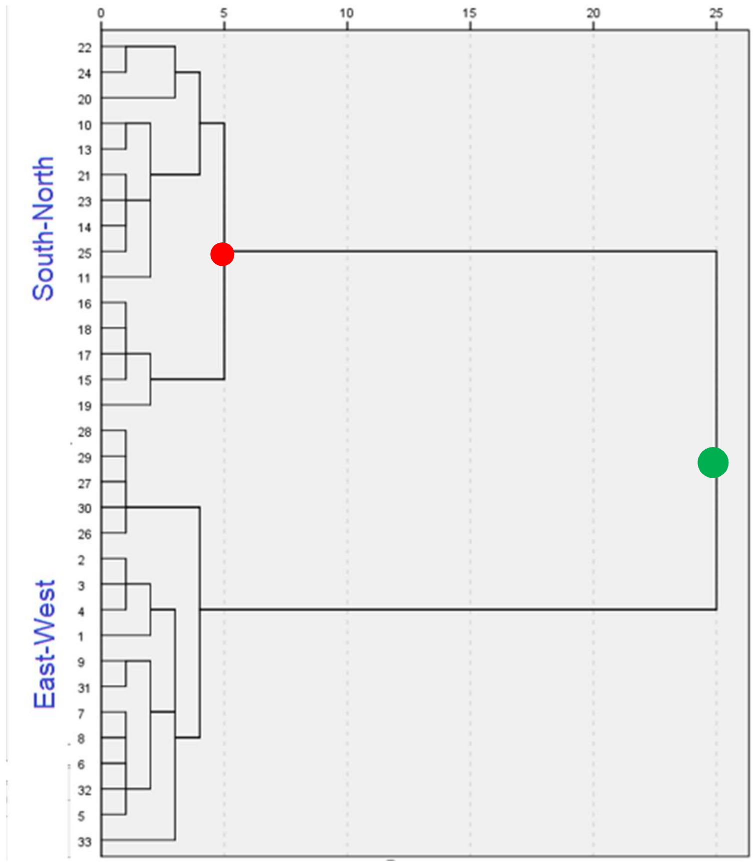


Figure 15: Dendrogram using Average linkage (between groups).

The above diagram showed a significant and clear distance between two major clusters, the set of buildings with a North-South orientation and those aligned to the East-West. The second major distance was found within the former group where one of them the largest glazing area was positioned towards the south and the other towards the north.

PHASE 1.3: IDENTIFICATION OF THE REFERENCE BUILDING

From the clustering results and after preliminary tests performed with dynamical simulation with two clusters (green spot), it was decided that an additional level (red spot) should be considered in the cluster analysis in order to accommodate significant differences found in the South-North cluster. Therefore, the following analysis was carried out considering three different clusters, as shown in Figure 16.

Furthermore, the reference buildings for the three clusters were identified by calculating the median of all cases within each group with the aim of having existing buildings as reference ones of the neighbourhood instead of creating new typologies from mean values. As a result, the building 8, 21 and 17 were the reference ones for cluster 1, 2 and

3, respectively, as was highlighted in Figure 16. The Figure 17 and Figure 18 show isometric views of all clusters.

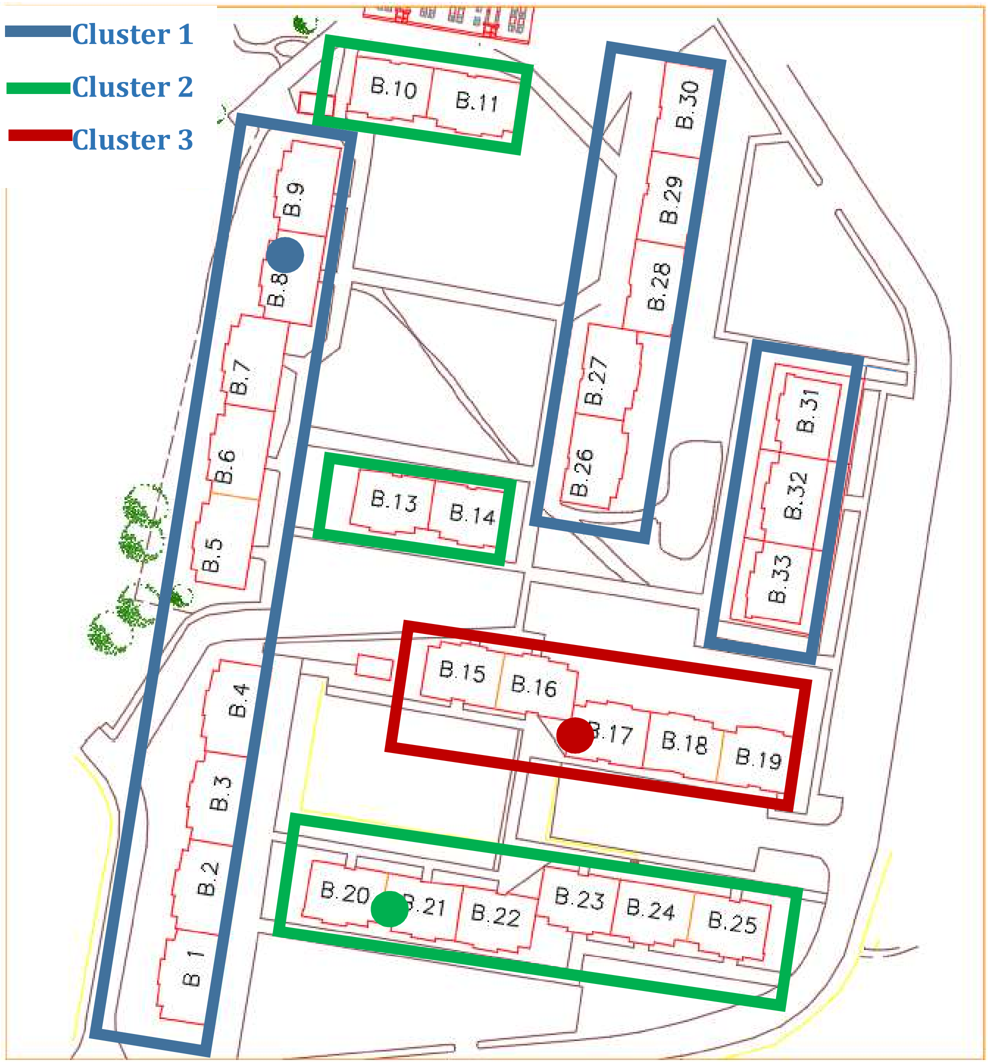


Figure 16*:* Grouping buildings into Clusters and Reference Buildings Identification in the neighbourhood.

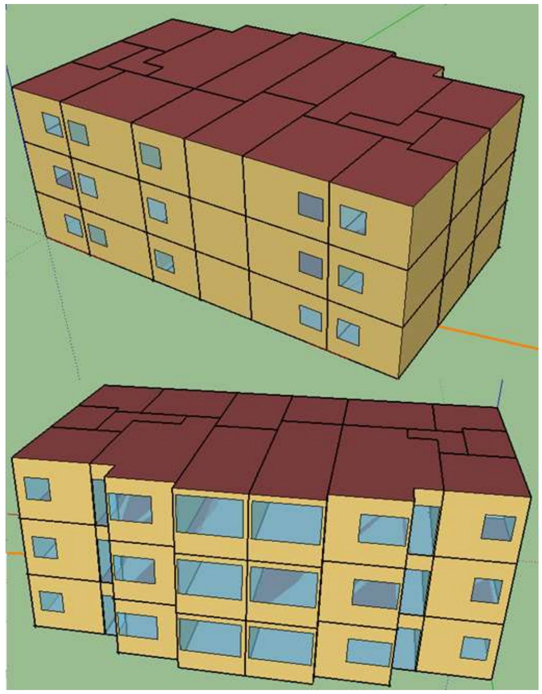


Figure 17: Isometric view – Reference Building 1 - Combination T3-T4.

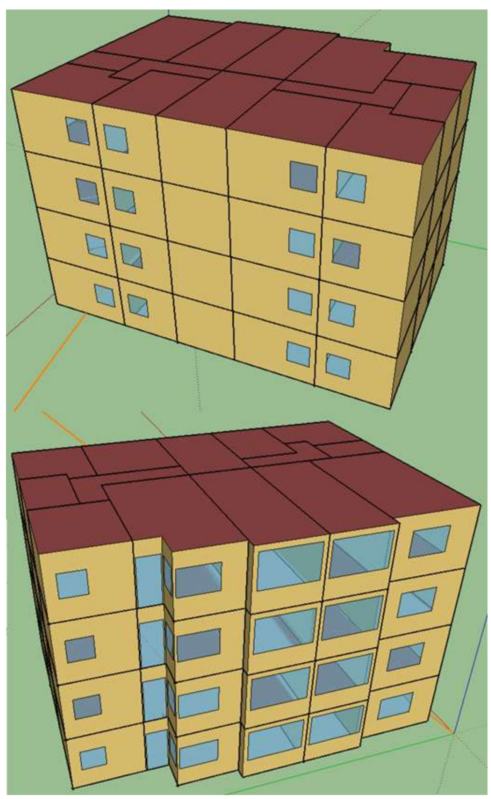


Figure 18*:* Isometric view – Reference Buildings 2 and 3 - Combination T2-T3.

5.2 STEP 2: ENERGY PERFORMANCE ASSESSMENT

In order to have reference values to evaluate and compare the results from the dynamic simulations the quasi-steady state method approach considered in the Portuguese Regulation of Energy Performance of Residential Buildings (REH, 2013) was applied and compared with the dynamic simulation. The cases used for the analytical technique were those obtained from the previous step, the reference buildings.

The values of this comparison is displayed in Table 14.

Table 14*:* Thermal performance comparative analysis – REH vs Dynamic simulation.

Typology	Floor	REH		Dynamic Simulation		Δ*(**)*	
		Heating	Cooling	Heating	Cooling	Heating	Cooling
		[kWh/m².year]				[%]	
T2-T3							
T2	1	66.0	3.9	44.4	8.5	-49	54
	2	69.9	3.6	36.6	15.3	-91	77
	3	69.9	3.6	45.4	17.0	-54	79
	4	193.0	19.7	193.7	34.3	0	43
T3	1	64.5	6.4	45.1	6.1	-43	-4
	2	68.4	5.9	38.2	11.3	-79	48
	3	68.4	5.9	47.4	12.9	-44	54
	4	196. 5	20.6	198.2	30.3	1	32
TOTAL(*)		**99.6**	**8.8**	**81.0**	**17.1**	**-23**	**49**
T3-T4							
T3	1	80.9	11.3	80.6	9.5	0	-19
	2	74.0	10.7	91.5	18.9	19	44
	3	214.5	26.2	241.1	38.3	11	32
T4	1	73.5	9.1	68.8	10.0	-7	9
	2	75.0	9.0	77.8	20.0	4	55
	3	204.5	24.4	227.7	39.4	10	38
TOTAL(*)		**120.2**	**15.0**	**130.7**	**22.7**	**8**	**34**

(*) The calculous of the heating and cooling total values [kWh/m².year] is the sum of the corresponding energy demand [kWh/year] of each floor and typology divided by the total area.

(**) The calculous of the variation (Δ) is the percentage difference between the results from dynamic simulation and REH.

In general, the outcomes of the comparison process showed coherent and reasonable differences for the heating energy demand calculation, reaching percentages of variations equal to -23% and 8% for the typology T2-T3 and T3-T4, respectively. However, for the cooling demand there was an underestimation in the quasi steady-state method compared to dynamic simulation technique.

This difference might be explained by the fact that the quasi-steady procedure, which represents a simplified method, provides noticeable variation in the cooling period, especially in buildings located in warm climates equipped with large glazed surfaces (Bruno, Bevilacqua, & Arcuri, 2019). Furthermore, in Corrado, Mechri, & Fabrizio, (2007) concluded the accuracy of the results from quasi-steady state model analysis was affected to a great extent by calculation assumptions, boundary conditions and input values. Also these authors added that although the driving force of the losses in the simplified model is the difference between the internal and the external air temperature, it should be pointed out that the heat transfer phenomenon is greatly affected by the heat transfer via the ground.

Considering the aforementioned about the influence of the heat transfer through the ground, it is noteworthy that this procedure was defined differently in both cases so that might explain in some extent the differences for the cooling demand. In the dynamic simulation was used a finite difference formulation while in the quasi steady-state analysis was considered a constant value for the ground thermal conductivity.

The energy assessment and variation analysis executed in this step were to evaluate how accurate was the dynamic thermal performance of the whole neighbourhood using just reference buildings by comparing and analysing the variation between this result and the one applying the existing buildings. In order to extend the assessment, a parametric analysis was developed applying different energy renovation measures on the building envelope to evaluate the variation on the results among the one with existing buildings and the other considering reference buildings.

Since the averaging when aggregated data, in this case a neighbourhood scale, might cover up significant variation within the groups or clusters, the variation of each cluster was analysed as well to check this out. The comparison separated by the three clusters and the total neighbourhood for all cases, including the renovation measures and the one with no intervention, is presented in Table 15.

Table 15*:* Heating and cooling energy demand variation using reference and existing buildings for initial state and renovation measures.

Measure		Existing Buildings				Reference Buildings				Δ			
		Cluster			Neighbourhood	Cluster			Neighbourhood	Cluster			Neighbourhood
		1	2	3		1	2	3		1	2	3	
		kWh/m²								%			
0	Heating	126.9	85.5	118.9	112.4	130.7	81.0	115.5	112.1	-3.0	5.3	2.9	0.3
	Cooling	22.2	17.5	10.8	18.9	22.7	17.1	10.6	18.9	-2.3	2.4	2.4	0.0
a	Heating	74.5	39.5	73.2	63.1	77.0	37.5	71.5	63.2	-3.3	5.2	2.3	-0.3
	Cooling	16.9	14.2	6.6	14.4	16.7	13.7	6.4	14.1	1.3	3.2	3.1	2.5
b	Heating	69.7	35.1	68.8	58.4	72.8	33.9	67.7	59.3	-4.4	3.4	1.5	-1.5
	Cooling	17.2	14.8	6.8	14.8	16.9	14.3	6.6	14.4	1.8	3.4	3.0	2.9
c	Heating	68.0	33.5	67.1	56.8	71.2	32.6	66.4	57.9	-4.8	2.6	1.2	-2.0
	Cooling	17.3	15.0	6.9	14.9	17.0	14.5	6.6	14.5	2.0	3.5	3.0	3.0
d	Heating	65.9	31.6	65.2	54.8	69.4	31.1	64.7	56.2	-5.3	1.5	0.7	-2.6
	Cooling	17.5	15.4	7.0	15.2	17.1	14.8	6.8	14.7	2.3	3.7	3.1	3.2
e	Heating	64.7	30.5	64.0	53.6	68.3	30.2	63.7	55.2	-5.6	0.9	0.5	-3.0
	Cooling	17.6	15.6	7.0	15.3	17.2	15.0	6.8	14.8	2.4	3.8	3.1	3.4
f	Heating	101.3	60.0	95.5	87.1	108.2	60.4	95.6	90.6	-6.8	-0.7	-0.1	-4.0
	Cooling	23.3	20.3	11.8	20.5	23.4	19.7	11.6	20.3	-0.3	2.8	1.9	1.3
g	Heating	83.5	49.2	81.8	72.2	83.7	44.2	78.0	69.9	-0.3	10.3	4.7	3.2
	Cooling	15.9	12.4	5.8	13.2	15.9	12.0	5.6	12.9	0.4	3.4	4.3	2.1
h	Heating	75.5	43.1	74.9	64.9	75.0	38.0	71.0	62.3	0.6	11.8	5.2	4.1
	Cooling	15.5	12.1	5.4	12.8	15.4	11.7	5.1	12.5	0.7	3.5	4.6	2.4
i	Heating	73.1	41.3	72.8	62.8	72.4	36.2	68.9	60.1	0.9	12.3	5.3	4.4
	Cooling	15.6	12.0	5.3	12.8	15.3	11.6	5.0	12.4	1.7	3.5	4.7	3.0
j	Heating	70.5	39.3	70.6	60.5	69.6	34.3	66.7	57.6	1.2	12.9	5.5	4.7
	Cooling	15.3	11.9	5.2	12.6	15.2	11.5	4.9	12.3	0.9	3.6	4.8	2.5
k	Heating	69.1	38.3	69.4	59.2	68.1	33.3	65.5	56.3	1.4	13.1	5.6	4.9
	Cooling	15.3	11.9	5.1	12.6	15.1	11.5	4.9	12.3	0.9	3.6	4.9	2.5
l	Heating	83.5	48.8	80.4	71.9	84.3	44.0	76.7	69.9	-0.9	9.8	4.6	2.7
	Cooling	17.3	13.5	6.7	14.4	17.3	13.1	6.5	14.1	0.1	3.3	3.8	1.9
m	Heating	74.0	40.6	70.3	62.7	74.8	36.3	66.7	61.0	-1.1	10.8	5.1	2.8
	Cooling	19.0	15.1	7.7	16.0	19.0	14.7	7.4	15.7	0.2	3.1	3.5	1.9

In order to have a better visualisation of the data from Table 15, the information was represented graphically separated by cluster and neighbourhood. The blue bar depicts the dynamic simulation results with the three reference buildings while the red one displays the results using existing buildings. The black line indicates the percentage of variation between both groups.

For cluster 1, the heating energy demand depicted in Figure 19 shows that the greater differences were located in the refurbishing measures applied in the walls getting a maximum percent equal to 6.8%. For the interventions on roof and windows the variations were much lower than the wall case achieving peaks of 1.4% and 1.1% in each element, respectively.

The same above trend shown in Figure 20 for the cooling demand but with percentages in absolute value much lower. The maximum absolute values were concentrated on the wall interventions with a peak of 2.4%, while in the roof most cases reached values below 1% except one with 1.7%, and the glazing the top value was 0.2%.

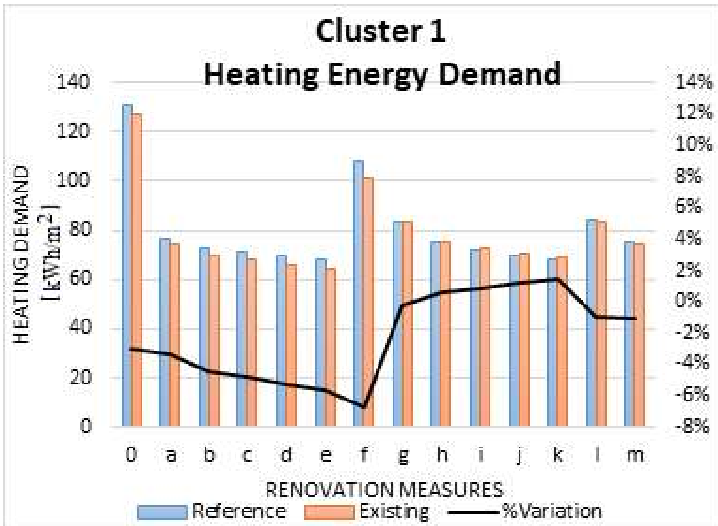


Figure 19: Heating Energy Demand Comparison for Cluster 1.

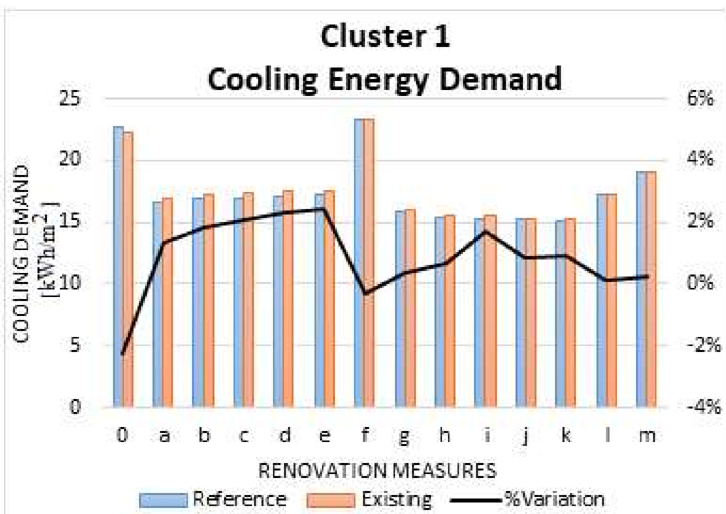


Figure 20*:* Cooling Energy Demand Comparison for Cluster 1.

For the second cluster the Figure 21 displays the heating energy demand, which concentrates the largest variations considering all cases for the three clusters, that were presented on the roof renovation measures achieving percentages in the range of 10.3% and 13.1%, followed by the glazing interventions with values equals to 10.8% and 9.8%.

For the wall case the difference were much lower with a values range between 5.2% and 0.7%.

As in cluster 1, the cooling energy demand showed in Figure 22, the values were significantly lower than those for the heating demand. However, the trend was different compared to the first cluster since the curve shape is rather flat, reaching similar values for all cases, with ranges between 3.8% and 2.8%, 3.6% and 3.4%, and 3.3% and 3.1%, for interventions on walls, roof and windows, respectively.

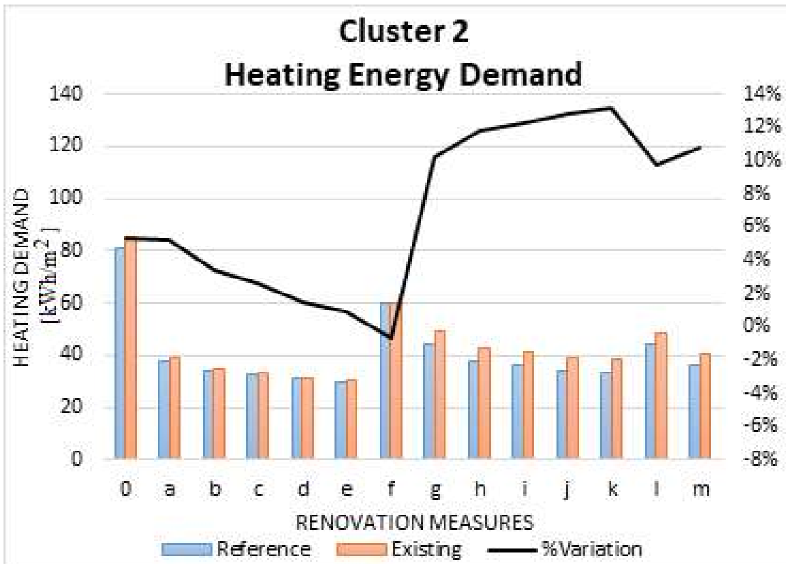


Figure 21*:* Heating Energy Demand Comparison for Cluster 2.

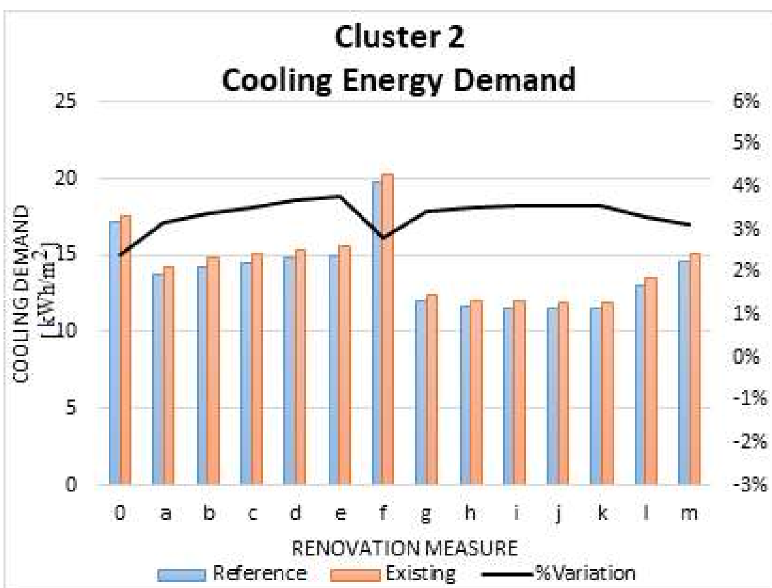


Figure 22*:* Cooling Energy Demand Comparison for Cluster 2.

The Figure 23 represents the heating energy demand for the cluster 3 which followed the same trend as the heating demand on cluster 2 where the biggest differences were in the interventions applied on the roof with value range between 4.7% and 5.6%, the glazing changes came after reaching values equal to 4.6% and 5.1%. In the case of the wall the variations were much lower with values between 2.3% and 0.1%.

As with cluster 1 for the cooling demand represented in Figure 24 the cluster 3 followed the same trend as its heating energy demand, the maximum differences were found on the roof with percentages between 4.3% and 4.9%, followed by the windows actions with a value range within 3.5% and 3.8%. The lowest variations with values among a range of 1.9% and 3.1% were in the wall interventions.

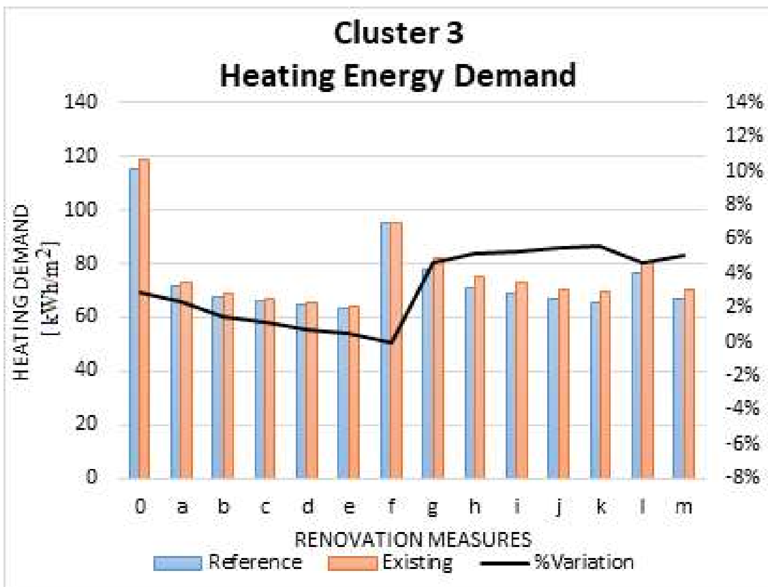


Figure 23: Heating Energy Demand Comparison for Cluster 3.

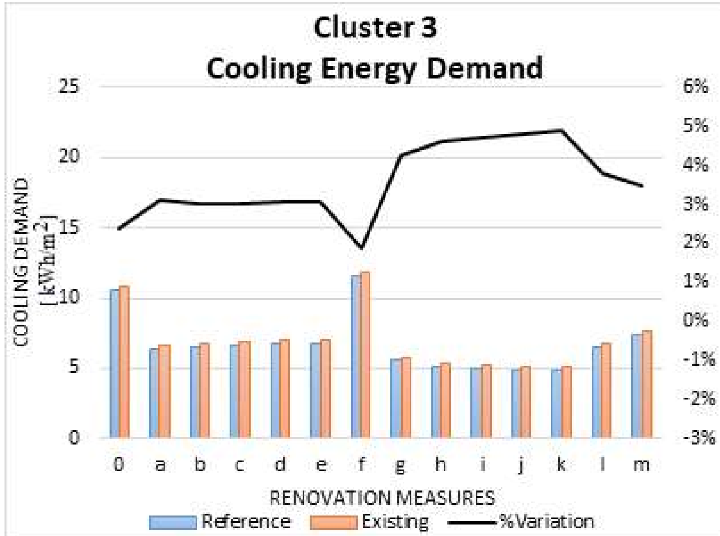


Figure 24*:* Cooling Energy Demand Comparison for Cluster 3.

Considering the evaluation of the results separated by cluster, it showed that the heating energy demand had much higher differences compared to the cooling energy demand for the three clusters. Besides, for the heating demand the largest variation values were located on the wall renovation measures for cluster 1 oriented East-West, whereas for cluster 2 and 3 oriented North-South were found on the interventions on roof and windows.

The Figure 25 and Figure 26 show the heating and cooling energy demand comparison results at a neighbourhood level. For the heating demand, the largest differences were found on the roof renovation measures reaching a range of values between 3.2% and 4.9%; for the windows case the percentages were a bit lower for the two interventions with 2.7% and 2.8%; and the wall measures got a wider range achieving variations in absolute value from 0.3% to 4.0%.

For the cooling energy demand, the variations were much lower than the heating case. The highest variations were presented in the wall renovation measures with a range of value between 1.3% and 3.4%; in the roof situation the variation rate reached values within 2.1% and 2.5%, while the windows measures got a difference equal to 1.9% in both interventions.

According to these results, in which the variations for the three elements in both heating and cooling energy demand showed slight differences with maximum variations equals to 4.9% and 3.4% respectively, the use of reference building seams a feasible strategy to assess refurbishing interventions at a neighbourhood scale.

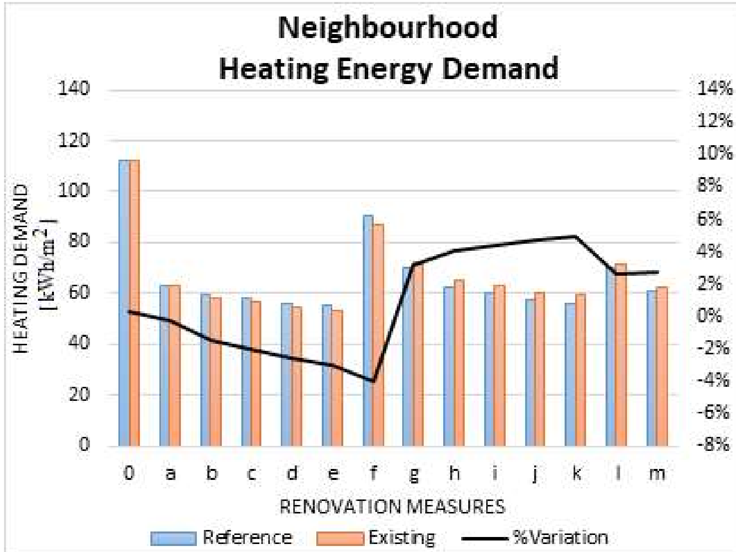


Figure 25: Heating Energy Demand Comparison at a neighbourhood scale.

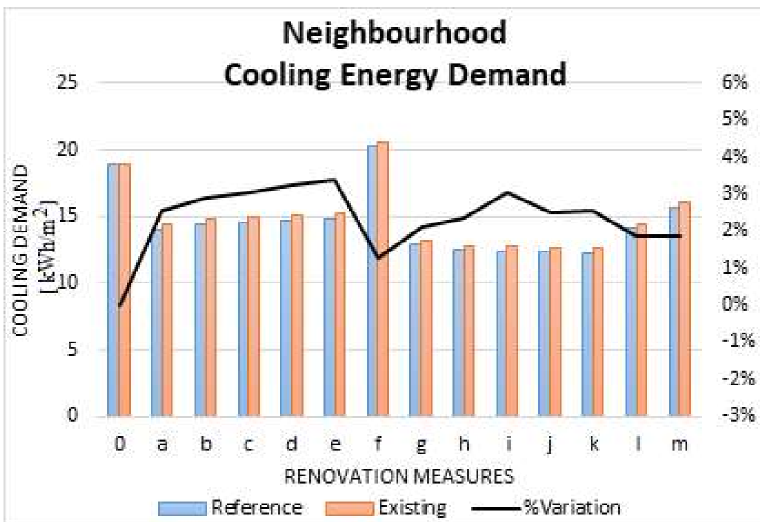


Figure 26: Cooling Energy Demand Comparison at a neighbourhood scale.

In conclusion, the results suggest that the use of reference buildings might be a viable approach to evaluate energy saving measures at a neighbourhood scale due to the accuracy level of the comparison outcomes between existing buildings and reference ones. Furthermore, the application of cluster analysis on getting reference building appears to be a suitable technique; however, it is highly important to know how to discriminate the number of clusters that represent better the neighbourhood for the energy performances since small geometric feature differences might lead to a large discrepancy on energy demand.

CHAPTER 6. CONCLUSION

In this chapter is highlighted the most relevant conclusions related to the objectives defined, which aimed to elaborate a methodology to obtain reference buildings for the characterization of neighbourhoods and their use in assessing the impact of different renovation interventions.

A methodology to define reference buildings was elaborated compound by two main procedures; Statistical Analysis and Energy Performance Assessment. The former one was in turn split in three phases named as: (1) Data Collection and Preparation, (2) Clustering, (3) Identification of the Reference Buildings. For the application of the method, a social housing neighbourhood located in Braga was utilised as a case study composed of 32 buildings built in 1983.

The statistical technique cluster analysis was chosen to group buildings with similarities in physical features that were the most influential on energy performance. Three clusters were obtained, the first one facing East-West and the other two the North-South. The difference between these two consists of the orientation of the largest glazing area, where in cluster 2 this was oriented towards the south and in cluster 3 it was oriented towards the north.

Energy Performance calculations were performed using numerical dynamic simulation. The results from the performed calculations indicated that energy efficiency in the neighbourhood was low, with an average of 112.4 kWh/m^2.y in terms of heating energy demand, which are the most significant in the neighbourhood used as a case study. The highest value was reached in cluster 1 with a heating energy demand of 126.9 kWh/m^2.y while the lowest one was obtained in cluster 2 with 85.5 kWh/m^2.y. In order to contrast model outputs, the dynamical model simulation were also compared with the quasi-steady state approach used in Portuguese regulation, showing significant differences mainly regarding cooling. The results were useful in order to have guideline points on which to base the values of the dynamic simulation models.

For the purpose of complement the analysis, a parametric study considering renovation interventions was carried out. In this context, thirteen renovation measures were applied on the buildings envelope varying insulation thicknesses on the roof and wall and applying different glazing types on the window. The simulation results showed, on the one hand, important reductions on the energy demand by comparing the renovated buildings cases to the initial state case, mainly for the heating energy demand achieving a minimum value of 53.6 kWh/m^2.y in the measure with a 16-cm insulation on the wall. On the other hand, regarding the variation analysis between the use of existing buildings and the reference ones, the results presented small level of variation considering the whole neighbourhood for both heating and cooling demand, achieving peak percentages equals to 4.9% and 3.4%, respectively.

Looking into each cluster, the variation analysis outcomes showed that the heating energy demand had larger differences than the cooling energy demand for the three clusters. Regarding the heating demand the greatest variation values were located on the wall renovation measures for cluster 1 oriented East-West, whereas for cluster 2 and 3 oriented North-South were found on the interventions on roof and windows. In particular, the highest variation values were obtained in the cluster 2 in the roof renovation measures, achieving percentages between 10.3% and 13.1%.

In summary, the results of the case study shows the use of reference buildings might be a feasible approach to evaluate energy renovation measures at a neighbourhood scale since the accuracy level of the comparison outcomes between exiting buildings and reference ones. Moreover, the employment of cluster analysis to obtain reference buildings seems an appropriate method when the number of clusters are properly defined since small geometric characteristics differences can lead to outcome disparity on energy performance.

6.1 FURTHER RESEARCH

The results of this study have the potential to be the basis of further investigations aimed at assessing cost optimality and cost effectiveness of sets of measures taking into account the technical viability of the renovation measures strategies. Furthermore, other studies may be carried out following the same method developed herein including different types and use of buildings or residential neighbourhoods with characteristics more heterogeneous and/or a larger number of units than those presented here.

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APPENDIX

Table A 1: Physical Properties at each side of the buildings (E: East, N: North, W: West and S: **S**outh).

	Building	Type	Wall Exposed Length [m]				Window Area [m²]				Room Number				Floor Area [m²]				N° Floor	Window/Wall Ratio			
			E	N	W	S	E	N	W	S	E	N	W	S	E	N	W	S		E	N	W	S
Orientation South-North	1	T4-T3	14.8	0	12.4	7.6	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	4	0.1	0	0.3	0
	2	T3-T4	14.8	0	12.4	0	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	4	0.1	0	0.3	0
	3	T4-T3	14.8	0	12.4	0	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	4	0.1	0	0.3	0
	4	T3-T4	14.8	7.6	12.4	0	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	4	0.1	0	0.3	0
	5	T3-T4	14.8	0	12.4	7.6	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	3	0.1	0	0.3	0
	6	T3-T4	14.8	0	12.4	0	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	3	0.1	0	0.3	0
	7	T4-T3	14.8	0	12.4	0	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	3	0.1	0	0.3	0
	8	T4-T3	14.8	0	12.4	0	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	3	0.1	0	0.3	0
	9	T3-T4	14.8	7.6	12.4	0	4.8	0.9	8.3	0.9	5	0	4	0	51.8	0	64.1	0	3	0.1	0	0.3	0
	26	T3-T4	12.4	0	14.8	7.6	8.3	0.9	4.8	0.9	4	0	5	0	64.1	0	51.8	0	3	0.3	0	0.1	0
	27	T3-T4	12.4	0	14.8	0	8.3	0.9	4.8	0.9	4	0	5	0	64.1	0	51.8	0	3	0.3	0	0.1	0
	28	T3-T4	12.4	0	14.8	0	8.3	0.9	4.8	0.9	4	0	5	0	64.1	0	51.8	0	3	0.3	0	0.1	0
	29	T4-T3	12.4	0	14.8	0	8.3	0.9	4.8	0.9	4	0	5	0	64.1	0	51.8	0	3	0.3	0	0.1	0
	30	T3-T4	12.4	7.6	14.8	0	8.3	0.9	4.8	0.9	4	0	5	0	64.1	0	51.8	0	3	0.3	0	0.1	0
	31	T3-T2	12.2	8.7	9.8	0	3.8	1.8	7.4	0.9	4	0	3	0	39	0	48.3	0	3	0.1	0.1	0.3	0
	32	T4-T3	14.8	0	12.4	0	4.8	0.9	8.3	1.8	5	0	4	0	51.8	0	64.1	0	3	0.1	0	0.3	0
	33	T2-T3	12.2	0	9.8	8.7	3.8	0	7.4	2.7	4	0	3	0	39	0	48.3	0	3	0.1	0	0.3	0.1
Orientation East-West	10	T2-T3	0	12.2	8.7	9.8	0.9	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0.1	0.3
	11	T3-T4	7.6	14.8	0	12.4	0.9	4.8	1.8	8.3	0	5	0	4	0	51.8	0	64.1	4	0	0.1	0	0.3
	13	T2-T3	0	12.2	8.7	9.8	0.9	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0.1	0.3
	14	T3-T2	8.7	12.2	0	9.8	1.8	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0.1	0.1	0	0.3

	Building	Type	Wall Exposed Length [m]				Window Area [m²]				Room Number				Floor Area [m²]				N° Floor	Window/Wall Ratio			
			E	N	W	S	E	N	W	S	E	N	W	S	E	N	W	S		E	N	W	S
	15	T3-T2	0	9.8	7.6	12.2	0.9	7.4	0.9	3.8	0	3	0	4	0	48.3	0	39	4	0	0.3	0	0.1
	16	T2-T3	0	9.8	0	12.2	0.9	7.4	0.9	3.8	0	3	0	4	0	48.3	0	39	4	0	0.3	0	0.1
	17	T3-T2	0	9.8	0	12.2	0.9	7.4	0.9	3.8	0	3	0	4	0	48.3	0	39	4	0	0.3	0	0.1
	18	T2-T3	0	9.8	0	12.2	0.9	7.4	0.9	3.8	0	3	0	4	0	48.3	0	39	4	0	0.3	0	0.1
	19	T3-T2	8.7	9.8	0	12.2	1.8	7.4	0.9	3.8	0	3	0	4	0	48.3	0	39	4	0.1	0.3	0	0.1
	20	T3-T2	0	12.2	7.6	9.8	0	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0.1	0.3
	21	T2-T3	0	12.2	0	9.8	0.9	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0	0.3
	22	T3-T2	0	12.2	0	9.8	0	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0	0.3
	23	T2-T3	0	12.2	0	9.8	0.9	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0	0.3
	24	T3-T2	0	12.2	0	9.8	0	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0	0.3
	25	T2-T3	7.6	12.2	0	9.8	0.9	3.8	1.8	7.4	0	4	0	3	0	39	0	48.3	4	0	0.1	0	0.3

Table A 2: Dynamic Simulation Results for both Reference and existing Buildings.

					Renovation Measures																										
			(0) Initial State		(a) Wall Insulation EPS t=3cm		(b) Wall Insulation EPS t=6cm		(c) Wall Insulation EPS t=8cm		(d) Wall Insulation EPS t=12cm		(e) Wall Insulation EPS t=16cm		(f) Injection Air Gap Wall EPS t=4 cm		(g) Roof Insulation EPS t=3cm		(h) Roof Insulation EPS t=6cm		(i) Roof Insulation EPS t=8cm		(j) Roof Insulation EPS t=12cm		(k) Roof Insulation EPS t=16cm		(l) Window Glass U-Value = 3,3 W/m².°C		(m) Window Glass U-Value = 2 W/m².°C	
N°	Type	Qty	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
			kWh/m²																											
Reference Buildings																														
C1	T3-T4	17	130.72	22.73	76.98	16.69	71.23	16.97	72.76	16.89	69.39	17.09	68.33	17.16	108.16	23.37	83.69	15.88	75	15.4	72.39	15.28	69.57	15.17	68.06	15.12	84.26	17.26	74.81	19
C2	T2-T3	10	80.99	17.12	37.47	13.73	32.58	14.51	33.87	14.29	31.08	14.79	30.2	14.96	60.38	19.72	44.19	11.99	37.99	11.66	36.19	11.58	34.27	11.51	33.29	11.47	44.03	13.05	36.25	14.65
C3	T2-T3	5	115.5	10.58	71.51	6.38	66.35	6.64	67.73	6.57	64.68	6.75	63.7	6.81	95.55	11.6	77.95	5.56	71.02	5.14	68.93	5.03	66.69	4.91	65.49	4.86	76.73	6.45	66.74	7.43
Existing Buildings																														
B1	T3-T4	1	115.93	21.99	70.26	17.88	63.58	18.37	65.36	18.22	61.45	18.56	60.21	18.69	89.92	23.22	80.57	16.93	74.02	16.61	72.06	18.56	69.94	16.54	68.81	16.47	79.36	18.23	69.68	20.17
B2 B3	T3-T4	2	114.62	21.94	69.77	17.82	63.76	18.22	65.36	18.1	61.87	18.37	60.76	18.47	90.82	22.98	78.62	16.93	71.97	16.61	69.98	16.54	67.82	16.47	66.67	16.44	77.5	18.24	67.81	20.24
B4	T3-T4	1	123.95	20.78	74.64	17.16	66.42	17.88	68.58	17.67	63.8	18.15	62.28	18.31	91.42	22.96	88.73	15.69	82.18	15.35	80.21	15.27	78.08	15.18	76.95	15.15	87.41	16.95	77.47	18.78
B5	T3-T4	1	132.67	22.6	78.36	16.5	71.99	16.83	73.69	16.73	69.94	16.97	68.76	17.06	108.23	23.31	86.42	15.69	77.85	15.21	75.28	15.09	72.49	14.97	71.01	14.91	86.93	17.05	77.57	18.71
B6 B7 B8 B32	T3-T4	4	130.71	22.73	76.98	16.69	71.23	16.97	72.76	16.89	69.39	17.09	68.33	17.16	108.16	23.37	83.69	15.88	75	15.4	72.39	15.28	69.57	15.17	68.06	15.12	84.25	17.26	74.81	19
B9	T3-T4	1	139.41	21.79	81.61	16.22	73.75	16.78	75.84	16.62	71.25	17	69.79	17.13	108.69	23.44	93.3	14.9	84.74	14.4	82.16	14.27	79.37	14.15	77.88	14.08	93.6	16.24	83.86	17.89
B26	T3-T4	1	124.67	22.6	70.48	16.86	64.12	17.23	65.81	17.13	62.09	17.39	60.91	17.48	100.1	23.48	78.53	15.98	70.09	15.55	67.56	15.44	64.84	15.34	63.39	15.29	79.09	17.32	69.91	19.03
B27 B28 B29	T3-T4	3	124.45	22.3	70.93	16.5	65.17	16.8	66.7	16.71	63.34	16.92	62.27	16.99	101.82	23.02	77.67	15.66	69.09	15.22	66.52	15.11	63.75	15	62.28	14.96	78.35	17.01	69.21	18.7
B30	T3-T4	1	133.02	21.33	75.43	16.02	67.62	16.6	69.69	16.43	65.13	16.81	63.69	16.95	102.33	23.08	87.08	14.67	78.6	14.19	76.06	14.08	73.32	13.96	71.85	13.91	87.51	15.97	78.03	17.56
B31	T2-T3	1	144.83	22.61	83.84	16.98	75.03	17.64	77.36	17.45	72.25	17.89	70.62	18.05	110.25	24.61	97.59	15.48	88.79	14.96	86.14	14.83	83.28	14.7	81.75	14.63	97.97	16.86	88.07	18.54
B33	T2-T3	1	135.09	23.36	78.73	17.07	71.9	17.43	73.72	17.33	69.72	17.59	68.44	17.69	108.81	24.13	87.7	16.24	78.93	15.73	76.3	15.6	73.46	15.48	71.95	15.42	88.16	17.64	78.48	19.38
B10 B13 B20	T2-T3	3	89.69	17.66	41.29	14.33	34.15	15.25	36.02	14.99	31.92	15.61	30.65	15.82	59.7	20.59	53.58	12.51	47.37	12.18	45.55	12.1	43.61	12.02	42.58	11.98	52.97	13.6	44.48	15.23
B11	T3-T4	1	84.8	17.28	39.43	14.02	33.26	14.88	34.87	14.63	31.34	15.2	30.24	15.4	59	19.97	49.43	12.3	43.38	11.99	41.62	11.91	39.73	11.84	38.73	11.81	48.82	13.37	40.55	14.99
B14 B25	T2-T3	2	88.86	18.37	41.13	14.95	34.28	15.85	36.08	15.59	32.14	16.19	30.92	16.41	60.1	21.15	52.72	13.18	46.52	12.85	44.71	12.77	42.77	12.7	41.75	12.66	52.13	14.29	43.69	15.97
B15	T2-T3	1	125.08	10.65	76.64	6.33	69.12	6.59	71.14	6.51	66.69	6.69	65.27	6.76	96.14	11.57	88.51	5.63	81.68	5.21	79.64	5.1	77.42	4.98	76.24	4.93	87.17	6.5	77.12	7.45
B16 B17 B18	T2-T3	3	115.5	10.58	71.51	6.38	66.35	6.64	67.73	6.57	64.68	6.75	63.7	6.81	95.55	11.6	77.95	5.56	71.02	5.14	68.93	5.03	66.69	4.91	65.49	4.86	76.73	6.45	66.74	7.43
B19	T2-T3	1	123.08	11.8	74.85	7.45	67.48	7.74	69.46	7.65	65.09	7.86	63.7	7.94	94.52	12.75	86.46	6.73	79.66	6.31	77.62	6.2	75.41	6.09	74.24	6.03	84.83	7.67	74.35	8.76
B21 B22 B23 B24	T2-T3	4	80.99	17.12	37.47	13.73	32.58	14.51	33.87	14.29	31.08	14.79	30.2	14.96	60.38	19.72	44.19	11.99	37.99	11.66	36.19	11.58	34.27	11.51	33.29	11.47	44.03	13.05	36.25	14.65