NOVA SCHOOL OF SCIENCE & TECHNOLOGY
DEPARTMENT OF ENVIRONMENTAL SCIENCES AND ENGINEERING

RODRIGO DA SILVA FELIX
Bachelor of Architecture and Urban Planning

BUILDINGS ACUPUNCTURE: REGIONAL CHARACTERIZATION AND ASSESSMENT OF PORTUGUESE RESIDENTIAL BUILDINGS

MASTER IN SUSTAINABLE URBANISM AND SPATIAL PLANNING

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"They did not know it was impossible, so they did it."
(Mark Twain)

ABSTRACT

One of Europe's largest energy consumption sources, the building sector is a focus area in the European Commission's plans for energy efficiency improvement and greenhouse gas emissions reductions. Although legislative instruments already target new buildings' sustainability, older buildings represent the biggest share of Europe's stock and should be renovated to effectively reduce emissions in the sector. In Portugal, about 70% of the buildings were constructed before the implementation of energy performance regulations in 1990 and are not energy efficient. The enforced remote routine from the Covid-19 crisis evidenced thermal insulation issues and emphasized residential energy poverty (EP) conditions of the Portuguese population.

Building owners can be key actors in the improvement of the national buildings stock's energy efficiency and should be included in the buildings' renovation process. Nevertheless, the great diversity of characteristics observed in the country's residential buildings can be a roadblock in assessing and providing information about the different dwelling types.

A bottom-up approach through the development of representative buildings typologies can be an optimizing tool in the building renovation aiming for energy efficiency improvement, enabling the proposal of sustainable retrofitting solutions for residential buildings on a larger scale. Therefore, this dissertation performs a cross-country assessment on the Portuguese residential buildings stock towards the definition of national representative typologies. A set of key building characteristics (e.g., area, floors, bearing structure) from the 2011 Census is used to identify predominant structural and architectural characteristics in the country's residential buildings' stock. Sub-regions' Energy Poverty Vulnerability Index (EPVI) results and climatic zones guide the identification of priority statistical subsections for residential renovation. Sub-regions' Energy Performance Certificates and subsections' street view images are also used to assess residential buildings' predominant constructive solutions and most distinctive visual elements. The most distinct building characteristics of the sub-regions were considered in the typologies' 3D models construction in SketchUp.

The results revealed Alentejo as the most distinct region regarding housing type and building's bearing structure. Açores, Madeira, Norte and Alentejo are the regions with the highest percentage of sub-regions raking top five in vulnerability to EP. Tâmega e Sousa, Madeira and Baixo Alentejo are the most representative sub-regions in the rank from different climatic zones. Key-feature tables gathering the various regions' residential buildings most distinct visual elements for all primary architectural components (roof, storeys, openings, envelope, access, plot) helped select examples of buildings used as a reference in the construction of the 3D models.

The main differences observed in the three typologies regards the presence of sub-levels (underground floor), façade ornaments and structures, main accesses, number of openings, and plot (land lot) placement. Baixo Alentejo stands out for its typology's lack of setbacks, with few openings, and façade ornaments; Madeira's most distinct visual element is the presence of an entry porch in its typology's main entrance; and Tâmega's typology is the only one with underground level and veranda, with a single flight of stairs and landing marking the main entrance.

The typologies resulting from this work can be optimizing tools for residential energy efficiency renovation in sub-regions with vulnerable buildings stock, helping determine sources of energy inefficiency through the estimative of the baseline energy demand of existing buildings, allowing the proposal of adequate alleviation measures, and assisting with the integration of their owners as indispensable stakeholders on a large-scale intervention.

Keywords: energy efficiency; residential typologies; renovation; Portugal.

RESUMO

Uma das maiores fontes de consumo de energia da Europa, o setor da construção é uma área foco nos planos da Comissão Europeia para a melhoria da eficiência energética. Embora instrumentos legislativos já visem a sustentabilidade de novas construções, edifícios antigos representam a maior parte do estoque da Europa e devem ser renovados para a redução efetiva das emissões no setor. Em Portugal, cerca de 70% dos edifícios foram construídos antes da implementação de regulamentos de desempenho energético em 1990 e não são energeticamente eficientes. A rotina remota forçada pela crise da Covid-19 evidenciou problemas de isolamento térmico e realçou as condições de Pobreza Energética (PE) residencial da população portuguesa.

Os proprietários de edifícios podem ser atores-chave na melhoria da eficiência energética do parque imobiliário nacional e devem ser incluídos no processo de renovação dos edifícios. No entanto, a grande diversidade de características observada nos edifícios residenciais do país pode ser um obstáculo na avaliação e fornecimento de informações sobre os diferentes tipos de casas.

Uma abordagem *bottom-up* através do desenvolvimento de tipologias de edifícios representativos pode ser uma ferramenta de otimização na renovação de edifícios visando a melhoria da eficiência energética, permitindo a proposição de soluções de retrofitting sustentáveis para edifícios residenciais em larga escala. Assim, esta dissertação realiza uma avaliação do parque de edifícios residenciais português para a definição de tipologias representativas nacionais. Um conjunto de características principais do edifício (por exemplo, área, pisos, estrutura de sustentação) extraídas do Censo de 2011 é usado para identificar as características estruturais e arquitetónicas predominantes no estoque de edifícios residenciais do país. O Índice de Vulnerabilidade à Pobreza Energética (EPVI) das sub-regiões e respetivas zonas climáticas orientam a identificação de subseções estatísticas prioritárias para renovação residencial. Os certificados energéticos das sub-regiões e imagens do Street View das subseções também são usados para avaliar as soluções construtivas predominantes dos edifícios residenciais e os elementos visuais mais distintos. As características de construção mais distintas das sub-regiões foram consideradas na construção de modelos 3D das tipologias no SketchUp.

Os resultados revelaram o Alentejo como a região mais distinta em termos de tipologia habitacional e estrutura portante do edifício. Açores, Madeira, Norte e Alentejo são as regiões com maior percentagem de sub-regiões entre as mais vulneráveis à pobreza energética. Tâmega e Sousa, Madeira e Baixo Alentejo são as sub-regiões mais representativas do ranking em diferentes zonas climáticas. As tabelas de características principais reunindo os elementos visuais mais distintos dos edifícios residenciais das diferentes regiões para componentes arquitetónicos primários (telhado, andares, aberturas, envelope, acesso, lote) ajudaram a selecionar exemplos de edifícios que foram usados como referência na construção dos modelos 3D.

As principais diferenças observadas nas três tipologias referem-se à presença de subníveis (subsolo), ornamentos e estruturas de fachada, acessos principais, número de aberturas e implantação no lote. O Baixo Alentejo destaca-se pela falta de recuos na sua tipologia, com poucas aberturas, e ornamentos de fachada; o elemento visual mais distinto da Madeira é a presença de alpendre de entrada na sua tipologia; e a tipologia do Tâmega é a única com cave e varandas, com um único lance de escada e patamar a marcar a entrada principal.

As tipologias resultantes deste trabalho podem ser ferramentas de otimização para renovação de eficiência energética residencial em sub-regiões com estoque de edifícios vulneráveis, ajudando a determinar fontes de ineficiência energética através da estimativa da demanda energética dos edifícios existentes, permitindo a proposição de medidas de alívio adequadas, e auxiliando na integração de seus proprietários como *stakeholders* indispensáveis em uma intervenção em larga escala.

Palavras-chave: eficiência energética; tipologias residenciais; renovação; Portugal.

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ABBREVIATIONS

- **BGRI** - Geographic Information Referencing Base
- **CENSE** - Centre for Environmental and Sustainable Research
- **ELPRE** - Long-term Strategy for Building Renovation
- **EPC** - Energy Performance Certificates
- **EPVI** - Energy Poverty Vulnerability Index
- **EP** - Energy Poverty
- **EU** - European Union
- **GHG** - Greenhouse gas
- **IEE** - Intelligent Energy Europe Programme
- **JRC** - Joint Research Center
- **NUTS** - Nomenclature of Territorial Units for Statistics
- **NZEB** - Nearly Zero Energy Building
- **OSS** - One-stop-shops
- **PNEC** - National Energy and Climate Plan 2030
- **PRR** - Recovery and Resilience Program
- **SDGs** - Sustainable Development Goals
- **SLIC** - Survey on Income and Living Conditions
- **TABULA** - Typology Approach for Building Stock Energy Assessment

1 INTRODUCTION

1.1 General context

The European Commission plans on cutting net greenhouse gas emissions in the EU by at least 55% by 2030 compared to 1990; it highlights energy efficiency as an essential component for action, electing the building sector as one of their focus areas. Responsible for about 40% of Europe's energy consumption and 36% of greenhouse gas emissions from energy (European Commission, 2020c), buildings are one of Europe's largest energy consumption sources, with roughly 75% of their stock in energy inefficient conditions. For the 2030 goal to be achieved, buildings' greenhouse gas emissions should be reduced by 60%, final energy consumption by 14%, and energy consumption for heating and cooling by 18%, compared to 2015 levels (European Commission, 2020a). Making buildings more energy-efficient, less carbon-intensive, and more sustainable is, for that reason, a priority for the European Union.

While energy consumption in new buildings is now half of those built over 20 years ago, older buildings represent 85% of Europe's stock, from which 85-95% are expected to still be in use in 2050 (European Commission, 2020c). Although legislative instruments such as the European Directive on the Energy Performance of Buildings already required new buildings to improve their energy efficiency to achieve a nearly zero-energy consumption since 2010, the inclusion of existing stock is imperative for the effective reduction of emissions in the building sector (Stein, B.; Loga, T.; Diefenbach, 2016).

The EU Commission (2020a) estimates that only 11% of the EU existing building stock undergoes some level of renovation each year and very rarely addresses the building's energy performance. When it comes to energy performance-focused renovation, that percentage can be as low as 1%. Supported by European Commission's "Next Generation EU" recovery plan and singled out in the European Green Deal as "a key initiative to drive energy efficiency in the sector and deliver on objectives" (European Commission, 2020d), the increase in energy-efficient renovations of both public and private buildings is crucial to achieve the goal for net-zero emissions by 2050.

In Portugal, about 70% of the buildings were constructed before the implementation of energy performance regulations in 1990. In some regions, that percentage goes as high as 74% with buildings in stone masonry and wooden roofs and floors (Palma et al., 2019), showing lesser ability to adapt to extreme temperatures. Although positively impacted by the latest improvements in the building industry and greatly motivated by the shift in the touristic scene in the country, Portuguese dwellings continue to present poor building quality. Even newly renovated houses – mainly focusing on vacation and tourism lodging – give away the low investment in thermal insulation, resulting in cold and humid dwellings in winter and hot in summer.

One of the most impactful effects of the COVID-19 crisis in our daily life, the enforced remote work and study significantly increased the amount of time we spent at home, emphasizing the importance and fragilities of residential buildings in our lives. This new routine evidenced the residential energy poverty issue, forcing us to face a problem frequently left in the background in the topic of energy efficiency. Having to spend more time at home during lockdown and lingering remote work and study arrangement, people were forced to deal with existing – and most of the times overlooked – energy efficiency issues in their houses (e.g., lack of insulation, single glazed windows), recurring to palliative solutions to reach a minimum thermal comfort. In Portugal during Winter, it was not uncommon to see remote classrooms and conferences attendees adding an extra layer of clothing and even wearing scarves and gloves during their meetings, substantial giveaways of the poor thermal condition experienced in the Portuguese household.

Vasconcelos et al. (2011) had already alerted for the health impacts of Portuguese poor housing conditions in its users, assessing the relationship between the country's high mortality rate during Winter and the housing stock deficient thermal insulation. Adding to the impact on their users' health, residential energy efficiency also plays a significant part in the march towards improved sustainability. The house stock quality directly impacts the operational energy requirements. Poorly insulated and overall low-quality homes implicate increased energy consumption to compensate for higher thermal losses, evidencing the importance of the energy efficiency of the residential building stock on the process. Investments in climatization facilities, as corrective measures, also tend to be more expensive in the long term, unaffordable by many and more energy-consuming.

The sudden changes in our conventional work arrangements caused by the 2020 Covid-19 crisis are expected to linger. More people working from home will represent an increase in the number of buildings being used to perform work-related activities that in the pre-pandemic world was condensed into a single building. As some of the effects of the pandemic continue to create new demands on our buildings and residential energy consumption tends to increase the overall energy intensity of the building sector (European Commission, 2020a; IEA, 2020), the renovation of the residential stock presents itself as an opportunity to improve the quality of life in our homes, improving thermal comfort and indoor air quality, while also contributing to achieve a greener and more sustainable built environment. Residential buildings renovation is an effective response to the energy poverty conditions shared by over 34 million Europeans unable to afford to keep their homes adequately heated in the winter or cool in the summer (European Commission, 2020a, 2020c) or even in increasing numbers with arrears on utility bills, and with mold, humidity in their dwellings affecting almost 100 million Europeans (Eurostat, 2021c).

An effective and sustainable approach towards a residential buildings' renovation wave must consider the house owners' part in the process. Provided with the needed information on the energy-saving potentials of their buildings and financial incentives to catalyze the process and include all classes, those key actors are indispensable in the residential renovation on a mass scale. In this regard, the assessment and availability of information encompassing the particularities in the houses needs can be a roadblock, especially considering the large variety of buildings' characteristics and types gathered in Portugal throughout its rich architectural history. For that purpose, a country typology analysis and representative 3D models of the most recurring buildings typologies represent an efficient way to handle that variety.

Proven to be a valuable instrument for a deeper understanding of the energy performance in different buildings types and categories (Stein, B.; Loga, T.; Diefenbach, 2016), a bottom-up approach through the development of representative buildings typologies can serve as an optimizing tool in the building renovation aiming energy efficiency improvement, enabling the proposal of sustainable retrofitting solutions to serve the residential building sector on a larger scale. Providing information on typical building characteristics (e.g., bearing structure, roof solution type, plot placement, window systems, etc.) classifying the Portuguese building stock into representative typologies can enable detailed analysis and ultimately provide needed information for energy renovation solutions in the residential building sector.

1.2 Research purpose

As defended by Gouveia & Palma (2019), tackling Portuguese residential buildings' deficient energy performance, a regional detailed characterization analysis over the particularities of its building stock can be an effective approach to help identify potential sources of energy inefficiency and to propose adequate alleviation measures. Therefore, the definition of regional representative typologies can support the assessment of energy inefficiency issues per typology for the subsequent proposition of custom retrofitting solutions, linking to existing regulations and financing supporting schemes.

Escalating the approach taken in the European project "Pan-European Approach on Sustainable Heritage: Regeneration by a Retrofitting Economy" and De Groene Grachten' "De Groene Menukaart" website (translated: The Green Menu), this dissertation aims at performing a cross-country assessment of the Portuguese residential buildings stock towards the definition of national representative typologies.

The work is carried out through the treatment of statistical data (2011 Census of Statistics Portugal) for the identification of predominant structural and architectural characteristics per region (NUTS 2), considering the subregions' (NUTS 3) Energy Poverty Vulnerability Indexes (EPVI) and their climatic zones in the definition of priority study areas (statistical subsections) for the assessment of its residential buildings' most distinctive visual elements using Google Maps satellite and street view images. This process is expected to gather visual information about the studied buildings' characteristic architectural elements (hereafter referred to as features), to be integrated into representative typologies constructed as 3D models for three sub-regions in Portugal to be, in the future, added to the Portuguese version of the Green Menu: www.menurenovacaoverde.pt.

For this purpose, the work intends to: consolidate a regional and subregional residential buildings profile of predominant structural and architectural characteristics; identify priority sub-regions in need for residential energy renovation; capture the different regions' residential buildings distinctiveness into representative typologies; construct 3D models illustrating the defined buildings typologies.

The proposed typologies are expected to serve as optimizing tools in the assessment of energy renovation opportunities the proposal of sustainable retrofitting solutions for the residential buildings they represent. The developed methodology can also be replicated to other regions (and countries) to improve the energy efficiency renovation progress of the national building stock, catalyzing the implementation of sustainable retrofit solutions to different Portuguese residential typologies in the mitigation of energy poverty, ultimately improving the conditions of comfort, efficiency, and sustainability observed in Portuguese homes.

1.3 Thesis structure

This thesis is divided into five chapters. Chapter 1 introduces the developed work, describing the problem behind the theme, the primary purposes guiding the work development, objectives, and structure in which the research, analysis, and study will be presented.

Chapter 2 presents the literature review on the assessment of residential energy efficiency, briefly contextualizing the energy poverty in Europe and its major impacts, with particular emphasis on the Portuguese reality. Highlighting the multivalent benefits of building renovation in heritage preservation, users' health, and energy consumption, this chapter touches upon the EU's main strategies and recommendations on sustainability and brings good examples of building renovation approaches through typology definition.

In Chapter 3, the work methodology is presented, which can be divided into two main phases. The first phase focuses on the definition of buildings typologies per region (NUTS 2) through the combination of statistical and visual information. The defined national building typologies were then constructed in 3D models featuring key visual details from its representative regions in the second phase.

Chapter 4 discusses the main results, showcasing the buildings' main characteristics extracted from the BGRI data set, the assessed regional building profile, the selected representative sub-regions, main visual features, and examples of buildings that guided the 3D models' representation of the respective residential typologies.

Finally, Chapter 5 presents the main conclusions, contributions, and future developments arising from this dissertation.

2 LITERATURE REVIEW

2.1 European Union: the big picture

Europe's rich history and cultural diversity can be easily read through its buildings stock. Its unique and heterogeneous architectural heritage – one of the main reasons that make the continent a global leader in international tourism – is heavily composed of old buildings that reflect the different periods throughout the continent's long history. Thankfully that mix of past and contemporary architectural examples will continue to be true for the years to come, since according to the European Commission (2020a), 85-95% of the existing buildings will still be standing in 2050.

Despite being expected and encouraged by urban planning principles of sustainability and 'smart growth', preserving Europe's building stock implies renovations beyond simple structural integrity maintenance. Around 75% of EU building stock was built before European building codes started incorporating specific regulations on thermal insulation of the building envelope in 1970 (European Commission, 2020a). Therefore, most existing buildings were built without energy performance requirements and are not energy-efficient.

With energy poverty affecting millions of Europeans and the considerable contribution of buildings on energy consumption and greenhouse gas emissions from energy – respectively 40% and 36% in the EU (European Commission, 2020a) – the construction sector is expected to incorporate new technologies that will help overcome the dependency of existing buildings on fossil fuels for heating and cooling.

United Nations Sustainable Development Goals

In effect since January 2016, the United Nations' 2030 Agenda for Sustainable Development is composed of 17 objectives, the Sustainable Development Goals (SDGs), translated into 169 actionable targets that intent to serve as a blueprint to achieve a better and more sustainable future – in the economic, social, and environmental dimensions – for all people and the world by 2030 (United Nations, 2015).

The Agenda emphasizes the eradication of poverty "in all its forms and dimensions" as an indispensable requirement and most significant challenge in achieving a sustainable development on a global scale. While other primary poverty issues, including access to food, education, and basic sanitation, still represent a central challenge in developing countries, residential energy poverty – undeniably present in conditions of extreme poverty – can be overseen as a less urgent issue.

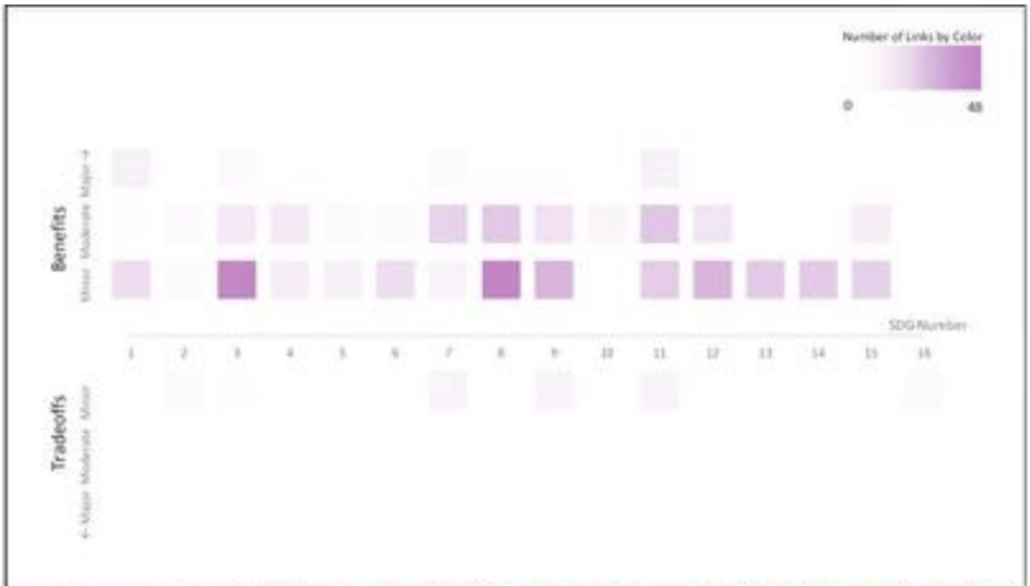
Working in two levels of interaction – the household and the city – the residential buildings quality directly impacts their resident's health and well-being (Goal 3) while also reflecting in the overall sustainability and resilience of the cities and settlements they are part of (Goals 11 and 12).

The environmental impact of the cities is nothing less than the sum of its units' impacts, which grants the residential building stock – by far the greatest portion of a city's building stock – an important position in achieving SDG 11's goal. Air quality, resource efficiency, mitigation, and adaptation to climate change are some of the levels of human impacts that can be reduced to reflect residential buildings' improvement.

A significant contribution to the overall objectives of SDGs 3, 11, and 12, the improvement of residential energy efficiency reflects at the same time, directly or indirectly, in many other SDGs. Residential insulation, for example, plays an important role in reducing our exposure and vulnerability to climate-related extreme events (Goal 1). In contrast, residential energy efficiency can greatly contribute to Goal 7's target of doubling the global energy efficiency improvement rate. On the residential level, existing technologies and practices can contribute to reducing the atmospheric concentrations of greenhouse gases and other targets set out by the United Nations SDGs by increasing the buildings' overall energy efficiency.

Financially viable, scalable, and scientifically validated energy efficiency solutions related to the building's insulation, high-efficiency space heating, and water heating systems, for example, can provide positive contributions to the targets aimed at energy efficiency, resource efficiency, and air pollution from building energy set on SDGs 7, 8, 9, 11 and 12, since all solutions would implicate a reduction in fuel and electricity consumption, also promoting economic growth through the adoption of new technologies (Frischmann et al., 2020).

The detailed analysis of the influence of building's solutions – including space heating and cooling, cooking, lighting, and water use efficiency improvement technologies – on the SDGs done by Frischmann et al. (2020) can be found in Figure 2.1.



Solution Links (Benefit /Tradeoff) to SDG	SDG1	SDG2	SDG3	SDG4	SDG5	SDG6	SDG7	SDG8	SDG9	SDG10	SDG11	SDG12	SDG13	SDG14	SDG15	SDG16
Biogas for Cooking	7/0	2/1	5/0	6/0	4/0	4/0	3/0	8/0	3/0	2/0	4/0	2/0	1/0	1/0	4/0	
Building Automation Systems			4/0			1/0	1/0	4/0	3/0		2/0	4/0	1/0	2/0	2/0	
Building Retrofitting			4/0			1/0	1/0	5/0	3/0		3/0	4/0	2/0	2/0	2/0	
District Heating			4/0			1/0	2/0	4/0	3/0		3/0	4/0	1/0	2/0	2/0	0/1
Dynamic Glass			4/0				1/1	4/0	3/1		3/0	3/0	1/0	1/0		
Green and Cool Roofs	3/0		4/0			1/0	1/0	5/0	3/0		4/0	4/0	2/0	2/0	2/0	
High-Efficiency Heat Pumps			4/0			1/0	3/1	5/0	3/1		3/0	4/0	2/0	2/0	2/0	
High Performance Glass	3/0		4/0			1/0	1/1	4/0	3/1		4/1	4/0	2/0	2/0	2/0	
Improved Clean Cookstoves	7/0	2/1	5/0	6/0	4/0	1/0	3/1	8/0	3/1	2/0	5/1	2/0	1/0		4/0	
Insulation	3/0		4/1			1/0	1/0	4/0	3/0		4/1	4/0	2/0	2/0	2/0	
LED Lighting	4/0		4/0	6/0			2/0	6/0	3/0		3/0	3/0	2/0	1/0	1/0	
Low-Flow Fixtures			1/0			2/0	1/0	2/0	2/0		3/0	3/0	1/0			
Net-Zero Buildings			4/0			1/0	2/0	4/0	3/0		3/1	4/0	2/0	2/0	2/0	
Smart Thermostats			4/0			1/0	1/0	4/0	3/0		3/0	3/0	1/0	1/0	1/0	
Solar Hot Water	1/0		4/0			1/0	3/1	4/0	3/1		4/1	4/0	1/0	2/0	2/0	0/1

Figure 2.1 - Influence of buildings solutions on the SDGs (Frischmann et al., 2020)

European Green Deal

Part of the EU Commission's strategy to implement the United Nation's 2030 Agenda and the sustainable development goals, the European Green Deal growth strategy aims to detach economic growth from resource use, setting a goal of reaching the net-zero emission of greenhouse gases in 2050, while allowing the EU to become a fair and prosperous society, with a modern resource-efficient and competitive economy (European Commission, 2019) (Figure 2.2).

Putting sustainability and well-being of citizens at the center of economic policy, the strategy tackle climate and environmental-related challenges resulting from the climate changes and the atmospheric heating observed in the world, aiming to protect, conserve and enhance the EU's natural heritage from environment-related risks and impacts.

Figure 2.2 – The European Green Deal (European Commission, 2019)

The Green Deal emphasizes the need to rethink policies, increasing the value given to the protection of the natural ecosystems and the improvement of human health and well-being, through sustainable use of resources, for a better integration of clean energy supply across all the economy, including the construction sector.

With regards to the existing buildings stock, responsible for 40% of energy consumption, the strategy encourages the EU and the Member States to engage in a 'renovation wave' of public and private buildings on the challenge to achieve energy efficiency and affordability in the construction, use, and renovation of buildings (European Commission, 2019).

The increase in the annual renovation rate of the Member States' building stock, currently between 0.4 to 1.2%, is also vital in reaching the EU's energy efficiency and climate objectives (European Commission, 2019). Lowering energy bills and improving the quality of the construction – and consequently, the well-being of users – energy and resource-efficient renovations also can reduce energy poverty, assisting costumers who struggle to keep their homes at a comfortable temperature and other energy services at affordable costs.

The design of new and renovated buildings is expected to be aligned with the needs of the circular economy, leading to a path of increased digitalization and climate-proofing of the building stock. On that goal, multiple efforts are in course to enforce the legislation related to the energy performance of buildings, including the 2020's assessment of Member States' national long-term renovation strategies under the Energy Performance of Buildings Directive, initiatives related to relative pricing of different energy sources to encourage more energy-efficient alternatives, and the revision of the Construction Products Regulation to align the marketing of construction products with the aimed sustainability goals (European Commission, 2019).

To overcome existing barriers to renovation, the Commission also proposes an open platform, bringing together the buildings and construction sector, architects, engineers, and local authorities, with innovative financing schemes targeting housing associations and energy service companies that could contribute to the renovation catalysis. Rented and multi-ownership buildings are also targeted by the Commission, which aims to overcome national regulatory barriers on energy efficiency investments, with particular attention to the renovation of social housing and households with financial difficulties in the payment of energy bills.

Renovation Wave strategy

Pointing to buildings renovation as a double feature solution for climate neutrality and economic recovery post-Covid, the European Commission (2020a) developed the Renovation Wave strategy with the objective to "at least double the annual energy renovation rate of residential and non-residential buildings by 2030" and the potential to promote the renovation of 35 million buildings units.

Besides the guiding principle of *energy efficiency*, the strategy's highlights the *affordability* of energy-performing and sustainable buildings to lower-income and vulnerable people and areas, the focus on user's health and protection against climate-related hazards through the implementation of *high health and environmental standards*, the integration of energy systems to help the *decarbonization and integration of renewables* and heritage conservation based on the *respect for aesthetics and architectural quality* in its contribution to people's quality of life and sustainable development of cities and rural areas (European Commission, 2020a).

Fit for 55

The Fit to 55 package (European Commission, 2021) builds on EU policies and legislation, further supporting a fair shift to climate neutrality, presenting a comprehensive set of proposals on clime and energy, setting the basis for a sustainable, resilient, and job generative economy.

A set of interconnected proposals driving towards the same goals of leading the EU to a fair, competitive, and green transition by 2030, the Fit for 55 package strengthens eight existing pieces of legislation. It presents five new initiatives on climate, energy and fuels, transport, buildings, land use, and forestry. It assumes the policy mix approach defended in the 2030 Climate Target Plan as a way to balance the opportunities and costs involved in the green transition (European Commission, 2021). Balancing between pricing, targets, standards, and support measures, the chosen policy mix aims to avoid the high economic burdens expected from an over-reliance on regulatory policies reinforcement and the inefficiency of overcoming market-related issues through carbon pricing interventions alone (European Commission, 2021).

2.2 Buildings (In)Efficiency and Energy Poverty

Energy Poverty

Defined as the situation in which a household is unable to access essential energy services, energy poverty is a significant challenge in the EU. In 2018, nearly 34 million Europeans could not afford to keep their homes adequately warm (European Commission, 2020b).

Despite being among the warmest countries in Europe, with the fifth-highest number of cooling degree-days and the third lowest heating degree-days in 2020 – 267 days considering a base temperature of 24°C and 1008 days considering a base temperature of 15°C, respectively (Eurostat, 2021b) – Portugal had the fourth-highest rate of households unable to maintain their dwellings adequately warm during winter (18.9%) of all the European member-states, in 2019, according to the EU Survey on Income and Living Conditions (SLIC) (Eurostat, 2021d).

The origin of such contradiction can be related to the Portuguese building stock condition and their population's low income. Portugal had the highest percentage of inhabited dwellings in poor conditions – leaking roof, damp walls, floors or foundation, or rot in window frames or floor – accounting for 24.4% of its population (Eurostat, 2021e), and 4.3% of the same population claiming to have arrears on utility bills (Eurostat, 2021a). Residential EPCs indicate poor energy performance and energy efficiency from Portuguese dwelling stock, with a prevalence of 'C' rate or less on over 70% of the certified buildings (ADENE, 2021).

Considering the population living in a dwelling not comfortably cool during summer, 35.7% in 2012, the second-highest in Europe, the issue of Portuguese energy poverty is further evidenced, estimated to affect between 20% and 36% of their population (Gouveia & Palma, 2021). Besides its direct impact on social inclusion, access to essential energy services related to heating, cooling, lighting, and electricity for power appliances is fundamental in achieving a decent standard of living and health (European Commission, 2020b). Therefore, the users' comfort and well-being directly depend on their access to those essential energy services.

Commission recommendation on Energy Poverty

On the matter of Energy Poverty, the European Commission provides guidance on indicators of energy poverty and the assessment of energy-poor households, also enlisting several recommendations for its Member States.

Prioritizing the most vulnerable groups, the Commission advises the use of available Union funding programmes to ensure access to support in overcoming existing energy poverty issues. That can be achieved through inclusive energy transition projects and measures based on close cooperation between all levels of administration, civil society organizations and private sector entities.

The assessment and handling of potential barriers to investment in energy-efficient housing are highlighted as an important topic to be taken into consideration. One of those barriers, the high upfront costs of residential renovations, receive particular attention. The Commission recommends the involvement of energy service companies and energy performance contracts in the provision of renovation financing solutions for energy-poor households, targeting low-income households as a category of beneficiaries of public funds and grants (European Commission, 2020b).

The identification of those priority groups can be catalyzed through a building typology approach. Ultimately classifying the diverse building stock into a national visual portfolio containing information of typical building characteristics regarding, for example, thermal insulation potentials could be of great assistance in reaching and providing sustainable solutions for dwellings in most need of renovation.

Long-term Strategy for Building Renovation

The Long-term Strategy for Building Renovation (Portuguese Republic, 2021a) was developed in the context of the Regulation (EU) 2018/1999, on the Governance of the Energy Union and Climate Action, the Directive (EU) 2018/844, amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency, and guidelines from the National Energy and Climate Plan 2030 (PNEC 2030), which sets goals and objectives, and implements policies and measures for the 2030 horizon.

Aligned with the European Parliament and the Council 2050's goals, the ELPRE aims to support the renovation of the Portuguese park of residential and non-residential buildings, public and private, into a decarbonized and energy efficient building stock, facilitating the transformation of existing buildings into Nearly Zero Energy Building (NZEB) (Portuguese Republic, 2021a). The strategy includes a roadmap with indicative measures and targets for the horizons of 2030, 2040 and 2050, and the respective link to the fulfillment of the European targets for energy efficiency and reduction of GHG emissions.

The elaboration and execution of the ELPRE considered the existing national buildings stock's energy consumption profiles and thermal comfort indexes to assess associated improvement opportunities (e.g., healthier, more productive population and decreased energy poverty). Moreover, the strategy identifies the implementation costs from required policies and measures, considering the covered buildings' particularities such as typology and geographic location.

With policies and actions organized into seven lines of action, ELPRE's measures include intervention in the buildings' surroundings, the replacement of inefficient systems, the promotion of renewable energy use, the adoption of technical solutions for energy renovation in the covered buildings, the development of financing programs and mobilization of public and private investment, as well as the reinforcement of policies aiming market incentive and monitoring.

National Long-term Strategy to Fight Energy Poverty 2021-2050

Portugal's National Strategy to Fight Energy Poverty 2021-2050 (Ambiente e Ação Climática. República Portuguesa, 2021) (draft version) aims to obtain the characterization of the energy poverty issue in the country, and to develop monitoring indicators and strategies, to set goals for reducing energy poverty in the medium and long term, at the regional and local scale, to propose specific measures to achieve these objectives, and forms of financing for its mitigation. The strategy is the Government first step in defining a strategic framework for combating energy poverty integrated into the broader approach on climate change, economic recovery, social equality and improvement in the overall life of the Portuguese population.

Acknowledging the importance of social inclusion in avoiding energy poverty exacerbation throughout the decarbonization and energy transition process, the strategy provides for a comprehensive and detailed understanding of the energy poverty reality in the country, identifying and highlighting potential energy poverty situations to propose concrete measures aimed at buildings renovation, energy efficiency promotion and the reduction of fossil fuel dependence.

Adding to the potential benefits originated from the ELPRE goals on building renovation, within the scope of the Recovery and Resilience Program (PRR in Portuguese), Portugal will grant 300 of the 610 million euros over the next five years allocated to energy efficiency in buildings to the residential sector. Household of all types, with emphasis on low-income and energy-poor households, are included through support initiatives and efforts to tackle initial investments challenges related to energy renovation, such as the "Vale Eficiência" ("efficiency voucher"), with an initial investment of 130 million Euros, and the maintenance of the "Edifícios +Sustentáveis" ("more sustainable buildings") with other 135 million Euros.

In addition to the investments in energy efficiency actions in residential buildings, the strategy short-term goals include the financial support for energy-poor households equipment replacement and adoption of more efficient solutions; the implementation of a national monitoring system on energy poverty through data collection and processing; the promotion of local structures to support and monitoring of energy-poor families; and the stimulation of self-sustaining communities' projects.

2.3 Examples to follow

One-stop-shops for buildings renovation

The concept of one-stop-shops (OSS) is appealing to clients and suppliers, serving at the same time as a valuable source of information to the general public and an innovative business model to connect suppliers to potential clients (Boza-Kiss & Bertoldi, 2018).

In the Directive 2018/844/EU, one-stop-shops for consumers and energy advisory services are considered as accessible and transparent advisory tools on energy efficiency renovations and financing instruments.

Based on the case studies of 63 OSS in the EU, the European Commission's science and knowledge service, the Joint Research Center (JRC), indicates the approach of OSS for energy renovation of buildings has a potential to increase the actual renovation rate, covering 5-6% of the renovation volume of 35 million buildings by 2030, as set out by the Renovation Wave Strategy, by supporting potential clients through the decision-making process of building renovation (Boza-Kiss et al., 2021).

Connecting the diversity and complexity of the residential building sector with the construction supply side, OSS can also contribute to the alleviation of energy poverty by adopting a holistic approach to building renovation in terms of energy performance, reaching out to vulnerable populations and facilitating the access to financing instruments at better rates with client-friendly methods (Boza-Kiss et al., 2021).

Project TABULA

Applying the concept of buildings typologies to the context of energy-saving strategies, the project TABULA (Typology Approach for Building Stock Energy Assessment) developed residential buildings typologies for 13 European countries, consisting of a classification scheme grouping buildings according to their size, age, and additional parameters with a set of exemplary buildings representing the buildings types.

Co-funded by EU Intelligent Energy Europe Programme (IEE), the project examined past experiences with buildings typologies in European countries to develop a concerted approach to the domain of residential buildings, aiming to enable a better understanding of the building sector in different countries in terms of structure and modernization processes, ultimately allowing encouraging the exchange of energy-saving strategies.

Focusing on energy consumption for space heating and hot water, the project also displays buildings' energy-related features, demonstrating the potential effects on energy savings by implementing refurbishment measures.

The typological criteria can be helpful to estimate buildings' energy performance based on specific parameters, including the buildings' year of construction, size, supply system conditions, and existing saving measures (Loga et al., 2012).

Project EPISCOPE

A follow-up of the TABULA project, the IEE project EPISCOPE developed targeted monitoring approaches, combined with scenario analyses and buildings typologies to improve the effectiveness and transparency of energy-saving processes in the European housing sector. With a concerted set of energy performance indicators, the project aimed to enable key actors and stakeholders to track and steer the refurbishment processes, evaluating the achieved energy savings (Stein, B.; Loga, T.; Diefenbach, 2016).

The project also provided base indicators for assessing refurbishment and energy-saving processes, allowing the projection of future energy consumption through building stock models and scenario calculations on a local, regional and national level.

The Green Menu

'De Groene Menukaart' (translated: The Green Menu) is a Dutch online platform that offers support for residents or owners of pre-war, monumental and protected buildings to renovate their homes in a sustainable way (De Groene Grachten, 2021). An initiative of De Groene Grathen, a Dutch consulting and process supervisor company specializing in the sustainable rehabilitation of historic buildings, The Green Menu was developed in 2014 in cooperation with the Association of Dutch Municipalities, various municipalities and provinces to be a national knowledge platform offering insight into technologies, regulations, financing and energy saving possibilities for more sustainable historical buildings.

Serving as a one-stop-shop for building renovation, the platform provides: information about sustainable solutions for buildings insulation, ventilation, electricity, heating and water management; contact with consultants for tailored technical advice and implementation guidance; financing possibilities for implementing the solutions through current subsides; information about required permits, contractor selection and implementation of solutions; and inspiration through example projects and other owners' experience with buildings renovation.

With the goal to expand the platform across Europe, specialists on heritage, sustainable retrofitting and energy efficiency from Slovenia, Portugal and the Netherlands have joined forces in 2020 in a pan-European project on sustainable heritage. Supported by EIT Climate-KIC the project intended to make the complex process of historic residential buildings renovation easier, accessible and scalable. As part of the project, the Portuguese and Slovenian versions of The Green Menu were launched in December 2020.

Representing three distinct European contexts and needs – Portugal: CENSE, NOVA School of Science and Technology, NOVA University of Lisbon; Slovenia: E-Zavod, Institute for Comprehensive Development Solutions; and Netherlands: De Groene Grachten – the project have the shared goal of gathering knowledge in supporting the sustainable renovation of the built environment, with particular interest for historic zones. In the national panorama, the Portuguese version of the Green Menu (CENSE, 2021) already counts with a building typology to reflect the characteristics of residential buildings in the historic centre of Lisbon.

3 METHODOLOGY

Bearing in mind the objective of this study to characterize the Portuguese residential building stock in representative buildings typologies, by combining alphanumeric and geographic data catalogued from 2011 Census' Geographic Information Referencing Base (BGRI) and visual information from Google Maps' satellite and street view images, the work developed herein was structured in several key actions, namely: extraction and treatment of BGRI's raw data (INE, 2011); selection of variables containing buildings characteristics information (e.g., plot placement, floor area); assessment of regional characteristics predominance; assessment of sub-regional characteristics predominance; selection of representative sub-regions based on representativeness, energy poverty vulnerability (as in Gouveia et al., 2019) and climatic zones diversity; location of representative buildings in statistical subsections; collection and quantification of buildings' primary visual features (e.g., roof type, floor levels, etc.); selection of key features and buildings samples; and ultimately, 3D models construction of the selected regions' representative buildings typologies.

The above actions were structured in three main phases. The first phase focused on data treatment work in spreadsheets, during which BGRI's data (INE, 2011) were extracted at the regional level (NUTS 2) from Census spreadsheets. Variables with residential buildings' aesthetics-related information (e.g., housing type, number of floors, bearing structure) were selected and used to assess the characteristics predominance per region, resulting in the regional buildings profiles presented in chapter 4.1.2.

The main goal in phase two was the delimitation of study areas. Aiming a more in-depth assessment of the buildings' visual features per region, specific sub-regions (NUTS 3) were selected to serve as references in the buildings' typologies definition. The selection was based on the sub-regions' contribution to the region's building profile (similarity between the two profiles), vulnerability to energy poverty, and respective climatic zones. Study areas for each selected sub-region were then narrowed to the smallest territorial subdivision (statistical subsections) based on the predominance of buildings sharing their region's profile.

Finally, phase three aimed at the typologies' visual representation. For that purpose, each subsection had their residential building stock studied using Google Maps satellite and street view images, having their main visual features (e.g., roof tile type, envelope finishes type, windows system type) collected, catalogued and quantified. The frequency of the elements was then assessed in the sub-regional level, the ones present in most of the residential building stock for two or more subsections being selected as regional key features. Examples of buildings portraying the key features were also collected to assist with the 3D models' construction in SketchUp.

The organizational chart below (Figure 3.1) outlines the above-described methodology adopted to develop this dissertation. It translates the activities workflow that took place throughout the process and their relationship.

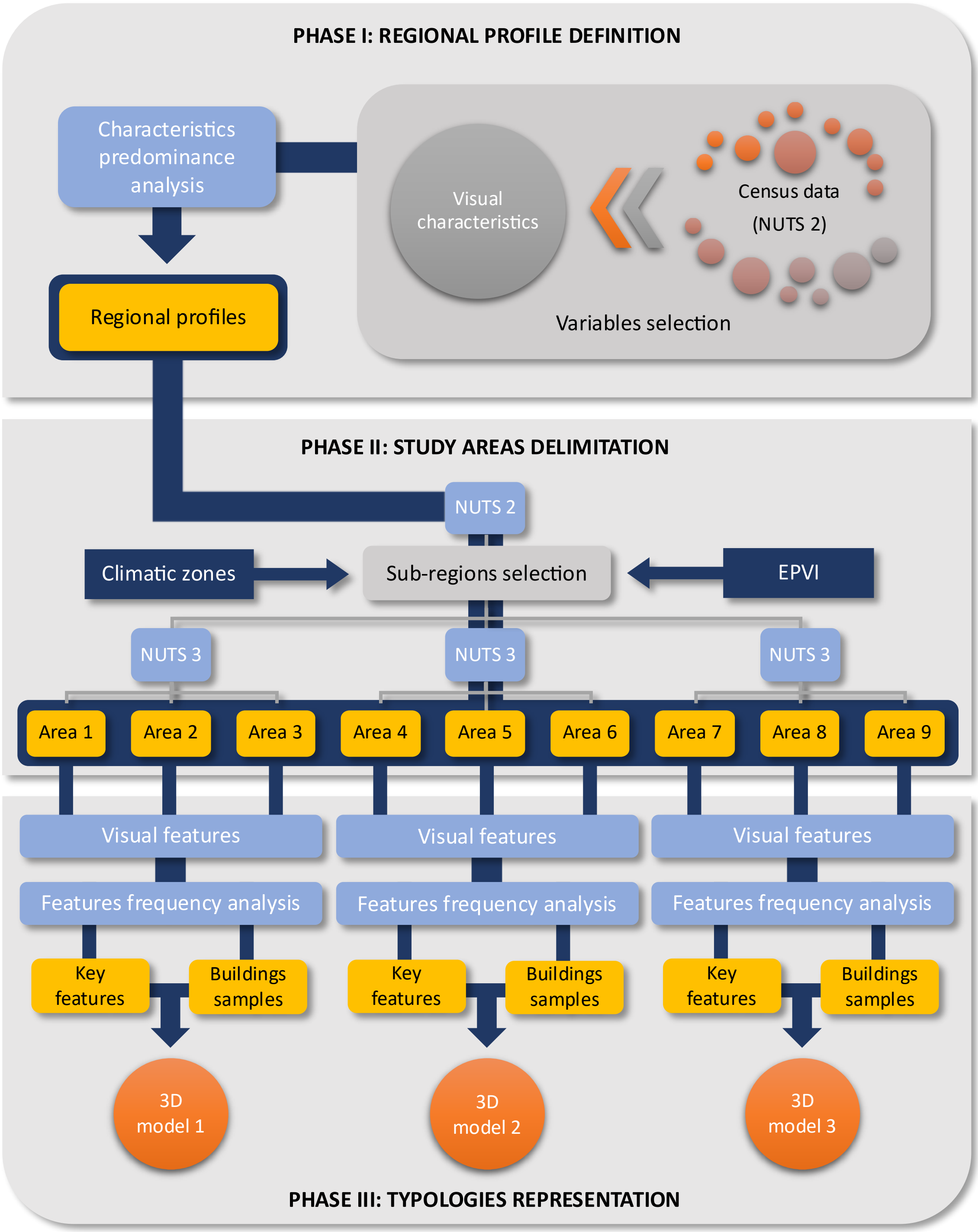


Figure 3.1 - Methodological scheme

3.1 Phase I – Regional profiles definition

Fonseca & Oliveira Panão (2017) defined that residential typologies are theoretical buildings representing the common characteristics shared by a group of real dwellings. In the typological characterization of the Portuguese residential building stock presented in this thesis, the country's territorial organization was the main criteria for the sample groups selection, each typology aiming to be identifiable as representative of a specific region.

Therefore, an overview of the regions' buildings stock was the starting point in identifying their main characteristics and particularities, ultimately drawing a regional buildings profile that would guide the search of key features and houses samples to be represented.

3.1.1 BGRI's raw data extraction and variables selection

In the regional profile definition, the 2011 Census of Statistics Portugal provides for the whole country structured relevant information for identifying typical buildings at different territorial levels, being selected as the primary resource of data in this first phase.

Publicly available on the institute's website, the Census files (BGRI dataset) are presented per municipality and organized following Eurostat's Nomenclature of Territorial Units for Statistics (NUTS) system. The NUTS system subdivides Portugal into three levels: NUTS 1 (the National level corresponding to the mainland and the Autonomous Regions of the Azores and Madeira), NUTS 2 (Regions) and NUTS 3 (Sub-regions).

Each Census spreadsheet gathers geographical data and statistical information relative to the buildings and their family unities (e.g., building's primary use, occupancy status, connection with the water and sewage system, residents' primary activity, education level, etc.). The information is presented per territorial level, namely: region, sub-region, municipality, civil parish, section and subsection. For the regional profile definition of this first phase, the data extraction and treatment focused on the regional level (NUTS 2).

After the regional lines of information were extracted and gathered, main groups of information were identified, including the building's year of construction, primary use, number of floors, resident's ethnography, etc. While some groups of information, such as the type of bearing structure, placement in the plot, year of construction and area, for example, presents useful visual characteristics for the profiling of the buildings' typologies, other information regarding its users (e.g., age, gender, literacy and employment status, etc.) hold less relevance to the present work. The selection of the groups of information to be further treated and analyzed was therefore based on their potential contribution to the typology's visual distinction and representativeness, as well as its potential impact on the overall energy efficiency, as in the approach used by Palma et al. (2019) and Lopes (2010).

3.1.2 Characteristics predominance analysis (regions)

Gathered in a single pivot table, the selected groups of information with the different regions' buildings characteristics were used to identify each region's most frequent aesthetics-related attributes per group (e.g., bearing structure, number of floors, housing type, etc.). As quantitative data, Census indicates the number of buildings catalogued under each characteristic. The columns with the highest number of buildings in their respective groups were therefore chosen as representative characteristics of that region's building typology (e.g., "bearing structure in reinforced concrete" from the "bearing structure" group). The seven regional profiles were composed of the identified predominant buildings characteristics.

3.2 **Phase II – Study areas delimitation**

While this broader analysis, at the regional level, of the most prevalent characteristics of their buildings stock, is a good starting point in the typification of the national household, further investigation in more precise locations, with concrete examples, is imperative to obtain more further visual information to capture the diversity of Portuguese residential buildings.

3.2.1 Characteristics predominance analysis (sub-regions)

With the overview of the region's buildings' characteristics defined in their profiles, a more in-depth assessment of the region's buildings' visual features was then needed to gather more concrete information to guide the typological characterization of the Portuguese residential building stock. For that purpose, the sub-regions lines of information (NUTS 3) were extracted, gathered, and assessed through the same process applied in NUTS 2.

Besides reassuring consistency in the regional profile regarding their sub-regions buildings characteristics, the process helped identify potential locations to find concrete housing examples to base the typologies definition. On that matter, the sub-regions buildings stock that more consistently shared their region's profile were highlighted as potential references in the buildings' typologies definition.

3.2.2 Sub-regions' selection

To provide further guidance in the selection of representative sub-regions from the initial number of potential candidates to choose from, while also adding extra layers on information with great impact on the household level of thermal comfort and energy efficiency, the sub-regions Energy Poverty Vulnerability Index (EPVI) and climatic zones were introduced to the analysis.

Energy poverty vulnerability

The energy poverty vulnerability index (EPVI), described in the work of Gouveia et al. (2019) and applied by Horta et al. (2019) to identify the most vulnerable areas of the country, by Gouveia et al. (2021) for characterizing Lisbon municipality, and adapted for Poland in Karpinska et al. (2021) was used to direct the selection by focusing on typologies that better represented those priority areas.

Made available by NOVA School of Science and Technology's Centre for Environmental and Sustainable Research (CENSE), an updated rank of Portuguese' EPVI (April 2021) helped identify sub-regions in higher vulnerability to energy poverty during winter and summertime.

The top five most vulnerable sub-regions were highlighted for each season (winter and summer) and then ranked based on their average vulnerability position. With some sub-regions occupying opposite positions for summer and winter in the vulnerability spectrum – presenting higher vulnerability during winter and low vulnerability during summer, for example – the annual average vulnerability ranking approach helped identify the sub-regions that still scored high when both seasons were taken into consideration.

Climatic zones

To assure more diversity to the typology selection, the sub-regions' predominant climatic zones were also considered in this phase to consider buildings with different energy needs and consumption profiles.

Based on current national regulation (Despacho nº 15793-F, 2013) and NUTS 3 classification also used in Gouveia & Palma (2019), all sub-regions climatic zones were combined with EPVI ranking, the most vulnerable sub-regions belonging to different climatic zones, and also included in the pre-selected representative sub-regions group, being finally chosen for a deeper analysis of their building stock.

From that group, the ones holding the greatest contribution to its region profile – with the higher number of catalogued buildings under its region predominant characteristics – were selected as the most representative sub-regions.

3.3 **Phase III – Typologies representation**

3.3.1 Sample selection

With regional building profiles defined and representative sub-regions selected, the study proceeded to find buildings reflecting their region's typical characteristics to serve as good examples in the national typologies' representation. In that task, the BGRI dataset was again used to identify precise locations with the prevalence of buildings sharing those identified characteristics, guiding the search and preventing partiality in the sample collection.

Location selection

The individual BGRI files from the municipalities belonging to the representative sub-regions were obtained from INE's website, having their specific line of information extracted and grouped per sub-region. The municipality with the most significant percentage of buildings catalogued under the characteristics included in their region's profile (e.g., bearing structure in a masonry wall with plate) was then selected to be further assessed.

From the selected municipality's BGRI file, the next territorial level's (parish or section, depending on the municipality's territorial organization) line of information was again extracted, gathered and assessed under the same criteria.

Following that process, each sub-region location was progressively defined until the smallest territorial unit available in the files (subsections), providing a precise location to identify potential buildings examples.

In that process, locations with increased consistency in all columns of characteristics (increased average) were preferred opposite those showing more significant discrepancies between columns. Availability of online visual information was also a criterion considered during the process.

With all subsections selected, the map view version of the 2011 Census' BGRI was then used to locate the subsections, which could be then navigated through with the help of Google Maps.

An initial "bird's eye view" navigation allowed to verify the presence of buildings reflecting the visual characteristics indicated in the original region's profile. Inconsistencies that could appear between INE's statistical information and Google Maps' visual sample can indicate different time frames between the 2011 Census dataset and images capture date.

Key visual features identification

A deeper analysis of the building stock was then performed on street view to identify the most frequent visual features added to the existing regional profile. Besides collecting visual examples of the verified statistical information, other visual characteristics not covered in BGRI files were also captured from multiple buildings to help determine the most common elements and construction solution types shared in that statistical subsection.

Visual aspects of the buildings' main component, such as openings, finishes, roof and enclosure, were assessed with particular attention to their material, construction solution type, shape, colour, placement in the building, and any other relevant information that would contribute to a more straightforward association of that specific building typology with its region.

The selected key visual features were then used to help determine the most representative building from that subsection, which would ultimately be an example of its sub-region into the composition of national typologies. Hence, the selected building would reflect the characteristics indicated in the regional building profile (e.g., households with 1 to 2 band units), gathering the majority of that subsection's key features (e.g., square masonry chimneys, narrow balconies with an iron guardrail, etc.). Figure 3.2 indicate the buildings main components and respective elements used in the sample assessment.

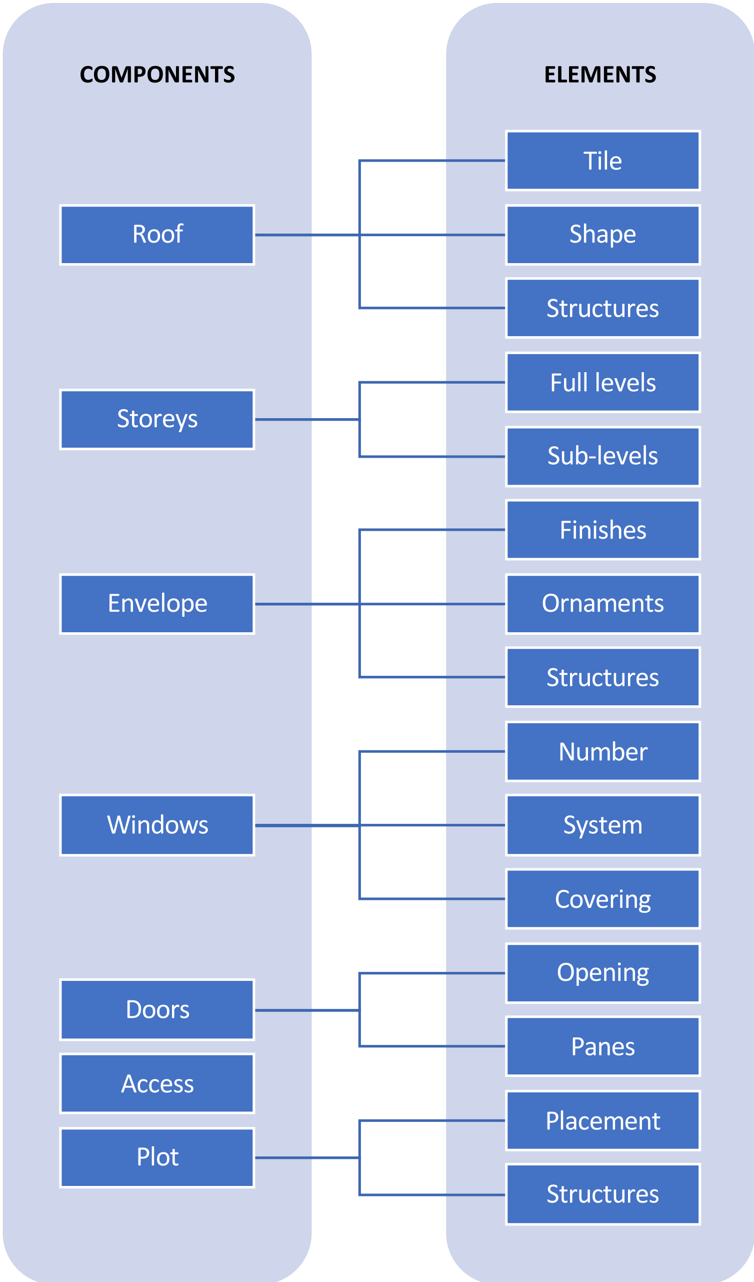


Figure 3.2 – Main buildings components and respective elements used in the sample assessment

Constructive solutions

Complementing the visual information obtained through Street View, the sub-regions' energy performance certificates were used to identify specific constructive solution types otherwise not easily identifiable by visual means.

The EPCs were gathered for each selected representative sub-region, from a database of over half a million EPCs. The available buildings components were evaluated for the presence of their respective types of constructive solutions (e.g., structural material, glass panels, etc.) in the sub-regions. The area of the different types of solutions was counted from each sub-regions' certificates. For each component, the constructive solution with the largest area was selected per sub-region.

3D models construction

With concrete national buildings examples selected, the following phase consisted of the typology's representation in 3D models using SketchUp. Each region's model was mainly based on the chosen building examples. The design aimed to capture key features that differentiate the region's building stock from others, allowing a visual association between the typology and the region it represents. Other relevant statistical information from BGRI and EPC dataset were also taken into consideration in this phase.

4 RESULTS

Reflecting on the methodological process followed and previously described, the presentation of the results will be divided into three sections: regional buildings profiles, studied areas and buildings typologies representation.

4.1 Regional profiles definition

This section presents the buildings profiles per region resulting from the data treatment work described in the methodology's first phase. The main findings leading to the profiles' definition are also presented. Namely: variables selection, characteristics predominance and regional building profile.

4.1.1 Characteristics selection

From the resulting spreadsheet compiling all seven regions' lines of information extracted from their respective Census folders at Statistics Portugal's website, 29 columns of information were gathered into the six groups of characteristics with the greatest relevance in the typologies definition, as indicated in Figure 4.1.

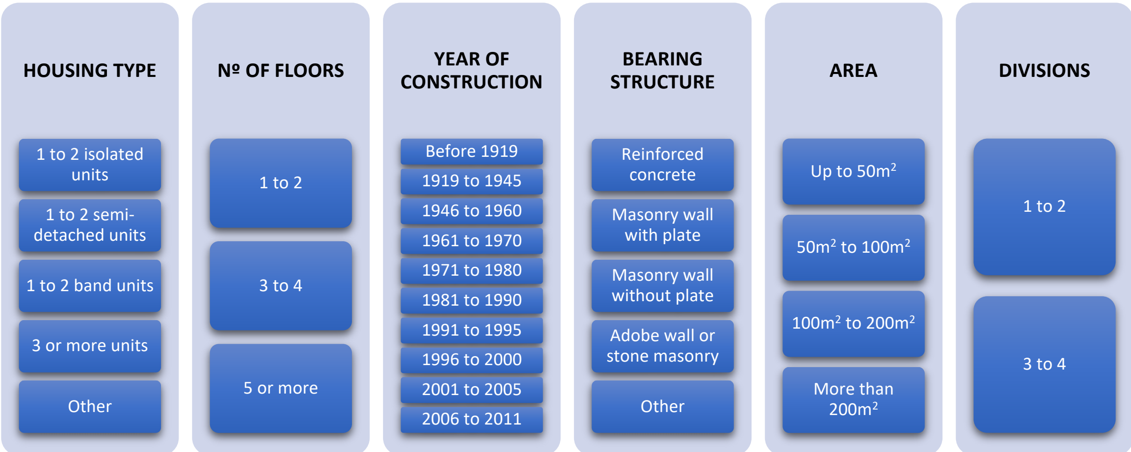


Figure 4.1 - Selected groups of buildings characteristics for representative regional building typologies definition. Based on 2011 Census (INE, 2011)

From Census 122 columns of information, the above 29 are the ones that are directly related to the built structure of the house. Whether to the buildings' visual characterization or its resulting energy need and thermal comfort, these groups were selected as they contain the most valuable insights to this thesis purpose.

The Housing Type group presents two valuable pieces of information to the typology definition: plot placement and number of units. Regarding the plot placement, it indicates whether the buildings are entirely detached from others; semi-detached, sharing one common wall with the next house; or placed in a row of attached houses sharing side walls. Besides the plot placement, that group of characteristics also gives us an insight regarding the number of house units contained in a single building, which will reflect in the number of accesses, openings and dimensions of the building. Although the last two characteristics of the Housing Type group ("3 or more units" and "other") do not contribute with any visual impactful information, only representing buildings with three or more house units and housing types that do not fit the defined criteria, they add to the total of buildings catalogued per territorial division for that group, and for that reason are needed for the percentual analysis in the regional profile definition.

Besides the Number of Floors, which is directly reflected in the height of the building, the remaining groups provide indirect visual contribution for the analysis. The different years of construction and bearing structure can influence visual aspects of the building such as façade elements and wall thickness, as well as can the total area and divisions in the buildings' dimension and number of openings.

4.1.2 Characteristics predominance (regions)

Resulting from the above characteristics' data analysis, the following graphics (Figure 4.2 to Figure 4.7) represent the predominance of buildings – total number of buildings catalogued under that characteristic – per group of characteristics per region.

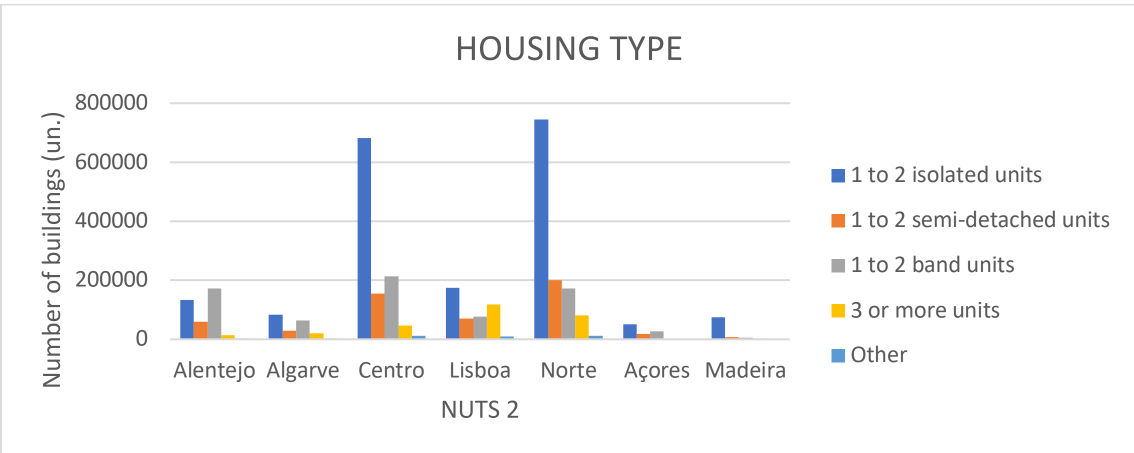


Figure 4.2 – Predominance of buildings by housing type per region (NUTS 2). Data extracted from 2011 Census (INE, 2011)

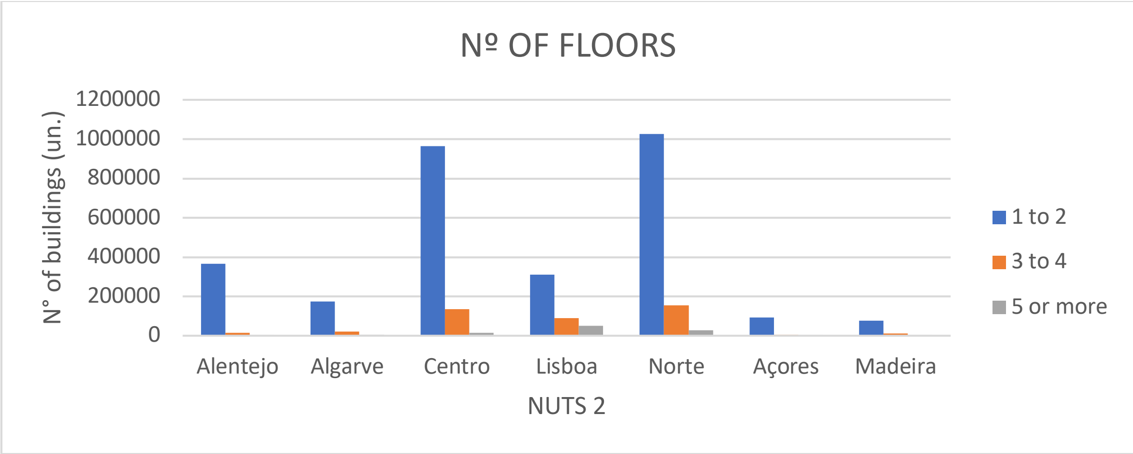


Figure 4.3 - Predominance of buildings by the number of floors per region (NUTS 2). Data extracted from 2011 Census (INE, 2011)

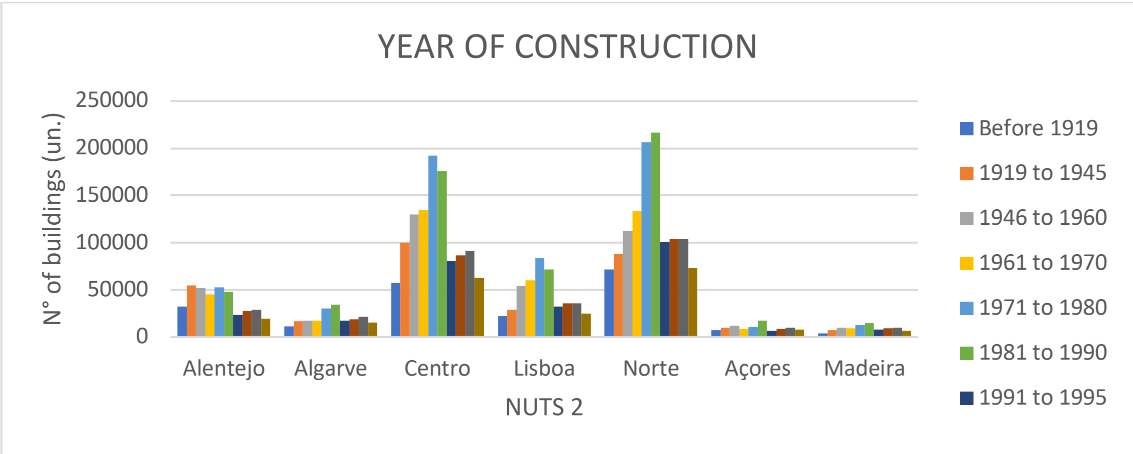


Figure 4.4 - Predominance of buildings by year of construction per region (NUTS 2). Data extracted from 2011 Census (INE, 2011)

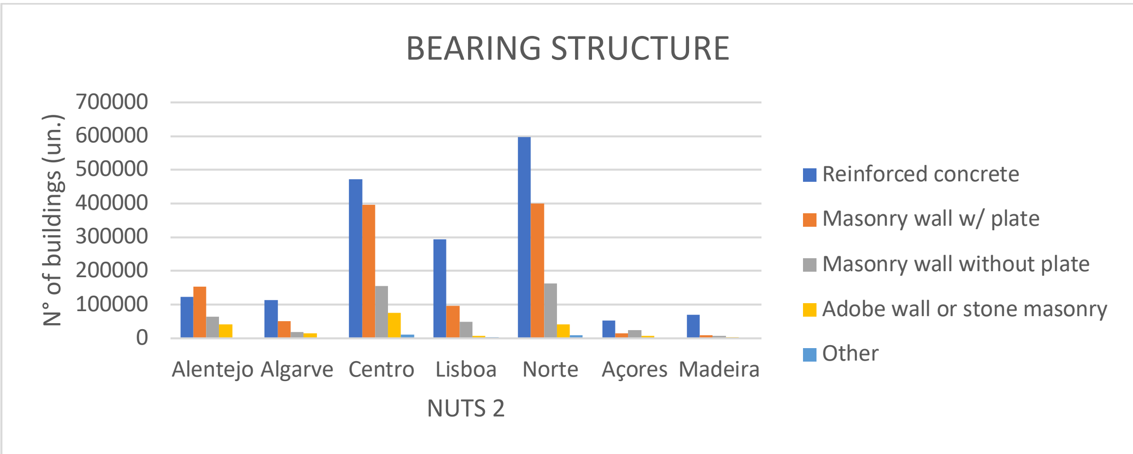


Figure 4.5 - Predominance of buildings by bearing structure per region (NUTS 2). Data extracted from Portugal Statistics (2011)

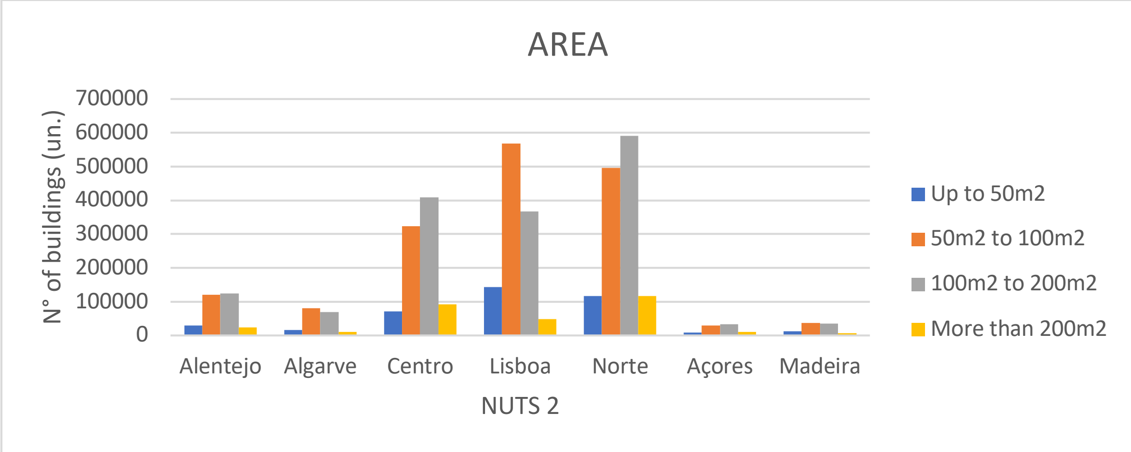


Figure 4.6 - Predominance of buildings by floor area per region (NUTS 2). Data extracted from Portugal Statistics (2011)

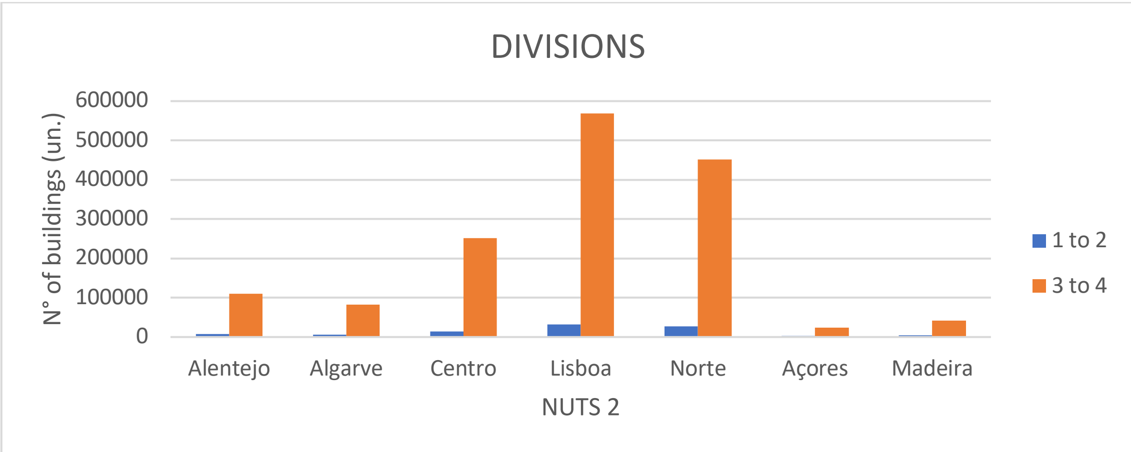


Figure 4.7 - Predominance of buildings by the number of divisions per region (NUTS 2). Data extracted from Portugal Statistics (2011)

Taking Norte as an example, the region's BGRI data indicate typology predominance of buildings with 1 to 2 isolated units, meaning that from the region's 1.209.911 buildings, the majority of 744.666 (60%) were designed to host 1 or 2 independent households.

The same analysis indicates the region's predominance of buildings with 1 to 2-floor levels (85% of the region total), built between 1981 and 1990, with 3 to 4 divisions on a floor area between 100 and 200 m^2. By aggregating each region's predominant characteristics based on the above charts, it was then possible to define regional building profiles, as indicated in the Table 4.1.

Table 4.1 – Main regional buildings' characteristics profile

NUTS 2	Housing Type	N° of Floors	Bearing Structure	Year of Construction	Area (m2)	Divisions
Açores	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Alentejo	1 to 2 band units	1 to 2	Masonry wall w/ plate	1919 to 1945	100 to 200	3 to 4
Algarve	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	50 to 100	3 to 4
Centro	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Lisboa	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	50 to 100	3 to 4

Madeira	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	50 to 100	3 to 4
Norte	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4

Overall, Alentejo is the region that stands out in three out of the six selected groups of characteristics, which may be related to its location, less central and more to the countryside, resulting in fewer interventions and renovations on its building stock in comparison to other more dynamic regions such as Lisboa and Porto. Those aspects point to Alentejo as good source of buildings typologies.

Nuances in the other regions are mainly noticed regarding the buildings' year of construction – with Centro and Lisbon as the second oldest building stock after Alentejo's – and floor area category in which Lisbon, Algarve, and Madeira appear as the regions with smaller floor area.

4.2 **Study areas delimitation**

This section presents the selected study areas resulting from the delimitation process described in the methodology's second phase. The following findings leading to the selection of subsections are also presented: sub-regional buildings profile and representative sub-regions.

4.2.1 Characteristics predominance (sub-regions)

On searching precise locations from which to select actual examples reflecting the initial regional profiles, the analysis of buildings' predominance on the NUTS 3 level revealed the sub-regions that more consistently shared their region's predominant characteristics (Table 4.2).

Table 4.2 – Sub-regional buildings' characteristics profile

NUTS 2	NUTS 3	Housing Type	N° of Floors	Bearing Structure	Year of Construction	Area (m2)	Divisions
Açores	Açores	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Alentejo	Alentejo Litoral	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	50 to 100	3 to 4
Alentejo	Alto Alentejo	1 to 2 band units	1 to 2	Masonry wall w/ plate	1919 to 1945	50 to 100	3 to 4
Alentejo	Alentejo Central	1 to 2 band units	1 to 2	Masonry wall w/ plate	1919 to 1945	100 to 200	3 to 4
Alentejo	Baixo Alentejo	1 to 2 band units	1 to 2	Masonry wall w/ plate	1919 to 1945	100 to 200	3 to 4
Alentejo	Lezíria do Tejo	1 to 2 isolated units	1 to 2	Masonry wall w/ plate	1971 to 1980	100 to 200	3 to 4
Algarve	Algarve	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	50 to 100	3 to 4
Centro	Baixo Vouga	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Centro	Baixo Mondego	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Centro	Pinhal Litoral	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Centro	Pinhal Interior Norte	1 to 2 isolated units	1 to 2	Masonry wall w/ plate	1971 to 1980	100 to 200	3 to 4
Centro	Pinhal Interior Sul	1 to 2 isolated units	1 to 2	Masonry wall w/ plate	1971 to 1980	50 to 100	3 to 4
Centro	Serra da Estrela	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Centro	Beira Interior Norte	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Centro	Beira Interior Sul	1 to 2 band units	1 to 2	Masonry wall w/ plate	1971 to 1980	100 to 200	3 to 4
Centro	Cova da Beira	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4

Centro	Oeste	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Centro	Dão-Lafões	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Centro	Médio Tejo	1 to 2 isolated units	1 to 2	Masonry wall w/ plate	1971 to 1980	100 to 200	3 to 4
Lisboa	Grande Lisboa	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	50 to 100	3 to 4
Lisboa	Península de Setúbal	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	50 to 100	3 to 4
Madeira	Madeira	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	50 to 100	3 to 4
Norte	Ave	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Norte	Douro	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4
Norte	Entre Douro e Vouga	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Norte	Grande Porto	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	50 to 100	3 to 4
Norte	Alto Minho	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Norte	Cávado	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Norte	Tâmega	1 to 2 isolated units	1 to 2	Reinforced concrete	1981 to 1990	100 to 200	3 to 4
Norte	Alto Trás-os-Montes	1 to 2 isolated units	1 to 2	Reinforced concrete	1971 to 1980	100 to 200	3 to 4

Reflecting the pattern observed at the regional level, the entirety of sub-regions has most of their buildings with 1 to 2-floor levels and 3 to 4 divisions. Thus, those two groups of characteristics (Number of Floors and Divisions) do not necessarily contribute to selection in this, particularly territorial level. However, the other groups – particularly the year of construction – present more diversity, being of greater assistance in the process.

Particularities in sub-regions building stock were indeed observed in the remaining four groups (Housing Type, Bearing Structure, Year of Construction and Area). Under Housing Type, for example, Beira Interior Sul sub-region reveals a predominance of buildings with 1 to 2 band units, diverging from its region's pattern for buildings 1 to 2 isolated units observed in Centro's other 11 sub-regions. Similarly, Alentejo Litoral and Lezíria do Tejo sub-regions indicated a prevalence of buildings with 1 to 2 isolated units, diverging from Alentejo's tendency for buildings with 1 to 2 band units.

Similar behaviour was observed in two out of the five Alentejo's sub-regions; namely, Alentejo Litoral and Lezíria do Tejo, instead of buildings with 1 to 2 band units, had most of their buildings with 1 to 2 isolated units.

As happened in Housing Type, Centro showed divergencies in three out of the remaining 11 sub-regions regarding their building stock's Bearing Structure, and one in the Year of Construction category, in which Norte shower greater divergencies as well in three out of its eight sub-regions.

Finally, other diverging sub-region were identified under the Area characteristics in the Alentejo region, resulting in a total of 19 potential representative sub-regions, five in the Norte, seven in Centro and two in Alentejo, besides from Lisboa's two sub-regions – both without variations from that region's profile - and Algarve, Açores and Madeira, that are both regions and sub-regions.

For the Norte region, between the five sub-regions that more consistently shared their regions' characteristics – namely Ave, Entre Douro e Vouga, Minho-Lima, Cávado and Tâmega – the latter holds the highest number of buildings under those categories, followed by Ave, therefore being a good candidate to represent Norte region.

The same process elects Baixo Vouga as Centro's representative sub-region (closely followed by Oeste) while Grande Lisboa and Alentejo Central hold their region's majorities (followed by Baixo Alentejo), this particular level of analysis being excused for Algarve, Açores and Madeira, due to their simultaneously classified.

4.2.2 Sub-regions selection

Energy Poverty Vulnerability Index and Climatic Zones

Latest results of CENSE's EPVI (adapted from Gouveia et al, 2019) indicates, Madeira, Açores, Ave, Grande Porto and Alto Alentejo as the top five sub-regions most vulnerable in winter, also revealing Tâmega e Sousa, Ave, Serra da Estrela, Alto Tâmega and Baixo Alentejo as the most vulnerable during summer, respectively (Figure 4.8).

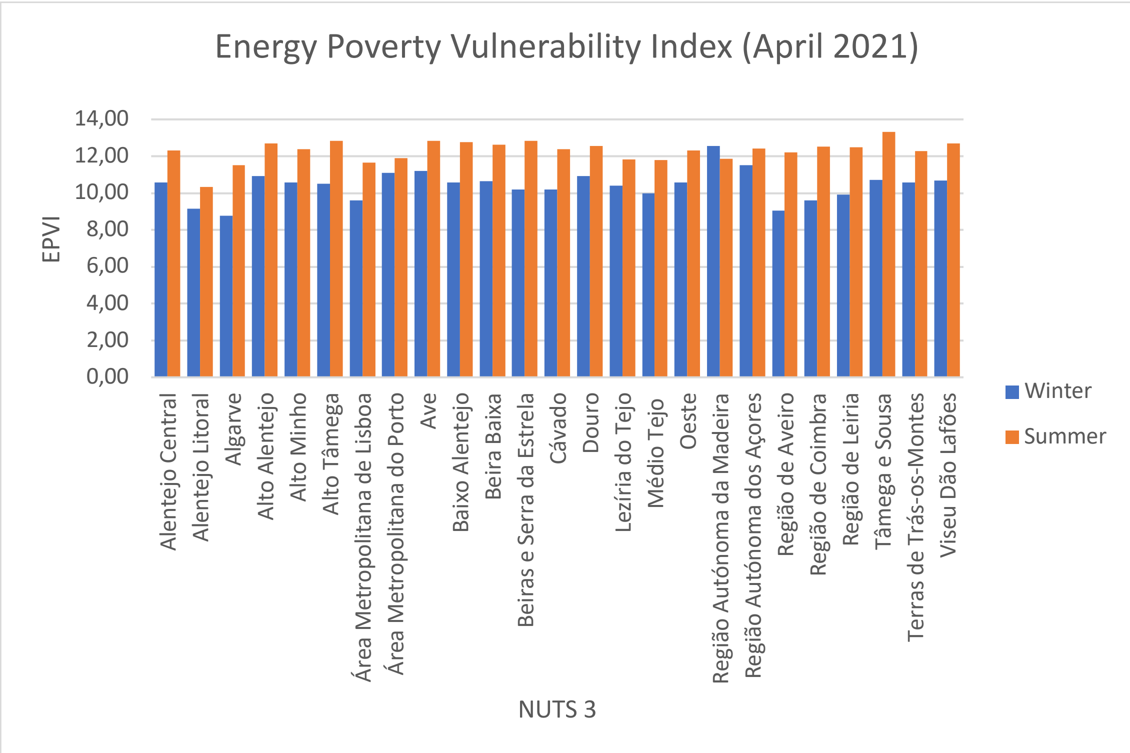


Figure 4.8 - Energy poverty vulnerability index (Adapted from Gouveia et al, 2019)

From the top five vulnerable sub-regions (nine in total), four are included in the previously selected group of representative sub-regions candidates. Namely, from to most to the less vulnerable: Madeira, Tâmega e Sousa, Açores and Baixo Alentejo.

Since Açores shares Madeira's climatic zone, Madeira, Tâmega e Sousa and Baixo Alentejo are finally selected as the sub-regions to be further studied for their distinctiveness, vulnerability to energy poverty and climatic zones.

4.2.3 Representative buildings location

For each representative sub-region, the municipality lines of information were imported from Census data and assessed regarding the similarities to the sub-region. The three municipalities with the highest number of buildings under the same columns of characteristics were selected to continue to process. Since the typologies representation will be based on concrete examples, municipalities with above the average percentage in all characteristics were preferred over those with higher number of buildings in one specific characteristic.

The narrowing down process continued for each of the three selected municipalities per sub-region, going from parishes to sections and finally resulting in the nine subsections chosen to serve as study areas, as indicated in the images below (Figure 4.9 to Figure 4.11).

Figure 4.9 - Baixo Alentejo's subsections (Adapted from Portugal Statistics, 2011)

Figure 4.10 - Madeira's subsections (Adapted from Portugal Statistics, 2011)

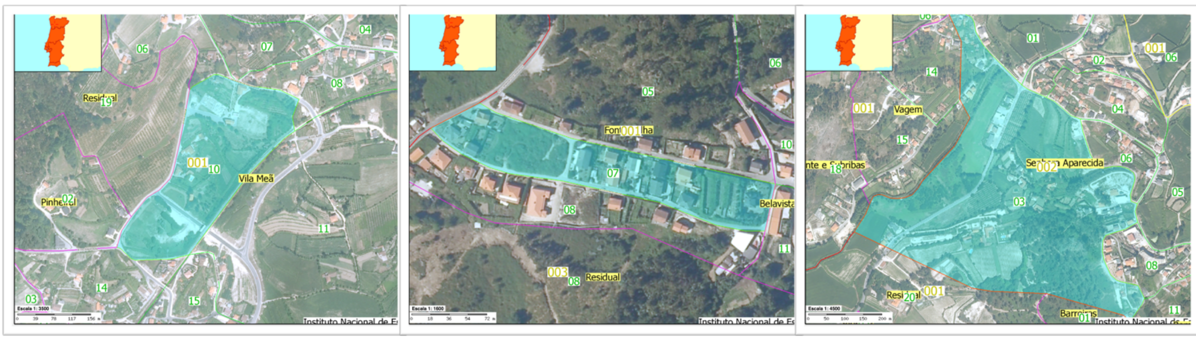


Figure 4.11 - Tâmega e Sousa's subsections (Adapted from Portugal Statistics, 2011)

4.3 Typologies representation

This section presents the three 3D models representing Baixo Alentejo, Madeira and Tâmega's residential buildings typologies resulting from the process described in the methodology's third phase. Specific findings leading to the models' development are also presented. Namely: study areas' main visual features, features quantification, sub-regions' key features and buildings samples.

4.3.1 Visual features collection and quantification

The study areas analysis revealed, as expected, similarities and differences in the buildings' aesthetics. From roof covering solutions to adjacency to their neighbours, the catalogued buildings inside the selected subsections had their main visual features collected using Google Maps satellite and street view images.

Buildings features not identified in the study areas were not added to the collection. Roof tile types such as beaver-tail and grey slates, usually preferred in Germany / Netherlands and French / Belgium / UK, were not present in any of the catalogued buildings in the subsections, so they were not considered for the features collection.

Since the typological characterization aimed in this thesis focuses on the Portuguese residential building stock, commercial buildings that were present in the study areas were not considered in the analysis.

Table 4.3 below presents a summary of the roof features identified throughout the nine subsections as illustrated in Figure 4.12 to Figure 4.14. Additional features tables for the remaining building components can be found in the appendix section. The features are grouped per roof elements based on the buildings' tile types used in the covering, the shape in which it was designed, and the complementary structures present in that specific building component. The different tile types applied in the buildings' covering, for example, are variations of the roof element "tile" that impact the final aesthetics of the "roof" building component.

Table 4.3 – Identified roof features

Features		
Component	Element	Type
Roof	Tile	Mission
		French
		Portuguese
		Undefined
	Shape	Shed
		Skillion
		Gabled
		Hipped
		Pyramid hip
		Intersecting hip
		Hidden
	Structures	Dormer
		Chimney
		Cornice
		Ornaments

While some features indicate variations of a buildings' element (e.g., roof tiles of the mission type), others represent attributes that can be cumulatively present in the buildings. In all the feature tables presented hereafter, mutually exclusive feature groups share the same cell colour. Element types from a features group with alternating cell colours can be present in their entirety in the buildings or not be present at all. The images in Figure 4.12 to Figure 4.14 below present visual examples of the identified roof features grouped per roof element.

Figure 4.12 - Roof tile types (Adapted from Google Maps, 2021)

Figure 4.13 - Roof shape types (Adapted from Google Maps, 2021)

Figure 4.14 - Roof structure types (Adapted from Google Maps, 2021)

Alongside the features collection, the number of buildings showcasing the respective features was also quantified for each subsection throughout the process, as indicated in Table 4.4 below. Additional tables with additional features quantification can be found in the appendix section.

Table 4.4 – Roof features quantification

Features			Baixo Alentejo						Madeira						Tâmega e Sousa					
Component	Element	Type	BA1	14	BA2	11	BA3	7	MA1	4	MA2	14	MA3	6	TS1	2	TS2	12	TS3	18
Roof	Tile	Mission	14	100%	2	18%	6	86%	0	0%	0	0%	0	0%	0	0%	1	8%	0	0%
		French	0	0%	0	0%	0	0%	0	0%	0	0%	1	17%	0	0%	3	25%	3	22%
		Portuguese	0	0%	7	64%	1	14%	3	75%	10	71%	5	83%	2	67%	6	50%	10	56%
		Undefined	0	0%	2	18%	0	0%	1	25%	4	29%	0	0%	0	0%	2	17%	5	28%
	Shape	Shed	4	29%	0	0%	1	14%	0	0%	2	14%	0	0%	0	0%	0	0%	0	0%
		Skillion	1	7%	1	9%	0	0%	0	0%	1	7%	1	17%	0	0%	0	0%	2	11%
		Gabled	8	57%	10	91%	4	57%	1	25%	3	21%	1	17%	0	0%	9	75%	7	39%
		Hipped	0	0%	0	0%	0	0%	2	50%	5	36%	1	17%	0	0%	2	17%	6	33%
		Pyramid hip	0	0%	0	0%	0	0%	0	0%	2	14%	0	0%	0	0%	0	0%	1	6%
		Intersecting hip	0	0%	0	0%	0	0%	1	25%	0	0%	3	50%	2	67%	1	8%	2	11%
		Hidden	1	7%	0	0%	2	29%	0	0%	1	7%	0	0%	0	0%	0	0%	0	0%
	Structures	Dormer	0	0%	0	0%	0	0%	1	25%	2	14%	0	0%	0	0%	1	8%	0	0%
		Chimney	4	29%	7	64%	5	71%	1	25%	2	14%	2	33%	2	67%	9	75%	17	94%
		Cornice	12	86%	9	82%	6	86%	1	25%	6	43%	2	33%	2	67%	0	0%	0	0%
		Ornaments	0	0%	0	0%	0	0%	1	25%	1	7%	1	17%	0	0%	0	0%	2	11%

In the table, the studied subsections are grouped per sub-region and named with their initials. The total number of buildings comprised by the Census' subsections area is indicated next to the subsections' name (e.g., subsection BA1 has a total of 14 buildings catalogued inside its area) and served to assess the feature's presence in the subsection's residential buildings stock. Taking the subsection BA3 as an example, six have their roofs in mission tile and one in Portuguese tile out of the seven buildings included in this area.

Due to limited visual data or reduced visibility, the total number of buildings had to be adjusted for the subsection MA2, TS1 and TS3. During the study areas delimitation process, Madeira revealed to be the sub-region with fewer routes available in street view. For the subsection MA2, for example, despite having 52 catalogued buildings inside its area, only 14 were accessible through street view. Similarly, subsections TS1 and TS3 have buildings with reduced or no visibility in Google Maps, requiring their total number of buildings to be lowered from 5 to 2 and 43 to 18, respectively. Additionally, buildings that were not possible to be assessed for a particular element due to data limitation (e.g., levelled terrain or building height preventing a proper view of the roof in street view and low resolution of satellite images preventing the tile type identification in birds-eye view) were counted as "undefined" on that features group quantification.

Below the subsections' total number of buildings, the table indicates the percentage of buildings showcasing the identified feature. Together with the added conditional formatting Excel function, the information aids the identification of the most frequent features per subsection. Subsection BA1, for example, has the entirety of its buildings' roof in mission tile. For subsection BA2, however, the predominant roof tile type is the Portuguese.

4.3.2 Sample selection and 3D models construction

Key features

The key features selection was based on the features' frequency at the sub-regional level. Knowing the predominant features per subsection, as a result of the features quantification previously performed, the predominance of the same features was easily identified per sub-region. On a mutually exclusive features group, the predominant feature in most subsections (two out of three) was selected as one of the sub-region's key features. Features from a non-mutually exclusive group were cumulatively chosen following the same rule (be predominant in at least two out of the three subsections for that sub-region).

Table 4.5 to Table 4.7 below list the key features per sub-region resulting from applying the aforementioned selection criteria on the features quantification tables presented in the previous topic.

Table 4.5 – Key-features: Baixo Alentejo

Features			NUTS 3
Component	Element	Type	Baixo Alentejo
Roof	Tile	Mission	x
	Shape	Gabled	x
	Structures	Chimney	x
		Cornice	x
Storeys	Full levels	Single storey	x
Envelope	Finishes	Smooth coat	x
	Ornaments	Half rendered wall	x
		Cased wall	x
		Cased openings	x
Windows	Number	2 openings	x
	System	Casement	x
Doors	Opening	Single leaf	x
	Panes	Door lite	x
Access	-	Levelled	x
Plot	Placement	Row	x

For Baixo Alentejo's subsections, most of the studied buildings have their windows blinds closed in the street view images, preventing the identification of the windows opening system. Those cases were catalogued as "undefined" in the features quantification table, which prevailed in the sub-region (two out of the three subsections). For that reason, the second most frequent system (casement in the case of Baixo Alentejo) was selected as the key feature instead. That also happened in Tâmega e Sousa, where the slider window system was chosen since it was the second most predominant.

Some features were not predominant (did not reach 51% of the subsection's catalogued buildings) in any of the subsections, indicating an increased diversity in the variety of the features with no prevalence for a specific element type. When that happened in a group of non-essential features (e.g., roof structures: chimney, dormer, ornaments), no feature was selected as representative. For the instances when that happened in a group of essential features (e.g., roof shape: gabled, hipped, hidden) the second most predominant feature was selected. Madeira, for example, does not reveal a predominance for a specific roof shape (none of its subsections had more than 50% of the buildings showcasing a specific roof shape), reason why the second most frequent shape (hipped, in this example) was selected as one of the sub-region's predominant features.

Table 4.6 – Key-features: Madeira

Features			NUTS 3
Component	Element	Type	Madeira
Roof	Tile	Portuguese	x
	Shape	Hipped	x
Storeys	Full levels	Single storey	x
Envelope	Finishes	Smooth coat	x
	Ornaments	Half rendered wall	x
	Structures	Front entry porch	x
Windows	Number	4+ openings	x
	System	Slider	x
	Covering	Blind shutters	x
Access	-	Levelled	x
Plot	Placement	Detached	x
	Structures	Driveway	x

Table 4.7 – Key-features: Tâmega e Sousa

Features			NUTS 3
Component	Element	Type	Tâmega e Sousa
Roof	Tile	Portuguese	x
	Shape	Gabled	x
	Structures	Chimney	x
Storeys	Full levels	Single storey	x
	Sub-levels	Underground floor	x
Envelope	Structures	Veranda	x
Windows	Number	4+ openings	x
	System	Slider	x
Doors	Opening	Single leaf	x
Plot	Placement	Detached	x
	Structures	Iron railing	x
		Driveway	x
		Garden	x

Constructive solutions

Specific constructive solution types for the buildings' covering, windows, walls and pavement – otherwise not easily identifiable by visual means – were obtained through the sub-regions' energy performance certificates. Regarding window solutions, for example, the EPCs indicate the variety of frame materials (wood, metal or plastic), glass type (single, double or triple), and existence of thermal insulation in the sub-region's certified houses.

Although not specific to the studied statistical subsections, the information provided by the EPCs are still indicative of the sub-regions' tendencies regarding constructive aspects that directly impact the users comfort and overall quality of the dwelling. They represent a relevant contribution for future assessment of residential energy efficiency and potential areas of intervention for sustainable retrofitting.

A total of 437 certificates were considered in the analysis, 193 from Tâmega e Sousa, 189 from Madeira, and 55 from Baixo Alentejo. The solutions accounting for the greatest portion of the sub-region components' area are indicated in the Table 4.8 abaixo.

Table 4.8 – Predominant constructive solutions per sub-region

Constructive solutions		NUTS 3		
Component	Solution type	Baixo Alentejo	Madeira	Tâmega e Souza
Covering	Horizontal covering without thermal insulation		x	x
	Sloped covering without thermal insulation	x		
Windows	Wooden frames with simple glass	x		
	Metallic frames without thermal insulation with simple glass		x	x
Walls	Single or double walls with cement render (after 1960)			x
	Simple wall with cement render (before 1960)	x		
	Single wall without thermal insulation		x	
Pavement	Floor without thermal insulation			

Buildings examples

The information gathered in Table 4.5 to Table 4.7 allows the identification of representative buildings portraying the indicated key features inside the respective studied areas. Residential buildings showcasing most of their sub-regions key features were considered as good representations, being selected to serve as a reference in the construction of the 3D models. Figure 4.15 to Figure 4.17 present the residential buildings selected for that purpose.

1 de Dezembro St., Barrancos

1 de Dezembro St., Barrancos

Juncalinho's St., Santo Aleixo da Restauração

Juncalinho's St., Santo Aleixo da Restauração

Juncalinho's St., Santo Aleixo da Restauração

Figure 4.15 - Buildings examples: Baixo Alentejo (Adapted from Google Maps, 2021)

ER 222., Prazeres

Banda D'alem's St., Caniçal

Pico Antonio Fernandes St., Santana

Figure 4.16 - Buildings examples: Madeira (Adapted from Google Maps, 2021)

Oliveira St., Vila Meã

Fonte Velha's St.., Lagares

Penoucas' St., Torno

Figure 4.17 - Buildings examples: Tâmega e Sousa (Adapted from Google Maps, 2021)

3D models

Using the selected buildings examples or the sub-regions' representative residential typologies, three 3D models were constructed in SketchUp. SketchUp is a 3D modelling computer program broadly used in architecture for buildings designing, and rendered with Indigo Renderer, a 3D rendering software that uses unbiased rendering technologies to create photorealistic images. The models represent the identified residential buildings typologies showcasing their key features as indicated in the respective sub-regions' key-feature tables (Table 4.5 to Table 4.7). The models are not intended to be exact replications of the building's examples but a visual source of information regarding the sub-regions most distinct characteristics that differentiate their residential buildings from the other parts of the country. Figure 4.18 to Figure 4.20 present the constructed 3d models followed by an overview of the typologies distinct characteristics.

The first typology showcases Baixo Alentejo's residential buildings, as illustrated in Figure 4.18. The most notable difference between this typology and the others is the lack of plot setbacks. Buildings in this subregion are placed in a row sharing both lateral walls with their neighbours, and façade and main entrance directly to the street. The roof in this typology is also the only one composed of clay mission tiles concave in shape and laid in rows with inverted positions. This type of roof is the most prone to leaks due to its simpler docking system and requires the ending tiles to be applied over the cement structure that constitutes the cornice, another typical feature in this typology. With two slopes directing the water to the front and the back of the building, this typology's roof shape creates an almost continuous roof line in the house rows with chimneys placed in different points of the covering.

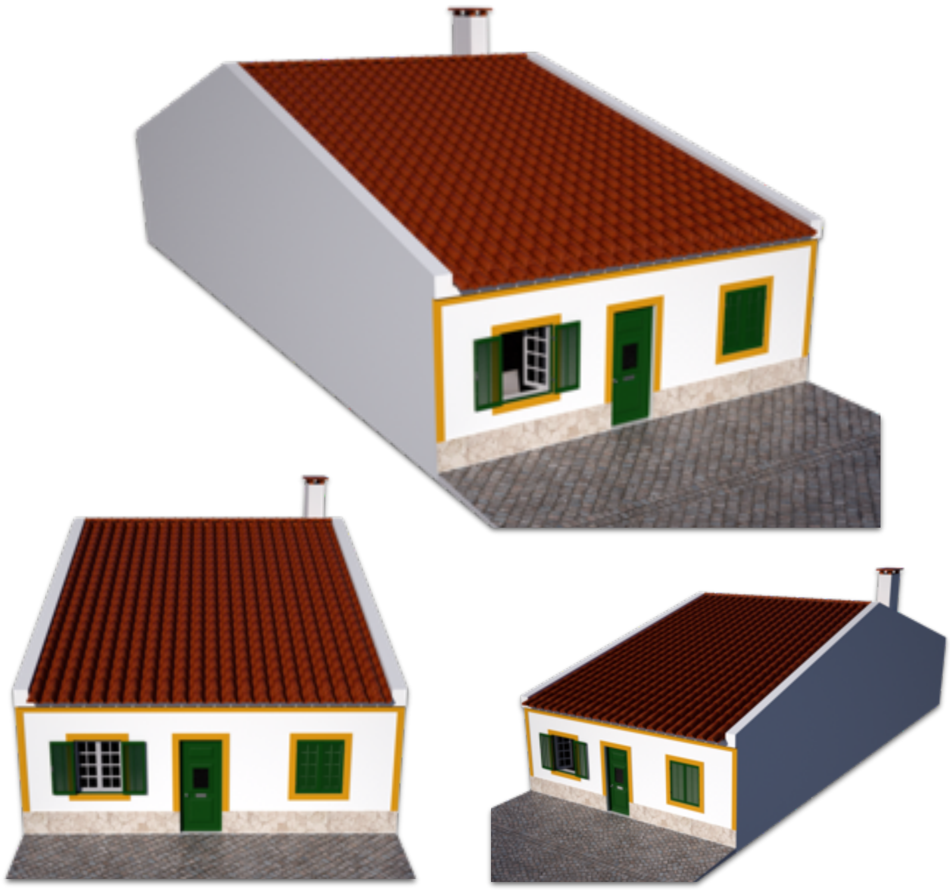


Figure 4.18 - Baixo Alentejo's residential typology

This typology's façade is also the most ornate with half rendered wall in stone, paint or ceramic tiles and cased wall and openings usually in coloured paint but also appearing in stone and ceramic tiles, over a white smooth coat surface. As a result of the lack of lateral setbacks, the number of openings in these residential buildings are limited to the front and back of the house, with usually only two windows with a casement system facing the street. That is another important feature with potential impact on the residents' comfort since the reduced number of openings directly affects the air quality and temperature of the house, especially in the summer. The reduced privacy and noise exchange caused by leaving frontal windows open can discourage the use of the natural ventilation system, reducing cross ventilation of the interior of the house.

Although partially solved by the blind shutters covering that allows air circulation through its slats while controlling the sunlight and providing privacy, alternative architectural solutions could be used for a better result, one example being the use of clerestory roof with windows placed between the roof slopes to allow thermal convection ventilation. Besides improving air quality and ventilation, that solution also provides an additional natural light source. Another effect of the reduced number of openings in this typology, the lack of natural sources of light is reflected in the presence of door lite in the house's main entrance. Serving as a scaled-down window for light, ventilation and identifying callers, this extra opening is another constant in Baixo Alentejo residences.

Except for the threshold's small step, the access in this single storey typology is levelled with the street, sometimes requiring the residents to use removable barriers to prevent water from entering the house during the rainy season.

Madeira's predominant residential buildings typology is represented in Figure 4.19 below. The hipped roof with Portuguese tiles is one of the features that differentiates this sub-region's houses from the others. Composed of four slopes with narrow roof eaves projecting from all façades, this roof type provides some protection from the weather elements while allowing sunlight to reach this typology's multiple openings. Different from Baixo Alentejo and Tâmega e Sousa, chimneys and other roof structures are not frequent in this sub-region – although the presence of an attic was observed in one-third of the studied buildings.

However, the most distinct visual feature in this typology is the presence of a front entry porch. Creating a transition area into the interior of the house, the porch marks the building's main entrance and protects it from the weather. For the 10 residences showcasing the feature – accounting for 75%, 21%, and 67% of the studied three areas' buildings in this sub-region – it was always located in the corner of the building facing the main street and slightly above the exterior of the house level.

Completely detached from the plot limits, this typology has windows in all façades and extra entrances in the side and/or the back of the house. As mentioned in the overview of the key features on page 31, the predominance of closed windows blinds compromised the precise determination of the sub-region's preferred window system type. Nevertheless, sliding windows and blind shutters were predominant in the houses where that analysis was possible.

Regarding the building's surroundings, a small masonry fence with an iron railing delimits the plot limits in Madeira's typology. Pedestrian and driveway gates are present and usually accessed through a narrow ramp or step overlaying the street gutter. The patio surrounding this sub-region's houses is usually covered with a pavement solution, stones slates and ceramic tiles being the most frequent.

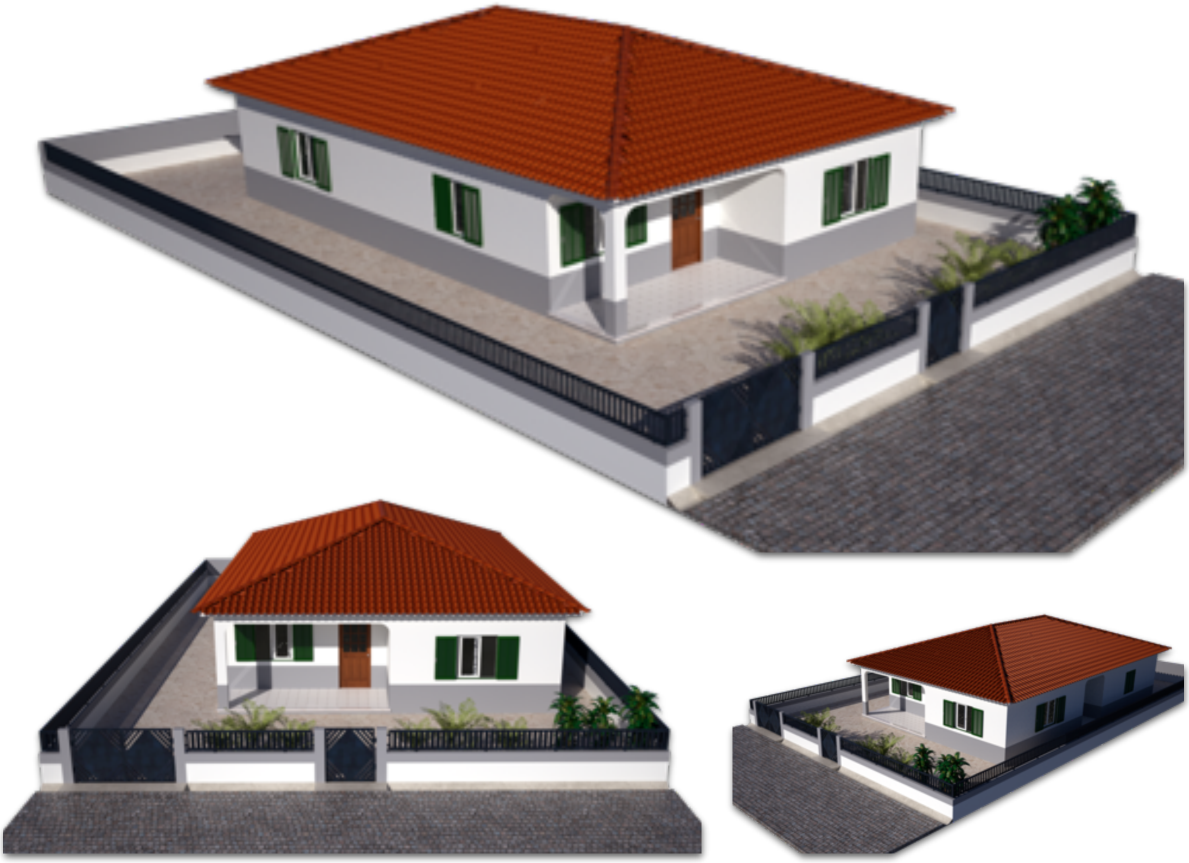


Figure 4.19 – Madeira's residential typology

Finally, Tâmega and Sousa's typology departs from the others with regards to the number of floors, main access and presence of verandas, as represented in Figure 4.20. Although most of this sub-region's houses show a one-story façade at street level, an underground floor is usually hidden in the terrain slope, being a predominant feature in the studied buildings. With pedestrian and driveway gates giving access through a small masonry or stone fence, a car ramp is often seen on the side of houses built parallel to the land slope. In contrast, in descending street, this access is almost levelled to the underground level, excusing the use of ramps. As a reflection of the underground level or sometimes due to descending streets, the main door is usually a couple of steps above the street level, accessible through a single flight of stairs with landing. In some residences, the main stairs also lead to projecting verandas that continue for sometimes two façades. Nonetheless, this sub-region's verandas are predominantly enclosed in the limits of the walls and facing the side or back of the plot.

A wide variety of roof shapes was observed in this sub-region's residential buildings, with no particular shape prevailing across the subsections. Gabled roof, however, was the one that presented the highest percentage of buildings in one of the three studied subsections, being directly followed by intersecting hip roof. Unlike Baixo Alentejo's gabled roofs, where the buildings are predominantly attached on both sides, obligating the roof to be contained inside the side walls limits, Tâmega's have eaves in the gable walls as well. Mostly detached from all sides for all three subsections, this sub-region's residences present roofs in a sloped concrete slab and Portuguese tiles, projecting itself from all the walls. Chimneys also prevailed in all subsections.

Figure 4.20 - Tâmega e Sousa's residential typology

5 CONCLUSIONS

5.1 Overall conclusions

This dissertation performed a cross-country assessment on the Portuguese residential buildings stock, applying a bottom-up approach to define representative typologies for three priority regions in need of residential energy renovation.

Statistical data on structural and architectural buildings characteristics extracted from the 2011 Census allowed the identification of the residential buildings' predominant characteristics for all seven regions (NUTS 2) and 25 sub-regions (NUTS 1) in mainland Portugal and islands. The assessment resulted in the compilation of the respective buildings' characteristics profiles on the regional and sub-regions level, revealing eight sub-regions that most significantly contribute for their regions characteristics profile, as a starting point for the selection of study areas from which to extract further characteristics.

On the identification of priority sub-regions for residential renovation, the analysis of their EPVIs revealed nine sub-regions ranking top five in vulnerability to energy poverty in the winter and/or summer, Açores, Madeira, Norte and Alentejo being the regions with the highest percentage of sub-regions in the rank. Four of the eight sub-regions previously highlighted for their representativeness in their region's profile appeared in the ranking. From those, Tâmega e Sousa, Madeira and Baixo Alentejo were finally selected as priority areas in this study, based on the diversity of their climatic zones.

The study of the residential buildings of the nine subsections with the highest concentration of buildings reflecting the characteristics of the three selected sub-regions, together with specificities on their constructive solutions obtained from the EPCs allowed the compilation of key-features tables gathering the different regions' residential buildings most distinct visual elements for all primary components (roof, storeys, openings, envelope, openings, access, plot), ultimately used in the definition of the three representative typologies constructed in 3D models.

The main differences observed in the three typologies regards the presence of sub-levels (underground floor), façade ornaments and structures, main accesses, number of openings, and plot (land lot) placement. Baixo Alentejo typology stands out as the only one without plot setbacks, placed in a row with the main entrance opening directly to the street, being the smallest house in floor area. It is also the only typology with cased façade and openings, and half rendered wall in stone. Madeira's most distinct visual element is the presence of front entry porch safeguarding the main entrance from the weather elements. That typology also departs from the others for its hipped roof shape, with four slopes and eaves in all façades. Finally, Tâmega typology is the only one with an underground level and veranda, with a single flight of stairs with a landing marking the main entrance.

5.2 Contributions

Contributing to the portfolio of typologies expected to integrate the Portuguese version of the Green Menu (www.menurenovacaoverde.pt), the residential typologies resulting from this work can be used to assess the residential energy performance of the studied regions' buildings stock. The identified particularities of the regions' residential typologies can help determine main sources of energy inefficiency by estimating the baseline energy demand of the existing building stock, allowing the proposal of adequate alleviation measures, such as sustainable retrofitting solutions.

In the context of a national renovation wave, the presented typologies contribute as an optimizing tool to catalyze the process of residential energy efficiency, helping the identification of the representative residential typologies for sub-regions with buildings stock in need of renovation and assisting with the integration of their owners as indispensable stakeholders on a large-scale intervention.

Finally, the applied data analysis approach can also be replicated to other regions to expand the national residential buildings typologies catalogue, tackling recurrent inefficiency issues in the country's diverse architectonic heritage in the improvement of Portuguese homes' comfort, efficiency and sustainability.

5.3 Limitations

Developed in the context of the 2019 Covid-19 crisis, this thesis resorted to Street View images as the sole source of visual information in the study of the sub-regions' buildings stock. This limitation of visual information sources may have affected the proper assessment of predominant buildings characteristics. As an example, the evaluation of predominant window system solutions had to be limited to houses with open blind shutters, which in some subsections were a minority in comparison to the ones with closed blind shutters. Other limitation in the use of Street View image, the quality of the images, distance from the house and visual obstacles (trees, vehicles, fixed structures, blind spots) often limited the overall visibility of the studied buildings.

The selection of the study areas was also limited by Street View routes availability. In the selection of respective municipalities, parishes, sections and subsections with highest concentration of buildings reflecting the region's characteristics, an alternative parish, section and subsection had to be selected due to the lack of routes in the first choice. That had particular impact during the selection of Madeira's study areas, where "Santana" parish was selected over "Ilha" and the third subsection in concentration of buildings examples compensated for the lack of imagens for the first two.

The use of online images also limits the assessment of other relevant aspects of the dwellings, such as the material of the building's components. Some frequently used materials today are made to mimic others, like in doors and windows with different finished mimicking wood of steal. In other cases, the assessment of insulation systems was not possible, like double glass windows. Although partially solved by information from the EPCs, the misleading visual information did not allow those aspects to be considered in the typologies, limiting their contribution in assessment of residential energy performance.

Furthermore, the lifespan of the information used in this work, particularly regarding the statistical dataset and the images source, also represent limitations for the findings presented. Considering the use of data from the 2011 Census, soon to be updated with the 2020 version, and the frequency of update of Street View images – most of the subsections with imagens from 2014, with three subsections from 2009 and only one from 2021 – possible changes in the national panorama of residential buildings characteristics over this time lapse of nine year can potentially impact the applicability of the proposed typologies.

5.4 Future work

Revisiting the findings presented in this thesis with the upcoming 2020 Census represents a possibility of next step in the improvement of the proposed typologies. The new statistical dataset would allow to validate the predominant characteristics identified in this work for the studied sub-regions' residential buildings stock. The new data will also be updated in accordance with the most recent administrative organization of national the territory, providing a more accurate indication of the different territorial units' buildings stock.

Future work can also involve expanding the proposed typologies catalogue with models for the remaining regions (Algarve, Centro and Açores) and eventually sub-regions (when typologies variations in this territorial unit reveals to be more diverse than the represented in the regional level), ultimately covering all existing national residential typologies.

For the effective contribution to the energy renovation process, the work developed in this dissertation can be carried towards the identification of the components with the greatest influence on the energy efficiency of the house. The correlation between buildings elements and energy efficiency for the typologies would allow the identification of potential inefficiencies that can impact the residence's thermal insulation, ventilation, humidity levels and air quality. This advance would represent a substantial step in the proposal of sustainable retrofitting solutions that could be made available for house residents and owners, inspiring and enabling them to renovate their buildings sustainably, and facilitating their involvement in the national renovation process.

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A. Appendix A – Identified features

Table A.1 – Features table: roof

Features		
Component	Element	Type
Storeys	Full levels	Single storey
		Two-storey
	Sub-levels	Attic
		Basement
		Underground floor

Table A.2 – Features table: envelope

Features		
Component	Element	Type
Envelope	Finishes	Stone
		Coarse coat
		Smooth coat
	Ornaments	Half rendered wall
		Cased wall
		Cased openings
	Structures	Front entry porch
		False balcony
		True balcony
		Veranda
		Terrace

Table A.3 – Features analysis: windows

Features		
Component	Element	Type
Windows	Number	1 opening
		2 openings
		3 openings
		4+ openings
	System	Casement
		Slider
		Hung
		Pivot/Fix
		Undefined
	Covering	Blind shutters
		Roller shades
		Solid shutters

Table A.4 – Features analysis: doors

Features		
Component	Element	Type
Doors	Opening	Single leaf
		Double leaf
		Undefined
	Panes	Door lite
		Transom
		Sidelite

Table A.5 – Features table: Access

Features		
Component	Element	Type
Access	-	Levelled
		Single step
		Single flight
		Flight with landing

Table A.6 – Features table: Plot

Features		
Component	Element	Type
Plot	Placement	Row
		Semi-detached
		Detached
	Structures	Masonry fence
		Iron railing
		Driveway
		Covered gate
		Sidewalk
		Garden

B. Appendix B – Features quantification

Table B.7 – Features analysis: storeys

Features			Baixo Alentejo						Madeira						Tâmega e Sousa					
Component	Element	Type	BA1	14	BA2	11	BA3	7	MA1	4	MA2	14	MA3	6	TS1	2	TS2	12	TS3	18
Storeys	Full levels	Single storey	12	86%	9	82%	3	43%	3	75%	8	57%	6	100%	2	67%	8	67%	4	22%
		Two-storey	2	14%	2	18%	4	57%	2	50%	7	50%	0	0%	0	0%	4	33%	14	78%
	Sub-levels	Attic	0	0%	0	0%	0	0%	4	100%	4	29%	0	0%	0	0%	4	33%	3	17%
		Basement	0	0%	0	0%	0	0%	0	0%	1	7%	0	0%	0	0%	2	17%	0	0%
		Underground floor	0	0%	0	0%	0	0%	1	25%	1	7%	5	83%	2	67%	3	25%	11	61%

Table B.8 – Features analysis: envelope

Features			Baixo Alentejo						Madeira						Tâmega e Sousa					
Component	Element	Type	BA1	14	BA2	11	BA3	7	MA1	4	MA2	14	MA3	6	TS1	2	TS2	12	TS3	18
Envelope	Finishes	Stone	0	0%	0	0%	0	0%	0	0%	2	14%	0	0%	1	33%	1	17%	6	33%
		Coarse coat	0	0%	2	18%	0	0%	0	0%	2	14%	1	17%	0	0%	7	58%	2	17%
		Smooth coat	14	100%	9	82%	7	100%	4	100%	10	71%	5	83%	1	33%	4	33%	10	56%
	Ornaments	Half rendered wall	14	100%	10	91%	14	200%	3	75%	9	64%	6	100%	0	0%	3	25%	2	11%
		Cased wall	8	57%	7	64%	8	114%	0	0%	0	0%	0	0%	1	33%	1	8%	0	0%
		Cased openings	10	71%	9	82%	10	143%	2	50%	5	36%	3	50%	2	67%	1	8%	5	28%
	Structures	Front entry porch	0	0%	0	0%	0	0%	3	75%	3	21%	4	67%	0	0%	4	33%	15	83%
		False balcony	0	0%	1	9%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
		True balcony	2	14%	0	0%	2	29%	0	0%	2	14%	2	33%	0	0%	1	8%	10	56%
		Veranda	0	0%	0	0%	0	0%	0	0%	3	21%	3	50%	2	67%	7	58%	10	56%
		Terrace	0	0%	4	36%	0	0%	1	25%	4	29%	0	0%	1	33%	0	0%	2	11%

Table B.9 – Features analysis: windows

Features			Baixo Alentejo						Madeira						Tâmega e Sousa					
Component	Element	Type	BA1	14	BA2	11	BA3	7	MA1	4	MA2	14	MA3	6	TS1	2	TS2	12	TS3	18
Windows	Number	1 opening	5	36%	3	27%	2	29%	0	0%	2	14%	0	0%	0	0%	0	0%	0	0%
		2 openings	8	57%	2	18%	0	0%	0	0%	7	50%	0	0%	0	0%	0	0%	0	0%
		3 openings	1	7%	3	27%	2	29%	0	0%	3	21%	0	0%	0	0%	0	0%	0	0%
		4+ openings	0	0%	2	18%	3	43%	4	100%	2	14%	6	100%	2	67%	12	100%	19	106%
	System	Casement	3	21%	3	27%	5	71%	1	25%	1	7%	2	33%	1	33%	1	8%	2	11%
		Slider	0	0%	1	9%	0	0%	0	0%	5	36%	2	33%	0	0%	4	33%	10	56%
		Hung	0	0%	0	0%	1	14%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
		Pivot/Fix	1	7%	0	0%	0	0%	1	25%	1	7%	2	33%	0	0%	0	0%	3	17%
		Undefined	10	71%	6	55%	2	29%	3	75%	8	57%	2	33%	1	33%	7	58%	6	33%
	Covering	Blind shutters	4	29%	6	55%	1	14%	4	100%	9	64%	6	100%	1	33%	2	17%	7	39%
		Roller shades	9	64%	1	9%	1	14%	0	0%	1	7%	0	0%	0	0%	9	75%	9	50%
		Solid shutters	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%	2	17%	0	0%

Table B.10 – Features analysis: doors

Features			Baixo Alentejo						Madeira						Tâmega e Sousa					
Component	Element	Type	BA1	14	BA2	11	BA3	7	MA1	4	MA2	14	MA3	6	TS1	2	TS2	12	TS3	18
Doors	Opening	Single leaf	10	71%	6	55%	3	43%	3	75%	5	36%	3	50%	1	33%	11	92%	15	83%
		Double leaf	6	43%	5	45%	4	57%	0	0%	1	7%	2	33%	1	33%	3	25%	2	11%
		Undefined	0	0%	0	0%	0	0%	1	25%	8	57%	1	17%	0	0%	0	0%	1	6%
	Panes	Door lite	11	79%	10	91%	7	100%	3	75%	7	50%	2	33%	1	33%	8	67%	9	50%
		Transom	1	7%	3	27%	0	0%	0	0%	3	21%	1	17%	0	0%	0	0%	0	0%
		Sidelite	0	0%	0	0%	0	0%	0	0%	0	0%	2	33%	0	0%	3	25%	9	50%

Table B.11 – Features analysis: access

Features			Baixo Alentejo						Madeira						Tâmega e Sousa					
Component	Element	Type	BA1	14	BA2	11	BA3	7	MA1	4	MA2	14	MA3	6	TS1	2	TS2	12	TS3	18
Access	-	Levelled	10	71%	5	45%	7	100%	4	100%	6	43%	6	100%	0	0%	5	42%	10	56%
		Single step	4	29%	5	45%	0	0%	0	0%	3	21%	0	0%	0	0%	2	17%	1	6%
		Single flight	0	0%	0	0%	0	0%	0	0%	4	29%	0	0%	0	0%	1	8%	1	6%
		Flight with landing	0	0%	1	9%	0	0%	0	0%	1	7%	0	0%	2	67%	5	42%	9	50%

Table B.12 – Features analysis: plot

Features			Baixo Alentejo						Madeira						Tâmega e Sousa					
Component	Element	Type	BA1	14	BA2	11	BA3	7	MA1	4	MA2	14	MA3	6	TS1	2	TS2	12	TS3	18
Plot	Placement	Row	14	100%	11	100%	7	100%	0	0%	3	21%	0	0%	0	0%	0	0%	0	0%
		Semi-detached	0	0%	0	0%	0	0%	0	0%	6	43%	2	33%	0	0%	2	17%	5	28%
		Detached	0	0%	0	0%	0	0%	4	100%	6	43%	4	67%	2	67%	10	83%	13	72%
	Structures	Masonry fence	0	0%	0	0%	0	0%	0	0%	9	64%	1	17%	1	33%	3	25%	5	28%
		Iron railing	0	0%	0	0%	0	0%	2	50%	4	29%	4	67%	1	33%	9	75%	11	61%
		Driveway	0	0%	7	64%	3	43%	4	100%	5	36%	4	67%	2	67%	10	83%	17	94%
		Covered gate	0	0%	1	9%	0	0%	0	0%	1	7%	1	17%	0	0%	1	8%	0	0%
		Sidewalk	0	0%	0	0%	2	29%	0	0%	0	0%	3	50%	1	33%	0	0%	10	56%
		Garden	0	0%	0	0%	0	0%	2	50%	5	36%	3	50%	2	67%	12	100%	17	94%

2021

RODRIGO DA SILVA FELIX

BUILDINGS ACUPUNCTURE: REGIONAL CHARACTERIZATION AND ASSESSMENT OF PORTUGUESE RESIDENTIAL BUILDINGS

NOVA SCHOOL OF SCIENCE & TECHNOLOGY