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Escola de Engenharia

Jorge Emanuel Pereira Fernandes

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Professor Doutor Ricardo Mateus
Professora Doutora Helena Gervásio

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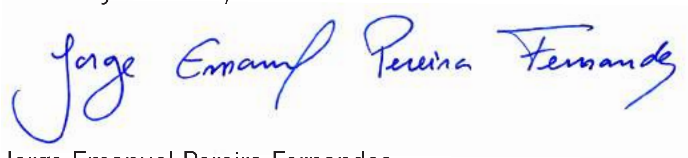
STATEMENT OF INTEGRITY

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

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

University of Minho, December 2020



Jorge Emanuel Pereira Fernandes

RESUMO | Modelação do desempenho do ciclo de vida de edifícios vernáculos portugueses: avaliação e contributos para a construção sustentável

A arquitetura vernácula caracteriza-se por incorporar e expressar uma pluralidade de fatores - geográficos, climáticos, económicos e culturais - dos locais em que se encontra. Na sua longa evolução, e inserida num contexto de escassez de recursos, foram desenvolvidas estratégias/técnicas pragmáticas de adaptação ao meio envolvente. Estas estratégias/técnicas são geralmente simples, possuem um baixo índice tecnológico e potencial impacte ambiental reduzidos, pelo que vários estudos as destacam como tendo potencial para melhorar o desempenho ambiental dos edifícios.

O contexto português é profuso nos tipos de arquitetura vernácula, cujas especificidades acabam por ser identitárias das diversas regiões, mas há um hiato de estudos sobre o seu desempenho térmico e ambiental. Neste sentido, o presente trabalho de investigação apresenta um estudo qualitativo e quantitativo sobre i) as estratégias passivas de mitigação dos efeitos do clima; ii) o desempenho térmico e as condições de conforto de diferentes edifícios vernáculos portugueses ao longo das diferentes estações do ano; iii) e o desempenho ambiental de ciclo de vida de materiais vernáculos. A investigação centrou-se em três casos de estudo, com características distintas e localizados em diferentes zonas de Portugal Continental. O desempenho térmico e as condições de conforto dos casos de estudo foram avaliados através da monitorização *in situ* dos parâmetros higrotérmicos, de questionários aos ocupantes sobre a sua sensação térmica, e os dados analisados segundo um modelo de conforto adaptativo. Para comparar a influência das estratégias nas necessidades anuais de energia para aquecimento e arrefecimento, foram realizadas simulações em condições dinâmicas para diferentes cenários. No caso dos materiais vernáculos, embora sejam percecionados como ecológicos, são parcos os estudos quantitativos disponíveis e que permitam estabelecer uma comparação equitativa com os materiais convencionais. Assim, a avaliação do ciclo de vida de dois materiais em terra, taipa e blocos de terra comprimida (BTCs), foi realizada com base em valores específicos de inventário de ciclo de vida obtidos numa empresa produtora, seguindo a metodologia preconizada na norma EN15804.

Dos resultados obtidos, em geral, verificou-se que os casos de estudo demonstraram um bom desempenho térmico recorrendo apenas a meios passivos, exceto durante o inverno, em que houve a necessidade de utilizar sistemas de aquecimento. No caso dos materiais, numa análise "do berço ao portão" de diferentes tipos de paredes, quando comparados com materiais convencionais, o uso de materiais em terra pode reduzir os impactes ambientais em cerca de 50%. Adicionalmente, os materiais em terra têm a vantagem de poderem ser reciclados/reutilizados numa abordagem circular.

Palavras-Chave: Arquitetura vernácula; Avaliação de Ciclo de Vida (ACV); Conforto térmico; Simulação Energética; Sustentabilidade.

ABSTRACT | Modelling the life cycle performance of Portuguese vernacular buildings: assessment and contribution for sustainable construction

Vernacular architecture is characterised by embodying and expressing a plurality of factors - geographic, climatic, economic and cultural - of the places in which it is located. In its long evolution, and inserted in a context of scarcity, a range of pragmatic strategies and building techniques of adaptation to the surrounding environment were developed. These strategies/materials are usually simple, low-tech and have a low potential environmental impact. From a sustainability point of view, several studies highlight them as having the potential to reduce the environmental impacts of buildings.

In Portugal, there are many expressions of vernacular architecture, whose specificities are an identity factor of several regions. However, there is a lack of quantitative studies on the thermal and environmental performance of vernacular buildings and materials in the Portuguese context. In this sense, this research work presents a qualitative and quantitative study of i) climate-responsive strategies; ii) the thermal performance and comfort conditions of different Portuguese vernacular buildings throughout the different seasons; and iii) the environmental performance of vernacular materials. The research focused on the study of three case studies, with specific features and located in three different zones of mainland Portugal. The thermal performance and comfort conditions of the case studies were evaluated through *in situ* monitoring of hygrothermal parameters, surveys on occupants' thermal sensation, and the data analysed according to an adaptive model of comfort. To compare the influence of some strategies on the annual energy demand for heating and cooling, simulations under dynamic conditions for different scenarios were carried out. In the case of vernacular materials, although these are seen as ecological, the quantitative studies available are scarce and that allow establishing an equative comparison with conventional materials. Thus, the life cycle assessment of two earthen materials, rammed earth and compressed earth blocks (CEBs), was carried out and based on specific life cycle inventory values obtained from a producer company, following the guidance provided by the standard EN15804.

From the results, in general, it was found that the case studies have shown a good thermal performance by passive means alone and that the occupants feel comfortable, except during winter when there was a need to use heating systems. In the case of materials, in a cradle-to-gate analysis of different walls, the use of earthen building elements can result in reducing the potential environmental impacts by about 50%, when compared to the use of conventional ones. Additionally, earthen materials have the advantage that they can be recycled/reused in a closed-loop approach.

Keywords: Energy Simulation; Life Cycle Assessment (LCA); Sustainability; Thermal Comfort; Vernacular Architecture.

CONTENTS

ACRONYMS AND SYMBOLS

ach	Air change rate
ADP_elements	Depletion of abiotic resources – mineral elements;
ADP_ff	Depletion of abiotic resources – fossil fuels;
AEC	Architecture, engineering and construction;
AP	Acidification potential of soil and water;
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
Bq	Becquerel
BSA	Building sustainability assessment;
CEB	Compressed earth block;
CED	Method to calculate cumulative energy demand;
clo	Thermal insulation provided by garments and clothing ensembles
CML-IA	Baseline, impact assessment method developed by the Center of Environmental Science of Leiden University;
CO_2	Carbon dioxide (ppm)
EE tot	Total embodied energy;
EMC	Equilibrium moisture content
EP	Eutrophication potential;
EPBD	Energy Performance of Buildings Directive
EPD	Environmental product declaration;
EPW	EnergyPlus Weather data file
ETICS	External Thermal Insulation Composite System
EU	European Union
GHG	Greenhouse gases
GWP	Global warming potential (climate change)
hPa	Absolute pressure
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor Air Quality
l	Litre
J	Joule
LCIA	Life cycle impact assessment;

LCA	Life cycle assessment;
LCI	Life cycle inventory;
met	Metabolic rate
MW	Mineral wool
nZEB	nearly Zero Energy Building
ODP	Stratospheric ozone depletion potential;
PCR	Product category rules
POCP	Photochemical ozone creation;
R	Thermal resistance (m^2.°C)/W
R&D	Research and development
RE	Rammed earth;
RH	Relative Humidity (%)
Sv	Sievert
U-value	Heat transfer coefficient (W/(m^2.°C))
V	Volt
W	Watt
WHO	World Health Organization
XPS	Extruded polystyrene
°C	Degree Celsius
Ø	Diameter
Θo	Operative Temperature (°C)
Θrm	Outdoor running mean temperature (°C)

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Mas todos estes seres de que te falei são dos que a natureza produz. Eles crescem de tal maneira que a matéria de que são feitos, as formas que revestem, as funções que comportam, os meios que possuem de se acordarem com as localidades e as estações do ano, estão invisivelmente ligados entre si por secretas relações; e é talvez isso que significam as palavras "produzido pela natureza". Na edificação, que é a actividade do construtor, matéria e princípios, corpo e espírito, exigem- se reciprocamente. O acto de construir mostra que é uma exigência dos próprios princípios adquirirem forma sensível, tal como em todos os actos humanos as almas parecem exigir os corpos.

(...)

O artesão não pode realizar a sua obra sem violar ou perturbar uma ordem através das forças que aplica à matéria para a adaptar à ideia que ele quer imitar e ao uso que ele prevê. Ele é, portanto, inevitavelmente conduzido a produzir objectos cujo conjunto é de um grau sempre inferior ao grau das suas partes. Se constrói uma mesa, o conjunto desse móvel é um arranjo bem menos complexo do que o da textura das fibras de madeira, e ele aproxima grosseiramente, numa certa ordem estranha, os pedaços de uma grande árvore que se tinham formado e desenvolvido com outras relações.

Paul Valéry in *Eupalino ou o Arquitecto*

Rendo-me. Diante disto rendo-me, e digo mais: que vale a pena, afinal, haver história, haver arquitectura e haver respeito por quantos souberam ser antes de nós bichos e poetas do seu casulo. (...) Para que me surja vivo e sagrado aos olhos o que os meus antepassados fizeram, é preciso que essa lição seja não só testemunho mas destino.

Miguel Torga in *Diário II*

CHAPTER 1

FRAMEWORK AND AIM

1.1 INTRODUCTION

During recent years, the building sector has undergone a paradigm shift. The rise of environmental awareness has highlighted several problems regarding energy efficiency and environmental impacts. Thus, the sector is changing from a paradigm relying mainly on mechanical systems and high embodied energy materials, less concerned about the climate context and environmental impacts of buildings, to a holistic (sustainable) approach. Buildings are a key sector to implement energy and environmental measures since it is one of the largest energy and natural resources consuming sectors [1], responsible for a third of global total primary energy use and CO_2 emissions [2, 3]. In the European Union (EU), for example, the Directive 2018/844 has set the long-term 2050 goal of reducing greenhouse gas (GHG) emissions by 80-95%, compared to 1990, ensuring an energy-efficient and decarbonised building stock and facilitating the cost-effective transformation of existing buildings into nearly zero-energy buildings (nZEB) [4]. On the materials side, the demand for environmentally friendly materials is growing and is also pushing the sector to shift to the "sustainability" paradigm. Thus, the sector is slowly starting to use materials with lower embodied energy and other environmental impacts, and those that are more compatible, for instance, with the local climate context.

In order to achieve the abovementioned objectives, there is an urgent need to develop new ways of building. According to some authors, it is necessary to reflect on the past because traditional buildings are an example of more sustainable construction and therefore they could have an important role to play in the future of construction [5–7].

Vernacular architecture provides examples of past building design approaches that should be studied. It is characterised by repeated attempts at the improvement over successive generations, striving to make the best use of the limited resources available. In the "Charter on the Built Vernacular Heritage", this type of architecture is defined as "the expression of the culture of a community and its relationship with the territory," in a "continuous process including necessary changes and adjustments in response to ongoing social and environmental constraints" [8].

In an era of globalization, in which the trend is towards the homogenization of cultures and consequently of ways to build [9], vernacular architecture is a crucial element in the discussion about cultural identity and the feasibility of returning to a form of construction which is intrinsically bound up with the local area or region [10]. Vernacular architecture could contribute towards reducing waste and energy consumption through the use of passive solar design, traditional techniques and local materials, in the process of on-going development in which solutions are adapted for specific cases, in accordance with the territory and climate [5, 9, 11, 12].

The approaches used in vernacular constructions to mitigate the effects of climate are usually low-tech and not dependent on non-renewable energy. At the same time, they do not require special technical equipment, which makes them suitable for contemporary construction, especially passive building design [5]. Introducing passive strategies into building design from the start would allow for the reduction of the level of use of mechanical equipment [13]. This is very relevant according to the study carried out by Passer *et al*. [14] which shows that technical building equipment has a notable influence on the overall life-cycle environmental impacts of buildings. In this sense, it is important to highlight that a passive house provides the lowest contribution in terms of such equipment, mainly because there is low need for conventional ventilation and air-conditioning equipment (HVAC) [14].

In Portugal, the study of the vernacular architecture within the scope of sustainability is still in the first stages. There are only a few studies, mainly qualitative, focusing on the passive strategies used and their thermal performance. The few quantitative studies conducted so far [15–19] focused on quantifying the contribution of the passive strategies used in Portuguese vernacular buildings. However, there is still a lack of results from *in situ* measurements that might demonstrate the influence of these strategies on thermal performance. Moreover, on the side of vernacular materials, these are frequently acknowledged as ecological, but currently, there are no quantitative data about their environmental performance that can be used by designers.

Therefore, the goal of this research work is to contribute to this field of research by: i) presenting an overview of the potential contribution of different Portuguese vernacular architecture approaches to passive building design and the analysis about the influence of different passive design approaches on the indoor temperature and humidity of different buildings; ii) assessing the life cycle performance of two materials manufactured in the Portuguese context, in compliance with standard EN15804, for allowing a fair comparison with other EPDs for construction materials or other materials assessed according to the same standard.

1.2 AIM

This research work aims to contribute to the development of knowledge through a quantitative study on the thermal performance and comfort conditions of Portuguese vernacular buildings but also on the environmental performance of vernacular building materials. Briefly, the research questions that will guide the study consist of understanding: How effective are the vernacular passive strategies in maintaining indoor comfort conditions? Are vernacular materials sustainable? What is their potential application to improve the performance of the current building environmental context?

In this direction, the R&D objectives of this research work are:

i. To characterise the materials and construction technologies used in vernacular architecture;
ii. To assess the passive climate-responsiveness of three case studies (located in different areas of Portugal) through *in situ* monitoring of the indoor and outdoor hygrothermal environments;
iii. To develop a calibrated hygrothermal model (and hygrothermal datasets and libraries related to the analysed building elements) to be used by the design teams in the design of renovating operations in vernacular buildings of the analysed zones;
iv. To assess the life cycle environmental performance and embodied energy of vernacular materials, produced in the Portuguese context;
v. To develop and disseminate knowledge about vernacular architecture and construction technologies in order to encourage its preservation and the use of its principles in the design of new constructions.

These objectives aim to overcome the following problems found in the state of the art:

i. Lack of technical information about vernacular building systems, that can enable architects and engineers to prepare more assertively their interventions on these specific buildings;
ii. Absence of data about the environmental performance of Portuguese vernacular materials for assessing the sustainability of buildings that use these types of techniques — in the near future only industrially-produced materials will have this type of data, which would generate a gap of information on vernacular materials again;
iii. Lack of information about the indoor environmental performance of these buildings throughout the different weather seasons, leading to the need to carry out *in situ* hygrothermal parameters monitoring;
iv. Lack of data to use in predictive tools that allow simulating the thermal performance of vernacular buildings with no need for long-term monitoring in all buildings to renovate. These tools can be useful to support design teams both in refurbishment projects of vernacular buildings and in the design of new buildings that use vernacular strategies and building systems.

1.3 STRUCTURE OF THE STUDY

The proposed research subject is presented and organised in 8 chapters, along which the following contents are exposed:

- In Chapter 1 are presented the framework and aim of the research work.

- In Chapter 2, a literature review is done on the relevance of studying vernacular architecture in the scope of sustainable building. In the literature review, two main topics of the research work are emphasised, namely, climate-responsive strategies and local construction materials, and on the importance to quantitatively assess the effectiveness of passive strategies and the environmental performance of vernacular materials in the Portuguese context.
- In Chapter 3, the correlation between Portuguese vernacular architecture and the different climatic and lithological variations of the country are briefly addressed, highlighting the advantages of taking into consideration these strategies in environmentally-responsive building design.
- In Chapter 4, the criteria to select the case study zones are described; the methods used to guide the research work, namely, the monitoring procedures and type of equipment used to evaluate the indoor environment quality (air temperature, relative humidity, thermal comfort, carbon dioxide and radon gas concentrations); the conditions to carry out the energy simulations; and the methods and procedures to assess the life cycle of two earthen materials.
- In Chapter 5, the results of the *in situ* thermal monitoring and evaluation of the indoor comfort of the three case studies are presented. To evaluate thermal comfort conditions the following parameters were measured: air temperature, relative humidity, mean radiant temperature, and air velocity. The methodology also considered occupant's metabolic activity rate and clothing insulation. In this evaluation, surveys on occupants' thermal sensation were also carried out. Regarding the indoor air quality, the carbon dioxide and radon gas concentration were measured.
- In Chapter 6, the results of the energy simulation under dynamic conditions of building models based on the case studies are presented and analysed. In the simulations are compared under the same conditions, the impact of different vernacular and conventional strategies/building solutions on the energy demand for heating/cooling.
- In Chapter 7 the results of the life cycle assessment of two earthen materials manufactured in Portugal are presented, namely, rammed earth and compressed earth blocks (CEB), in compliance with Product Category Rules for Type III environmental product declaration of construction products.
- In Chapter 8 are addressed the main conclusions of the research work, limitations and suggestions for future developments of the work.

The study presented has given rise to six papers already published in international peer-reviewed journals, two book chapters, fourteen papers in conference proceedings and four papers in periodical magazines.

CHAPTER 2

THE IMPORTANCE OF VERNACULAR ARCHITECTURE FOR A SUSTAINABLE BUILDING DESIGN

2. THE IMPORTANCE OF VERNACULAR ARCHITECTURE FOR A SUSTAINABLE BUILDING DESIGN

Since the dawn of humankind, Man has needed to seek refuge for shelter and protection. But it is in the Neolithic period, when Man changes his way of life from nomadic to sedentary, that agriculture is born and that human communities need to settle in places to develop their subsistence activities. It is in this period that the first permanent dwellings appeared and the line of evolution of architecture begins.

In the past, due to the lack of technology to use the various sources of energy available, buildings were constructed using passive, simple and ingenious strategies. These strategies were the result of pertinent concerns arising from geographical characteristics, insolation, solar orientation, geometry, shape, materials, etc. Even without mastering the concept of thermal energy, or knowing the laws of thermodynamics, Man had, through a sensory and empirical approach, the notion of the relationship between climate, shape, construction material and physical well-being. Many generations were necessary for the people of the most diverse cultures to empirically arrive at the creation of forms and processes of construction. These approaches had their styles and characteristics, perfectly related to the various types of climate and the different geographical factors [20, 21].

Due to the complexity of variables that the term "vernacular architecture" covers, it is important to define it before developing the theme. According to the "Encyclopedia of Vernacular Architecture of the World", due to the many dimensions that the term covers — types of buildings, shapes, traditions, contexts, among others — the definition is not easy, so one based on the etymology of words is proposed [22]. Thus, "Architecture" is defined as being the science or the art of building, with roots in the Greek word for "Architect" (*arkhi+tekton*) which means chief-builder; while "Vernacular" derives from the Latin word *vernaculus* and means "native" [22]. So, the definition of "native art of building", or proper for a place [22], seems adequate for this study.

The interest in studying vernacular architecture within the scope of sustainability is increasing since its features and strategies are the basis for what is now defined as sustainable building design [23].

The industrialisation of construction (materials, systems, etc.) led to the standardisation of buildings. All over the world, regardless of climatic context, buildings became more similar, and this trend is still visible (Fig. 2.1). As a consequence, they became more dependent on heating, ventilation, and air conditioning (HVAC) systems to satisfy comfort conditions, which led to the routine installation and operation of these mechanical systems, even if not necessary. This situation led to the disregard for the vernacular knowledge, changing not only the way buildings and indoor spaces were designed (commonly arranged by function and thermal needs) but also the occupants' living habits [24]. These issues have been discussed by several authors [24–27], since it is not possible to standardise humans and environments globally, and local-specific factors that influence comfort, such as climate, cultural and social habits, that must also be taken into account.

However, nowadays, climate-indifferent buildings are still largely built. Therefore, the paradigm must move towards climate and environmentally-responsive building designs [29]. On this subject, vernacular architecture is a particularly interesting research topic, since several building techniques and forms have been developed over time to address specific local conditions better [21, 30]. In recent years, several qualitative and quantitative studies, developed in different regions of the world, have reported similar conclusions, e.g. that it is possible to achieve acceptable comfort conditions in vernacular buildings during most of the year by passive means alone [15, 16, 23, 31–33] and that vernacular strategies are effective and still practicable nowadays. Thus, this empirical knowledge could contribute towards reducing the heating/cooling energy demand of buildings [7, 11, 27, 34].

The relationship between built and natural environments has been embodied in architecture at least since the development of the Roman mythological concept of the *Genius Loci*. The significant differences

FIGURE 2.1. (left) Lake Shore Drive Apartments in Chicago, U.S.A., completed in 1951 (Architect: Mies van der Rohe)[28]; (right) Office building in Oporto, Portugal, completed in 2020 (Architecture: Broadway Malyan).

between the way house-construction developed in northern Africa and northern Europe, for example, demonstrates that this was not a random process; similarly, in Portugal, there are considerable differences between the houses of Trás-os-Montes (in the north) and the houses of Alentejo (in the south).

The importance of such architectonic forms for sustainable architecture is well illustrated in the diagram created by Stefan Behling [35] (Fig. 2.2), in which it is argued that in the future buildings should give primacy to architectonic form and passive systems, to reduce the importance of active systems [35]. It seems pertinent to add a triangle to the diagram, representing the past, which is made up of only two elements: architectonic form and passive systems [36]. This new triangle is highly relevant for future planning because understanding the two systems is the first step towards improving the techniques used in

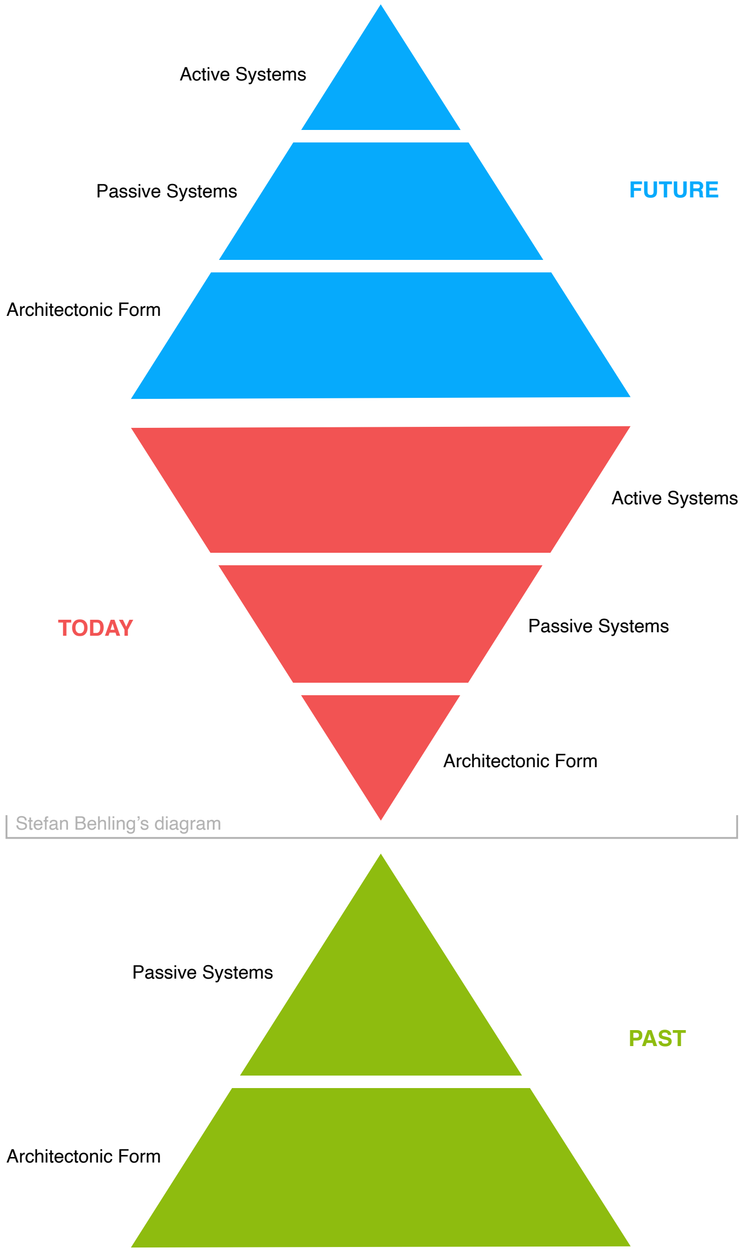


FIGURE 2.2. Stefan Behling's diagram (Today and Future triangles) [35]; Past triangle [36].

specific vernacular construction to adapt them for contemporary construction purposes. The good design of such systems would minimise the need for active systems and consequently reduce energy demand.

In this sense, the definition of the future of architecture and construction should seek a blend of tradition with modernity, thus aiming at a hybrid system that allows the exploration of new aesthetic and functional concepts [12, 35]. To ignore the knowledge and technological potential that exists today would be a mistake when it is aimed at achieving high-performance buildings [37].

2.1 THE CONTRIBUTION OF VERNACULAR PASSIVE STRATEGIES FOR A CLIMATE-RESPONSIVE ARCHITECTURE

In the past, due to the lack of technology for the maximisation of thermal comfort, buildings were built using passive approaches. While simple and smart, these were based only on the available endogenous resources. Vernacular architecture was shaped by multiple constraints – geographical, economic, social, historical and cultural – from sites and from communities that created and inhabited them [10, 38–40]. Nothing was wasted, disregarded or ignored because communities knew from experience that their welfare depended intrinsically on maintaining the harmony with the surrounding environment [9]. For these reasons, the knowledge deriving from this form of architecture should provide the basis for sustainable development [33].

Several studies carried out in different countries are aimed at proving scientifically that the features of vernacular architecture are relevant and feasible today. For example, those of Singh, Mahapatra, and Atreya [11], Singh *et al.* [41], Zhai and Previtali [42], Kimura [12], Engin *et al.* [39], Shanthi Priya *et al.* [32], Esteban Sáiz [10] or Cañas and Martin [43] discuss the advantages and effectiveness of using passive vernacular solar techniques to increase energy efficiency.

From the available literature on the topic of vernacular architecture, and generalising, it can be said that over time it started from a generalist approach, more focused on questions of architectural form and its relationship with the surrounding environment, and came to progressively focus on the areas of bioclimatic, energy efficiency and, more recently, in the broader scope of sustainability. In the last thirty years, at least, there seems to be a consensus among the various authors who have devoted themselves to the subject about the need to find in these constructions of the past the lessons that can support sustainable development.

This trend may have been driven, even if indirectly, by the 1973 energy crisis and the "Limits to Growth" report [44], from which the concept of the ecological building was developed and whose premises (traditional forms of construction, use of natural materials, renewable energy sources, etc. [45]) have affinity with the most valued features of vernacular constructions. Research on energy efficiency has started in this period and, although not long after the discovery of new oil reserves has alleviated the crisis, it has not stopped until today. However, its materialisation in architecture focused primarily on the development of increasingly complex smart and active solutions [35] which led to buildings controlled by this type of technology, losing the relationship with the site and the climate. Fernández-Galiano [46] even considers that this type of active solar architecture, being composed of so many active systems, is a good successor to Le Corbusier's *Un machine d'habiter* (A machine for living).

An illustrative example of the considerations mentioned above is that of Paul Oliver [6], an essential author in the field, who in 1978 published an article on "Why study vernacular architecture?". In this work, the author addresses the importance of studying this type of architecture supporting his ideas through a qualitative analysis of examples of constructions in different points of the world. He highlighted the ecological balance of many of these societies in the relationship between the available resources and their consumption, emphasizing the sophistication and simplicity of vernacular technologies. In this article, he defended the need to conduct more specific field studies and that the architectural principles present in these constructions should be used as teaching methods, particularly for architects. In 2002, after a long list of published works, Oliver [6] focused on the topic of necessity and sustainability, where he disputes that the discussion around sustainability focuses too much on the urban environment at the expense of the rural and that there is no reference to vernacular architecture which is in its nature a sustainable architecture. The author argues that vernacular architecture has proven over time to be the only sustainable solution for housing, being able to solve future problems in this area such as impacts on land use, environment, materials, water and energy use, CO_2 emissions, among others. He also argues that the regeneration of rural areas would allow decentralising economies, benefiting not only these areas but also cities, which would be released from the pressure of this economic centrality [6].

Plemenka Supic [47] shares the same convictions and in an article related the climatology with buildings physics through several examples of vernacular architecture scattered around the world, based on the academic work of its architecture students. The method of analysis was exclusively qualitative and based on culture, nature and materials. From the examples analysed, the author concluded that they were all conceived to respond to climate conditions and that their main virtues were the genuine expression of their content, simplicity and subtle inventions, economy and efficiency of the means available, awareness and respect for people and things.

The research carried out by Kimura [12] goes one step further in the analysis of vernacular architecture, seeking to identify the passive strategies used in Japanese vernacular architecture and to understand how they could be integrated into contemporary architecture to reduce the fossil energy demand. According to Kimura, by listing several examples, the passive strategies in Japanese vernacular architecture can be applied to modern buildings and thus contribute to achieving thermal conditions without using fossil fuels. However, according to the author, the acceptance of this type of strategy presents some obstacles: the first due to the indifference of modern architects regarding energy issues; the second because society is accommodated at its convenience and is not very receptive to living in a traditional type of housing, partly because the perceived standards of comfort are lower than the current requirements. In this sense, the author recognises the need to reconcile current comfort standards with low energy consumption and that it is essential to study the performance of vernacular technologies to find positive ways of introducing them into contemporary architecture. To this end, he conducted several on-site monitoring experiments (temperature, humidity and solar radiation) to understand the influence of different strategies on the interior comfort of various types of housing. In this way, the author established comparisons between vernacular construction systems and current systems, with the first obtaining an advantage over the latter.

A year after the discussion and negotiation of the Kyoto Protocol, the book edited by Gallo *et al.* [48] is focused on the debate about the relationship between architecture, energy and comfort. The aim was to understand how previous generations lived in extreme climates without abundant sources of energy and, however, managed to conceive buildings that provided comfort conditions and were in harmony with the surrounding environment. In their work, the authors show the advantages of natural lighting, ventilation and bioclimatism, with several articles/chapters focusing specifically on vernacular architecture and its relationship with climate and comfort. Coch [38] presents an interesting and comprehensive approach, linking the major types of climate in the world to the corresponding types of vernacular architecture. With several examples for each kind of climate, geographically distant, the author identified the strategies that buildings use in that specific climate and showed that despite the geographical distance, several approaches are similar. Nonetheless, the author also reveals that there are several different strategies and considers the fact an asset in the study, demonstrating that there are a variety of effective solutions to respond to the same type of climate. The author also considers that many strategies of vernacular architecture have the potential for application in contemporary architecture and can contribute positively to reducing the dependence on artificial lighting and air conditioning systems. The author also adds that vernacular architecture should be further studied and that more works should be published for the training of the key players in the construction sector. This will value more this type of architecture in opposition to the “representative architecture” (a type of architecture more concerned in to impress and dominate, which creates more artificial environments than integrations with the natural environment) [38].

In the same publication, Sayigh & Marafia [49] discussed and compared the performance of Qatar’s vernacular and modern buildings qualitatively but based on some quantitative data from other authors. The comparison was made on the comfort and effectiveness of strategies and materials used to respond to the climate. The authors intended to demonstrate that vernacular techniques used in the buildings of Qatar are more appropriate than those used by contemporary buildings to guarantee comfort conditions, especially during periods of heat. For the abandonment of vernacular construction techniques, the authors point out as the primary cause the introduction and dissemination of electric energy in the country, largely subsidised, which allowed modern technologies to be adopted without any study of applicability to climate and culture. In this context, Qatar’s contemporary buildings were built under British and American influence and without any concern for energy consumption in their design. The materials used such as steel, glass and concrete were unsuitable for the region’s climate, and this inability manifested in very high energy use. Given this problem and based on the experimental tests of Hassan Fathy [49], in which the performances of test cells built using traditional and “modern” materials are compared, the authors argue that the contribution of traditional materials to the comfort is high. Finally, the authors demonstrated that vernacular passive cooling strategies are applicable to modern buildings without any aesthetic disadvantage, presenting some successful examples where the Qatar University building stands out by the intelligent integration of vernacular strategies with contemporary aesthetics (Fig. 2.3).

FIGURE 2.3. Wind catchers of the Qatar University building, completed in 1985 (Arch. Kamel El Kafrani). Left [50]; Right [51].

In the last decade, mainly, perhaps influenced by a growing concern and demand for reducing energy use and the environmental impacts in the building sector, the scientific production in the crossing area of vernacular architecture with sustainability has focused not only on qualitative analysis but also increasingly in quantitative analysis of vernacular architecture examples. The new concepts and objectives for high energy-efficient buildings, with less environmental impact, as the nZEB (nearly Zero-Energy Buildings) [52], in which performance is estimated for its entire life cycle (construction, operation and demolition), it is necessary to understand as rigorously as possible in what order of magnitude vernacular constructions were more effective and efficient in guaranteeing comfort conditions without the use of non-renewable energy. But beyond the issues of energy for air conditioning, it is necessary to understand in a more comprehensive way how sustainable these constructions are in the overall use of the available resources (land use, materials, water, etc.).

In the works published, during this period, it is evident that these are from both developed and developing countries, or with emerging economies, which reflects a certain unanimity in the importance and relevance of continuing today to deepen knowledge in the area of vernacular architecture as a sustainability model for the future. With this purpose, Kim [53] compared the techniques used to control the indoor environment of traditional and contemporary Korean buildings. In this study, using a qualitative analysis of several Korean vernacular techniques, the author argues that they can be adapted to new buildings to control indoor environment without mechanical systems, something that contemporary Korean architecture had lost.

With similar objectives but with a more in-depth study, Canãs & Martín [43] tried to determine for the types of Spanish vernacular architecture which strategies are most relevant according to the climate and thus defining the bases of a bioclimatic construction based on traditional construction. Their research work is interesting due to the intersection between the various bioclimatic strategies present in Spanish vernacular architecture and the climates in which they are. The methodology presented by the authors is simple, and based on the following steps: i) to survey the most relevant examples of Spanish popular architecture; ii) to identify the types of climate existing in Spain; iii) to structure the research according to the type of bioclimatic strategies and their respective function; iv) to cross-relate information by mapping the location of strategies on specific cartography regarding the climate effect directly related (e.g. precipitation, radiation, temperature, etc.).

Through an overlay of graphic elements on several maps, the authors confirmed that specific strategies correspond to particular types of climate, thus being able to deduce the correlation between the two. Based on the results, the authors argue that, for new constructions, location is an important condition and that the incorporation of the bioclimatic strategies identified will have advantages in comfort and energy savings, and that vernacular buildings that incorporate these strategies should be preserved as a way of valuing History.

The same group of authors [31] continued the previous work, but this time focusing on the indoor thermal performance of buildings with high thermal inertia located in Navalos, Spain. In this study, the authors chose as their object of study three buildings in the same location, two traditional constructions (adobe and stone) with high thermal inertia and a more recent one in prefabricated timber construction. Through *in situ* monitoring (indoor and outdoor: temperature and relative humidity), the authors collected a set of quantitative data that allowed them to compare the indoor thermal performance of the three buildings during winter and summer conditions. From the analysis of the data, they concluded that traditional buildings with high thermal inertia presented an overall thermal performance higher than the timber building with low thermal inertia. In the summer period, the two traditional buildings maintained the indoor temperature within the comfort parameters, with low fluctuations throughout the day, while in the timber building there were problems of overheating. In the winter period, the three buildings had temperature values below comfort levels, even with two small heaters in the timber house. Due to the high thermal inertia of traditional buildings, which allows stabilising temperature, the installation of a heating system would allow reaching indoor comfort levels during winter, requiring less energy than that used in the timber building.

The growing demand for research on the field of Sustainability has led to the need to complement qualitative studies with validations and quantitative analyses of the performance of vernacular buildings and construction techniques. In addition to understanding the operation of the strategies adopted in the buildings, there is a need to obtain measurable data, mainly on-site monitoring, which allows numerically quantifying their contribution and thus being able to establish comparisons with the performance of current buildings. This is important to demonstrate and validate whether vernacular techniques have a positive contribution to buildings' performance, indeed, thus allowing to remove subjectivity from both the most sceptical and the most believing arguments. Although the work developed by Tzikopoulos *et al*. [54] does not focus specifically the performance of architectural vernacular, the results seem to illustrate well the mentioned problem. Their study on modelling energy efficiency in bioclimatic buildings had the objective of establishing a correlation between the several essential factors for a bioclimatic building design (solar orientation, climate, natural lighting, wind protection, etc.) and quantifying their contribution to energy efficiency. Even though the work was based on other studies that reported significant contributions from passive solar strategies on the energy efficiency of buildings, the authors concluded from their model that the passive strategies found in the buildings studied (77 buildings in 11 European countries) do not significantly influence energy efficiency, with some cases showing a reduction. The results of the study surprised the authors, who state that it is necessary to verify these results with further studies using a broader set of data. Probably one of the problems with this study was that it intended to generalize the topic to a too extensive set of countries. But the result of this study is significant from the point of view that the contribution of bioclimatic strategies may not always have the performance attributed to them. In this sense, and establishing the bridge to vernacular buildings, after a qualitative analysis of the strategies, the study should be complemented with quantitative data.

In this context, there is a set of authors that disclosed a consistent and sequential methodology of the research work carried out in this area, such as Singh *et al*. [11, 21, 33, 41]. In the first publication referring to this research [21], the authors set out to find relationships between bioclimatism, socio-economic and cultural status and their influence on the vernacular architecture of the different bioclimatic zones of north-eastern India. The methodology adopted consisted of: i) to study a group of vernacular buildings over 70 years old in representative locations of each climatic zone (14 buildings in each climatic zone in a total of 42 buildings analysed); ii) dimensional surveys of buildings (dimensions of doors and windows, floor areas, ceiling height, wall thickness, etc.) and photographic survey of the various passive solar strategies found; iii) characterisation and correlation of the materials used and passive solar strategies for each climate zone. The authors concluded that the solutions found seemed to have a good match with climate constraints, that most passive solar strategies helped to reduce energy needs and that the use of local materials reduced processing and transportation costs. Thus, this type of architecture was less energy intensive and presented a better environmental performance. However, the authors assumed that the study had some limitations because most of the aspects studied were only analysed from a qualitative point of view and that quantitative studies should be developed to generate more scientific information on the topic.

In the works published later, Singh *et al*. [33, 41] already present quantitative studies on the topic of research. In the first one, Singh *et al*. [33] aimed to experiment, validate and quantitatively analyse the thermal performance of vernacular buildings in north-eastern India, but also to determine the degree of comfort of the inhabitants and the range of comfort temperatures throughout the year. The study is quite complete because the authors also sought to explore the extent to which occupant behaviour can influence indoor comfort conditions. The study consisted of the analysis of 150 buildings and the thermal sensation vote of 300 occupants, according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal sensation scale, and the monitoring of three representative buildings (one for each climate zone). The authors indicated that *in situ* measurements are the most reliable for determining the comfort temperature in naturally ventilated buildings. However, as the range of comfort temperatures is difficult to define, because it involves various environmental parameters, human adaptability, perception and expectations, the study was based on both objective and subjective measurements. *In situ* monitoring, outdoor and indoor measurements of temperature, relative humidity and luminance were included. These measurements were carried out for a period of 25-day periods for each season. With this study, the authors were able to conclude that the monitored dwellings had temperatures within the comfort limits throughout the year, except for one case, in the winter period, when the temperature was slightly below the comfort limits.

In a later publication, Singh *et al*. [41] continued the previous work based on the carried quantitative studies. They tried to understand the dynamic behaviour of the vernacular buildings monitored and adapted the predictive comfort equations to the contexts under investigation. By using this approach, it would be possible to estimate the indoor temperature of buildings where measurements are not possible. The authors managed to make the adapted predictive models to be reliable and with a reduced and stable margin of error for the various periods of the year. However, they presented a limitation since the models can only be applied to buildings with the same characteristics as those analysed, and the equations cannot be generalised. The lessons drawn from this work are the peculiarity of each location, and each type of building requires an in-depth study and that the path to sustainability must be based more on variety than on generalisation.

Based on the field study carried out, Singh *et al*. [11] systematised the passive solar strategies found in vernacular buildings (150 case studies) and presented the advantages of their integration in contemporary architecture. The following identified strategies were considered the most relevant: the solar orientation, the shape of the building, the envelope, shading, use of natural ventilation, arrangement of indoor spaces and activities of its inhabitants. The study explanation by climatic region emphasises the importance of this factor in the determination of strategies. Moreover, it also facilitates the comprehension of all the factors that led to the development of these strategies in response to a specific climate. From the authors' conclusions, in addition to the importance of passive strategies for energy efficiency, other issues related to sustainability are highlighted in the vernacular architectures, namely the use of local materials. They stated that the use of local materials offers advantages because the material comes from the same climatic conditions, resulting in higher adaptability, higher durability and higher savings than other materials. From an environmental point of view, the advantages are: a) low environmental impact on production, renewability and low end-of-life impact; b) a significant reduction in the embodied energy (related to processing and transportation).

The research methods presented by the previous group of authors stand out for having a good structure, sample size, rigour and comprehensiveness of the study within the scope of sustainability. It also presents a clear definition of the phased path that must be developed to study and validate the sustainability potential present in vernacular strategies. The same methods, although without so much detail, were also applied in the same scope and with the same objectives for other regions of India in the research work of Dili *et al*. [55] and Shanthi Priya *et al*. [32]. Despite the regional difference, the conclusions presented by the authors were similar: the passive strategies identified have the potential to be applied to new buildings, increasing their sustainability, namely through higher energy efficiency and the maximisation of human comfort.

The study by Cardinale *et al*. [23] starts from a different basis and introduces a new variable in the investigation of vernacular architecture, i.e. the ability to simulate dynamically the behaviour of these buildings using computer programs. The study aimed to validate, through *in situ* monitoring, the numerical code previously provided by the dynamic simulation in computer programs (DesignBuilder/EnergyPlus) of two types of vernacular houses in southern Italy - the Sassi district of Matera and the Trulli district of Alberobello - well known for their good comfort conditions. Thus, through experimental measurements of the thermal properties, energy performance and indoor hygrothermal comfort of the two types of houses, it was intended to compare the data collected *in situ* with the simulated data and to check if there was an agreement. The main problem identified by the authors in evaluating the performance of existing buildings by simulation was the lack of some evaluation parameters related to the material properties of the buildings' envelope. To fill this gap, the methodology adopted for the study consisted of three phases of analysis: i) indoor and outdoor monitoring of environmental parameters; ii) *in situ* and laboratory measurements of material properties; iii) dynamic simulation using the DesignBuilder and EnergyPlus software. To validate the computer program, they compared the data measured *in situ* with the simulated data, concluding that the results obtained by dynamic simulation can be reliable. However, the authors emphasised that *in situ* measurements and laboratory measurements were essential to making the simulation reliable. As a result of the study, it is also important to note that the two buildings had comfort conditions difficult to attain in contemporary buildings despite not respecting the thermal transmittance limits of current regulations. Added to this is the fact that the measured values have shown that these vernacular buildings were able to have almost constant indoor temperature values throughout the year without using air conditioning systems. During winter, a simple heating system such as, for example, a fireplace, is sufficient to ensure comfort levels. This study demonstrates that simulation is a reliable tool to understand and accurately assess the thermal behaviour of traditional buildings in a given region, as long as the model is properly calibrated with data from measurements performed *in situ*.

In short, the strategies present in the various manifestations of vernacular architecture have the potential to contribute to improving the energy efficiency of buildings, where the specificities of each location must assume particular relevance.

From the studies mentioned, it is possible to verify that several authors in different parts of the world aim to prove scientifically that vernacular strategies are relevant and feasible today. Despite the diversity of studies in the scope of vernacular architecture, i.e. from the most holistic studies in the area of sustainability to the more specific studies in the field of materials/construction systems, there is a focus on discussing the advantages and the effectiveness of using vernacular solar passive strategies on the thermal performance of buildings, such as the works developed by Kimura [12], Cañas & Martín [43], Martín *et al*. [31], Engin *et al*. [39], Singh *et al*. [11, 21, 33, 41], Zhai & Previtali [42], Dili *et al*. [55], Shanthi Priya *et al*. [32] or Cardinale *et al*. [23].

From the analysis of these studies, it is possible to conclude that the most recent investigations developed in this area of knowledge have adopted similar methodologies to achieve the objective mentioned above, also reporting similar limitations and conclusions. In general terms, the research methodology used by these works, to study and validate the sustainability potential of vernacular strategies, is structured as follows:

- Qualitative analysis of the strategies used in vernacular buildings and their relationship with the specific local conditions (the collection of qualitative data usually focuses on characteristics such as the shape of the building, solar orientation, envelope, shading devices, fenestrations, use of natural ventilation, internal organisation of spaces, thermal inertia, materials, etc.);
- Quantitative analyses, which complement the results of the previous step, through *in situ* monitoring (indoor and outdoor) of the environmental parameters that influence thermal comfort (temperature, relative humidity, airspeed, etc.) and the characterisation of the building systems;
- Finally, the impossibility of monitoring all buildings creates the need to develop tools for predicting thermal behaviour. In this area, computer tools of parametric analysis under dynamic conditions, due to the set of variables they manage to simulate and the ability to model buildings in a virtual environment, are the most advanced and the most useful for designers [23].

2.2 THE POTENTIAL OF VERNACULAR MATERIALS FOR A SUSTAINABLE BUILDING DESIGN

The building industry is one of the largest consumers of natural resources [1, 56]. The majority of the industrialised building materials used today have significant environmental impacts in their Product Stage [34, 57, 58].

The global environmental awareness and the rising demand for environmentally friendly materials are pushing the sector to shift to the "sustainability" paradigm. Thus, the sector is slowly starting to adopt materials with lower embodied energy and other environmental impacts, and those that are more compatible, for instance, with the local climate context [59].

Materials are essential for construction and have significant environmental impacts, especially most of the materials with industrial processing [56, 58, 60]. Life cycle assessment (LCA) of materials are highly complex, making it difficult to describe all the embodied impacts from the extraction of raw materials to the deposition in landfill at the end of life ("cradle to grave") [57, 61]. Furthermore, the results of these life cycle assessments cannot always be extrapolated directly to local contexts [57]. According to Sassi [61], the use of materials with origin in very remote places makes it more difficult to perceive the cause and effect of this use (ex: the use in Europe of wood panels from the tropical forest and the deforestation of the Amazon and the displacement of communities and the consequent extinction of species) than a closer situation, such as the intensive use of the car and the increase in pollution.

In life cycle assessments of buildings, the environmental impacts associated with all stages of a product's life are estimated [61]. One of the most relevant components in these assessments is the global warming potential, related to the emission of greenhouse gases (GHG). In turn, GHG emissions, in particular, carbon dioxide, are closely related to energy use or embodied energy [57]. In this topic, LCA analyses of buildings include the operating energy (energy required for the operation of the building, i.e. air conditioning, lighting, etc.) and the embodied energy (energy used to produce and maintain the materials during the various stages of the building life cycle) [57]. With the increasing energy efficiency of buildings, the embodied energy of materials gained more relevance. For example, Thormark [62] estimated for one of the most energy-efficient buildings in Sweden that the embodied energy represented about 40% of the total energy needed for the building operation over a 50-year life cycle. In the Portuguese context, Mateus *et al*. [63] estimated for a conventional building (with a life cycle of 50 years) that the embodied energy in the construction materials represented between 10-15% of the total energy used during the operation stage. Pacheco-Torgal *et al*. [64] consider that with the decrease of the operating energy, due to the implementation of the EPBD directive, embodied energy will represent about 400% of the operating energy [64].

Following the exposed facts, reducing the embodied energy of materials is a premise to reduce environmental impacts and achieve more sustainable buildings [65]. In addition, reducing the embodied energy will also decrease the cost of materials in particular and of buildings as a whole [65]. One way to reduce the embodied energy of materials is to reduce their transportation. For example, Harris [66] estimated for the United Kingdom that, through the use of local wood, the embodied energy could be reduced by about 70 times when compared to imported tropical wood. Another way to reduce the embodied energy is through the use of materials and techniques that require low processing. In this sense, it is pertinent to emphasise the use of local materials and techniques as a principle of sustainability.

From the available literature on the topic of vernacular architecture, references to the use of local materials as a way to improve the sustainability of the built environment are frequent. However, many of these references are based only on qualitative analyses. More recently, investigations on the theme have increasingly focused on quantifying the contribution of vernacular techniques and materials from a sustainability point of view. In the following sections, a set of studies on the topic and their results will be discussed.

2.2.1 VERNACULAR MATERIALS VERSUS CONVENTIONAL MATERIALS

The majority of conventional building systems rely on industrially-based materials with high embodied energy and other potential environmental impacts (e.g. concrete, aluminium, steel, glass, etc.) [67, 68]. There is the need to change the methods and production chains to follow a path towards environmental protection and sustainable management of resources, e.g. by closing the cycles of the products [56], [65, 67]. To achieve this goal is necessary to move from a linear to a circular production model, which is characterised by a continuous cycle of recycling> production> use> recycling, thus preventing the production of waste [58]. The actual linear production model dates back to the Industrial Revolution (about 250 years ago). Nevertheless, all technological developments remain virtually unchanged [58]. Therefore, according to Wadel *et al.* [58], the architecture, engineering and construction (AEC) industry should adopt a pre-industrial model in which the cycle of materials was closed and the waste reduced, i.e. a model of a society fundamentally organic, using biosphere resources according to the natural ability to produce them and assimilate the waste generated. According to the authors, the simulation and sustainability assessment tools are useful to help to reduce environmental impacts. Still, without changing the paradigm of the linear production system, it is difficult to achieve "sustainability". The construction sector's slowness in adapting to new developments, but also the complex network of actors and construction materials makes it challenging to implement actions that allow closing the cycle of materials, most of which are converted into waste at the end of their lifetime [58]. In this sense, the authors refer that the sector must rethink its methods, by using materials with low environmental impact, renewable and recyclable, giving priority to local raw materials and producers and that traditional techniques deserve to be reviewed under the scope of sustainability. Therefore, a possibility in the path to achieving a circular model is to revisit old habits and building techniques and to use the best current technical and scientific knowledge to improve them. Nevertheless, in the contemporary society and ways of living, this idea seems a utopic vision.

To change this reality, several authors [56, 57, 60, 65, 69–71] have focused their attention on researching alternatives to current building technologies. Some of these "alternatives" are traditional or vernacular construction technologies used by communities for centuries.

The rising interest in vernacular materials and techniques on the scope of sustainable buildings comes from the following properties (i) close relation with local conditions, i.e. the materials are locally sourced; (ii) the techniques were developed in accordance to a specific climate; (iii) low requirements for transportation from the extraction of the raw materials to the manufacturing site; (iv) low embodied energy, due to the simpler manufacturing processes, and consequently reduced potential environmental impacts; (v) some materials are organic, biodegradable, renewable and can be framed into a "cradle-to-cradle" life-cycle approach (e.g. straw and reeds); and (vi) local workforce is used to produce them [34]. For example, the studies carried out by Fernandes *et al.* [34], Zabalza Bribián *et al.* [67] and Melià *et al.* [72] have quantitatively compared several materials and concluded that vernacular materials have considerable lower embodied energy and carbon dioxide emissions than conventional materials. These studies also highlighted the importance of promoting the use of low-processed and locally sourced materials to reduce the embodied environmental impacts. The use of alternative building materials and techniques such as the vernacular ones (rammed earth, adobe, traditional vaults, etc.) can reduce environmental impacts, as shown by several studies [60, 69, 71–75].

In the case of Morel *et al.* [56], the study based on practical examples of a building construction tried to demonstrate that the use of local materials can contribute to reducing the embodied energy and environmental impacts. The method adopted by the authors for the construction of a house in France using local materials was as follows: i) inventory of materials available on the site; ii) selection of materials; iii) building shape definition. The local materials selected for the construction were: earth, for mortar; stone, for masonry; and wood, for the structure of the floors and roof. To determine the environmental benefits of using these materials compared to a similar building with conventional construction and a reinforced concrete structure, the authors used bibliographic sources, namely from the United Kingdom, considering that it was a country with a level of development similar to that of France. The authors concluded that the use of local materials would reduce the embodied energy by approximately 215%, and the impact of transportation by 453%. Despite the advantages, the authors reported licensing difficulties by the French authorities. The materials used do not follow the conventional construction standards, and are also not completely traditional, having been necessary to obtain a special agreement based on scientific justifications on the performance of these materials. In summary, the authors of this study emphasised the possibility of reducing embodied energy in buildings through the use of local materials; that each project must take into account specific local materials and that construction professionals need to be informed, encouraged and trained to use local materials wherever possible.

Ramesh [64] focused only on the issues of reducing the embodied energy of roofing solutions (horizontal and pitched) but reported interesting results. The embodied energy in different alternative solutions was compared with that of conventional solutions, but only at the level of the energy used in the material processing stage. For horizontal roofs, results showed that the most efficient building solution was the slab of one-way prestressed concrete joists with infill blocks. The alternative vernacular solution, based on traditional timber structure roof covered with brick and lime, despite being one with the best results, revealed an embodied energy 55% higher than the previously mentioned solution. For pitched roofs, traditional timber structure systems proved to be more economical (for around 40%) and less energy-intensive (70-80% less energy) than reinforced concrete slabs. The results of this study are interesting because they demonstrate that traditional solutions are not always the most eco-efficient. However, in most solutions, the use of vernacular materials allowed reducing the embodied energy considerably [64]. The author also stated that the building cost is directly related to the amount of embodied energy in it. In this sense, the author considered that energy efficiency and vernacular materials are concepts that must be contemplated to reduce the cost of construction, without however neglecting the best available technologies.

Beyond the environmental advantages, Morel *et al*. [56] and Ramesh [65] also concluded that using local materials has socioeconomic benefits, such as to reduce the cost of construction and to foster local economies by paying the value of materials and labour locally.

The social and economic dimensions have to be taken into account to achieve a truly sustainable development. In the construction sector, it is critical to have the ability to understand these dimensions.

Edum-Fotwe & Price (2009) divided the process of building in three levels — urban, buildings and materials — and for the latter defined a set of social parameters to be considered for improving the sustainability of the built environment, such as: employment, health, safety, wellbeing, education and training skills, and culture/heritage. Analysing the potential benefits of using vernacular materials, we can conclude that they fit in all the social parameters defined in the abovementioned study. Regarding employment, several studies report the need for more and more skilled workforce as a disadvantage of traditional construction techniques. But taking into account that the direct cost of these materials and structures is often inferior to that of conventional building systems, the allocation of the structure cost to workforce seems to be an advantage. The distribution of the income among more stakeholders is socially fairer than just allocating it to the price of a material. The local production of materials is not only economically cheaper, as it also enables creating jobs for unemployed people [77]. Additionally, the need for skilled workforce leads to education and training on these vernacular building systems, contributing not only to improve the qualifications of the several construction stakeholders but also to preserve and continue a local heritage and cultural legacy. The education in vernacular building systems is also crucial for politicians, sociologists and economists who make decisions about the built environment [6].

The fact that these materials came from the same local climatic conditions, where they were applied, has the following advantages: greater adaptability, economy and increased durability [11].

In matters of health, advantages are mainly related to the fact that these materials are of natural origin, with low toxicity, no volatile organic compounds, some of them with properties capable of regulating the temperature and indoor air quality [1], as the example of earthen architecture.

In terms of economy, Goodman [78] argued that an industry of ecological construction must have their production units near the place of consumption, using local renewable resources, focusing on processes that require little energy and produce reduced pollution. Furthermore, he argued that decentralisation could increase corporate decision-making centres and have a clearer idea of the context in which they labour, especially relationships between decision-makers and local resources. In this sense, Oliver [6] also argued that the discourse on sustainability is too oriented to the cities scale, requiring the implementation of decentralisation policies in economies that contribute to the regeneration of rural areas. The redevelopment of these areas could be a way to stop the expansion of cities.

In order to promote and implement this kind of intent, it is necessary to involve the local authorities. Each site has its own peculiarities that must be taken into consideration in the definition of specific policies adapted to its context [79]. Supporting sustainable local development means also preserving the cultural heritage of construction knowledge inherent to regions.

However, despite the advantages of these materials, the knowledge and potential that exists today cannot be ignored, since it would be a mistake when aiming to achieve high-performance buildings [36] in all sustainability indicators. In conclusion, the concerns of site integration and the fusion of traditional and contemporary knowledge, are synthesised by Leatherbarrow & Wesley [37] in what they defined as the three essential points to guide architectural practice in the future:

1. Each work of architecture (urban or rural, or between the two) must be designed with ecological culture, in which cultural issues are inseparable from environmental concerns;
2. The essential task of architecture within a cultural ecology is to provide a framework for visualising and knowing the place, practices and objects of that culture;
3. Despite the attraction of vernacular architecture, current design and construction must use the best of tradition and contemporaneity in technologies and materials.

For the reasons mentioned above, vernacular materials are relevant research subjects on the scope of the sustainability of the built environment and therefore it is necessary to develop detailed LCA studies to allow the comparison with conventional materials

2.2.2 EARTH AND TIMBER AS ECOLOGICAL BUILDING MATERIALS

The use of earth and timber as building materials has a long tradition in architecture from all around the world, including Portugal. These two materials are frequently acknowledged as ecological and some studies have shown that they have the best environmental performance [57], thus deserving a specific section in the literature review.

2.2.2.1 EARTH

From all vernacular materials, earth is probably one of those that has more supporters nowadays. The case of vernacular earthen architecture is a relevant research topic since earth is used as a building material/technique for over 9000 years, and a third of world's population is still living in earthen buildings [80]. Earthen techniques are generally connoted with poverty and underdevelopment and thus have being abandoned in favour of other materials which allow a faster building process, such as concrete. However, in the last decades, the interest for these techniques has increased due to the raising awareness on environmental issues [81, 82]. Some studies have shown that the use of earthen materials can significantly reduce the potential environmental impacts of buildings [34, 60, 69, 72, 74, 83–85]. Therefore, environmental issues can be the turning point in favour of earthen materials. Moreover, beyond these advantages, there are also health and socioeconomic benefits [1, 15, 34, 80, 86], since, among others, these materials have low toxicity and high capacity to regulate indoor relative humidity; the valorisation and use of vernacular earthen techniques lead to the need to educate and train skilled construction workers, contributing to preserve local heritage and maintain a cultural legacy; and the local production of materials is economically cheaper, creates jobs and fosters local economies.

From the review paper by Cabeza *et al*. [57], it can be highlighted that the materials with the best performance, at the level of embodied energy and CO_2 emissions, are timber and earthen materials. Rammed earth is one of the most common earth building techniques, and it is divided usually into two types: stabilised and non-stabilised rammed earth. The difference between the two is that stabilised rammed earth contains additives (cement or lime) to overcome some weaknesses of the soil used. For non-stabilised rammed earth walls, and depending on the production process, it can be stated that it is a more environmentally-friendly solution [57, 71].

Regarding cement stabilised rammed earth walls, Venkatarama Reddy & Prasanna Kumar [84] quantified the total embodied energy of this solution and concluded that it increased linearly with the increase in cement content (400–500 MJ/m^3 for a cement content in the range of 6–8%). Arrigoni *et al*. [71] have also focused on analysing the environmental impacts of several stabilised rammed earth solutions and concluded that it is possible to have durable stabilised rammed earth mixes without using stabilisers with high potential environmental impact. Moreover, they stated that the environmental performance of the mixes was heavily influenced by cement manufacture and transportation [71].

In what concerns earthen blocks, Shukla *et al*. [60] used the LCA method to analyse the embodied energy of an adobe house and concluded that it had a lower life cycle environmental impact than conventional buildings. By using low energy-intensive materials, the reduction of CO_2 emissions was about 101 tons/year. Chel & Tiwari [70] have also studied the embodied energy of adobe buildings, but with vaulted roofs. According to this study, the embodied energy of a conventional housing with a reinforced concrete structure and about 95 m^2 of floor area is of 3702.3 MJ/m^2; while for the adobe building, the value is of 2298.8 MJ/m^2. In the specific context of India, the authors concluded that adobe buildings are more eco-efficient than those built with conventional building materials.

In the case of vaulted roofs/ceilings, Sanz-Calcedo *et al*. [74] evaluated the efficiency of using this technique in nowadays construction. To demonstrate the possibility of integrating traditional techniques with current construction techniques, they applied the following method: i) they tested various dimensions of real structures (one vaulted and the other in reinforced concrete) designed to meet the same functional requirements; ii) they performed a life cycle assessment covering the different building solutions based on the parameters of the embodied energy, CO_2 emissions in the construction process, quantity and quality of labour, waste production during construction and construction cost. From the results of the study, it was concluded that, globally, vaulted structures had a more "sustainable" performance than the concrete structures because they use 75% less energy; produce 69% less carbon dioxide emissions; they have an equivalent cost to that of concrete slabs. Nevertheless, they require a larger quantity of labour and more qualified. The need for more, and more specialised, labour is stated by the authors as a disadvantage but, considering that the cost of these structures is not higher than that of conventional slabs, the allocation of the cost of structure to labour seems to be an advantage. The distribution of wealth to more actors is socially fairer than just allocating it to the cost of a material [36]. Moreover, the local production of materials, in addition to being economically cheaper, allows employing unemployed labour [87].

Although these studies are relevant to understand the impact of choosing conventional or alternative building solutions, they are not based on a standardised LCA method, or they use generic life-cycle inventory data, i.e. data that do not consider the real manufacturing contexts of the materials used. The LCA studies carried out by Maza [88], and Aillapán [89] follow the methodology defined in standards ISO14040 and 14044 and are on CEBs manufactured in the specific context of two South American countries. The first study analysed five types of walls, in a cradle to gate perspective, to compare the environmental performance. The study considered the following materials for the walls: hollow concrete blocks; fired clay brick; and CEBs with different stabilisers (cement-lime, lime and gypsum). The author used the Eco-indicator 99 life cycle impact assessment method to estimate the potential environmental impacts. The results showed that, for 1 m^2 of a wall, the clay brick wall has four times more impact than concrete blocks, five times more than CEB (cement-lime) and eight and thirteen times more than CEB (lime) and CEB (gypsum), respectively [88]. These results also showed that a reduction in the cement content results in a decrease in environmental impacts. Additionally, the study also showed that the industrialisation of the manufacturing and construction processes increased the embodied environmental impacts. However, this study does not consider the energy used by the equipment during the manufacturing process, and the data for several processes are based on scenarios and literature.

The study conducted by Aillapán [89] used the Cumulative Energy Demand and IPCC2007 methods. The results showed that the embodied energy of 1 m^2 wall of CEB (including mortar) was 104 MJ and the GWP 13.4 kg CO_2 eq. For one block, the total embodied energy was 1.03 MJ and the GWP 0.0494 kg CO_2 eq. Although it follows the procedures of the standards, several processes were not considered (e.g. transportation of ancillary materials, soil preparation and mixing equipment) and some processes are based on the use of generic data. These two studies showed the potential of these materials for sustainable building. Nevertheless, the fact that these two studies used different methods to assess the environmental impacts and embodied energy makes it difficult to compare the results.

In the Portuguese context, Pereira [90] assessed the life cycle environmental impacts for a specific Compressed Earth Block (CEB) developed in the scope of a research project. The author concluded that the CEB wall had lower environmental impacts and embodied energy than a conventional hollow brick wall. Analysing the Global Warming Potential (GWP) category, the CEB had 27% less impact than the conventional wall, 19.8 kg CO_2 eq. and 25.2 kg CO_2 eq., respectively. It has to be highlighted that, although the CEB wall was three times heavier than the conventional wall, it stills had almost 30% less impact. Although this kind of studies is useful to understand and compare the environmental impacts of materials, it used generic data from databases. The fact that the study does not use real data from a producer in a specific context may reduce the accuracy of the results and the analysis. This type of issue was also mentioned by Arrigoni *et al*. [71] in their study. The use of different type of data is relevant because it is frequently difficult to compare the results of various studies for the same kind of material – because they have different sources of data, assessment methods, system boundaries, cut-off criteria, etc. – as stated by Almeida *et al*. [91], particularly for non-conventional materials as the earthen ones. For the specific case of rammed earth, it was not found any study that follows the steps to develop an Environmental Product Declaration (EPD). Therefore, studies for specific regional contexts are needed so that the accuracy of the results allows a transparent comparison between materials within that context.

2.2.2.2 TIMBER

Timber is a ubiquitous building material in Portuguese vernacular architecture. Depending on the local availability of this resource, its use in construction goes from the occasional use as a structural element (e.g. roof) to the entire dwelling. Regarding the latter, the examples of the *palheiros* built in the coast of mainland Portugal, the *Avieiros* in the banks of Tagus River and the houses of Santana in Madeira Island stand out. The abundant forest in these places and, at the same time, the lack of other materials promoted the use of timber as a building material. In addition, the use of timber in these places was consistent with the climatic conditions, since it shows good behaviour against the humidity of the sea or river basins [92].

Nowadays, the advantages of timber construction in the framework of sustainable construction lie in the fact that it is a renewable, reusable, recyclable and biodegradable resource and, as such, it fits into a cradle-to-cradle life cycle. Furthermore, its feature of being a sequestering carbon material is also highlighted, since during the lifetime of the timber products the biogenic carbon stays out of the atmosphere [1, 93]. If used in its natural form, i.e., without artificial treatments that improve its properties (e.g. glued laminates), timber is a material that needs low processing to be used in construction and allows prefabrication — which contributes to reducing the construction waste. Even the waste, if of pure wood, can be crushed and recycled as raw material for other building products, such as particleboards and oriented strand boards, or just used as an energy source (biomass) [1]. However, when chemical glues, surface treatments and impregnating agents are used, the waste of timber products can be hazardous [1]. As timber requires low processing to be applied in construction, timber buildings have a relatively low embodied energy that, in some cases, could be reduced even more if sawmill systems such as those used on Madeira Island continued to be used, taking advantage of the energy from water streams [36]. In the topic of reuse of timber, this technique has a long tradition in Scandinavian countries, where the components can be easily dismantled and reassembled without producing any waste [1]. The sequential exploitation of a resource during its use, by reuse and recycling, improves the efficiency of the raw material use, and in the case of pine, its service life could be extended from about 75 to more than 350 years [93]. Moreover, from an economic point of view, old timber market price is higher than new timber since it has the advantage that, since it is “dead”, it does not twist, and thus has more quality for some applications [1].

Depending on the construction method, it can be considered that timber buildings also allow for an economical and more efficient maintenance with the possibility of replacing component-by-component, as was the case of the *palheiros* of the Portuguese coast, without jeopardizing the construction structure [36].

The use of construction materials from local sources, or with low transportation demand, is essential in the scope of sustainable buildings and timber is no exception. The study by Coelho *et al.* [94] on the life cycle assessment of a timber dwelling reveals the importance of using local resources of raw material and production to reduce the transport needs that affect the environmental performance of this type of construction.

Taking into consideration the environmental advantages of timber construction, its use should be promoted wherever it is suitable. The incentive may include the attribution of tax benefits to those who choose to build in wood and which can simultaneously promote local/national trade in the production and transformation of wood for construction, consequently promoting the forestation cycles necessary for the sustainability of the industry [36]. Planned reforestation/afforestation also has several environmental advantages, including increasing the capacity for capturing carbon dioxide, helping regulate the climate, containing soil erosion, retaining water in the soil and creating the conditions for the development of biodiversity (fauna and flora) [95].

The incentive to timber construction can also be an incentive to the sustainable management of the Portuguese forest, necessary in the face of climate changes that pose new challenges to the preservation of the forest [96]. According to Silva [96], silviculture must reflect the need to manage water resources, and the choice of species for afforestation must take into account the productive potential in future climate scenarios, taking planning to the field of management of viable ecosystems that ensure productivity and the permanence of the forest environmental services. The measures to promote timber construction, and consequently a sustainable management of the Portuguese forest, in addition to the environmental benefits, can contribute to the decentralization of economies and the redistribution of wealth, namely by creating jobs in the various areas related to these.

2.2.3 THE RELEVANCE OF ASSESSING THE LIFE CYCLE OF VERNACULAR MATERIALS IN THE CURRENT BUILDING CONTEXT

In order to promote the use of environmentally friendly materials, there is a need to ensure an equative and quantitative comparison between building materials. Thus, the assessment of the environmental impacts of materials is essential to obtain comprehensive and more precise data, on all the stages of the life cycle of the building materials (extraction, processing, use, transportation and end-of-life scenarios). This assessment is complex, making it difficult to describe all the impacts that result from all the life cycle stages [57, 61] and results cannot be directly extrapolated for specific local contexts [58], mainly when products come from a remote source. Nevertheless, this information is essential to tell the materials that really have low embodied environmental impacts from those that only claim to be "green" and "eco" [1].

A way to communicate this information to the market is through the Environmental Product Declarations (EPDs). According to ISO 14025 [97], EPDs are a type III environmental label that allows communicating (business-to-business) quantified information on the environmental performance of products and services, based on the list of environmental life cycle assessment (LCA) parameters defined by the ISO 14040 group of standards [98, 99]. Since it allows comparing different products that meet the same functional requirement, it also fosters the competitiveness between manufacturers to improve the environmental performance of their products [91, 100]. According to Ibáñez-Forés *et al*. [101], from the point of view of the companies, the main factors for adopting EPDs as an environmental communication tool are the communication of objective information and the improvement of their corporate identity. Nevertheless, there is still a work to be done by consumers regarding the interpretation of this information, since less than 40% consider that ecolabels provide clear and easy to understand information about the environmental impact of products [101]. Many companies find this latter aspect as the main issue hampering the application of EPDs [101].

Notwithstanding the abovementioned advantages, it is difficult to compare products since the number of EPDs available is still scarce [102]. The fact that it is a voluntary declaration, involving a complex work and skilled professionals, is one of the barriers that explain the lack of EPDs, particularly for the products of small and medium-sized enterprises [102]. In the case of Portugal, the development of such information is still in its infancy – only thirteen EPDs were available in June 2020 [103] – covering only industrially-based building products.

Probably due to market communication strategies, the scale of production and the companies dimension, the EPDs available worldwide until now for construction products are only for industrially-based products [104, 105].

In the case of vernacular materials (i.e. materials that are sourced, produced and applied locally), these are frequently acknowledged as ecological due to the perceived lower embodied environmental impact, since most of these materials have low-tech processing and are low energy-intensive. Although designers recognise this advantage in comparison with conventional materials, currently, there is no quantitative data about the environmental performance of these materials, and no EPDs are available worldwide [104, 105]. The probable reasons to explain this are the local character of these materials, the heterogenic properties from site to site and consequently the difficulty to standardise, and the small production scale. This situation is hindering the use of these materials since LCA, or Building Sustainability Assessment (BSA) practitioners do not have the necessary quantitative data to show the environmental benefits of such materials compared to the conventional practice.

There are many different vernacular building materials in Portugal. Still, in this study, the focus is in the development of the LCA of two of the most used materials, which have still potential to grow in the future, namely rammed earth and compressed earth blocks. In this context, this research work aims to contribute to this field by assessing the life cycle performance of two earthen materials in compliance with standard EN15804, i.e., with Product Category Rules for Type III environmental product declaration of construction products [106], based on data collected from a manufacturer of such materials, located in Portugal. Thus, the results of the assessment can be compared with other EPDs for construction materials or other materials assessed according to the same standard. The results of the study can be useful to promote the environmental advantages of this type of vernacular materials and to support designers' decision-making on choosing low environmental impact materials.

2.3 THE CASE OF PORTUGUESE VERNACULAR ARCHITECTURE

Vernacular architecture, as mentioned above, can have a contribution in responding to sustainability challenges of today's society, since it is a pragmatic type of construction, being the paradigm of the close relationship with local conditions. Portugal is no exception, since the plurality of the continental and insular territory, with many geographical and climatic differences, originated a profuse variety of manifestations of vernacular architecture. Its regional differentiation is expressed in the use of local materials and techniques, in the adaptation to the surrounding climate and the economic activity of families [39]. It was not random how the differences were coined, for example, between the house of Trás-os-Montes and the house of Alentejo, or even between houses in islands of the same archipelago.

Research on Portuguese vernacular architecture has an important milestone in the 1960s with the publication of "Arquitectura Popular em Portugal" (Popular Architecture in Portugal) [92]. Although it was not the first study done in Portugal, this publication is probably the most important on the topic within the national panorama, and today it remains an essential work in the study of Portuguese vernacular architecture. It can be said that the popularity of this publication has triggered and widespread the interest in the topic and the number of publications focusing on it has not ceased, being nowadays also associated with the theme of sustainable construction.

In Portugal, vernacular architecture has been investigated mainly from an interpretative perspective and with qualitative analyses. Therefore, there is a lack of quantitative studies that allow understanding thermal and comfort conditions and the environmental performance of this type of constructions.

In the study previously developed on the contribution of Portuguese vernacular architecture to the sustainability of buildings [36], carried out based on the various surveys on popular architecture in Portugal [40, 92, 107, 108], several sustainability principles in these constructions were identified such as: i) management of the territory according to its capacity, i.e. building on less fertile areas and adaptation of crops to the soil and climate; ii) efficient management of resources; iii) use of local materials and techniques; iv) use of renewable resources, both through the use of bio-materials, as well as through the use of the energetic potential of the wind, watercourses and tides; v) rainwater harvesting and use; vi) passive solar strategies; among others. The results obtained in the study demonstrated that sustainability principles and the existing strategies in Portuguese vernacular architecture, due to their simplicity and pragmatism, have a high potential to be considered, both in the design of new buildings and in refurbishment operations. The work developed so far has been approached from a qualitative point of view, being necessary to continue the research work by complementing it with quantitative studies, to scientifically verify their effectiveness and feasibility in the current building context.

The contents presented in this chapter are, entirely or partially, published in the following publications:

Thermal Performance and Comfort Condition Analysis in a Vernacular Building with a Glazed Balcony
Energies (2020), 13, 624. doi:10.3390/en13030624
Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks.
Journal of Cleaner Production 241 (2019) 118286. doi:10.1016/j.jclepro.2019.118286
Passive strategies used in Southern Portugal vernacular rammed earth buildings and their influence in thermal performance
Renewable Energy (2019), 142, 345–363. doi:10.1016/j.renene.2019.04.098
Contribution of Portuguese Vernacular Building Strategies to Indoor Thermal Comfort and Occupants' Perception
Buildings (2015), 5, 1242–1264. doi:110.3390/buildings5041242
Portuguese vernacular architecture: the contribution of vernacular materials and design approaches for sustainable construction
Architectural Science Review (2015), 58, 324–336. doi:10.1080/00038628.2014.974019

CHAPTER 3

ENVIRONMENTALLY RESPONSIVE STRATEGIES IN PORTUGUESE VERNACULAR ARCHITECTURE

3. ENVIRONMENTALLY RESPONSIVE STRATEGIES IN PORTUGUESE VERNACULAR ARCHITECTURE

After a period of a construction context based on industrial materials and relying mainly on mechanical systems to provide healthy and comfortable conditions for occupants, the rise of an environmental awareness implies giving relevance to environmentally responsive strategies that take advantage of available endogenous resources.

Portugal is a diverse territory; there are many different manifestations of vernacular constructions and, consequently, different strategies have been developed for their adaptation to the surrounding environment. From north to south, and from the interior to the coast, buildings change to accommodate different strategies that serve different ways of living in specific territories. Therefore, based on the need of designing buildings adapted to a particular climate and territory, it is worth studying Portuguese vernacular buildings to develop and integrate their design strategies in the current construction context.

In this section, the correlation between Portuguese vernacular architecture and the different climatic and lithological variations of the country is addressed, highlighting the advantages of taking into consideration these strategies on environmentally responsive building design. The data on vernacular strategies was collected from the main surveys on Portuguese vernacular architecture [40, 92]. The work presented in this section focuses on some case studies located along the mainland of the Portuguese territory. Different strategies were chosen to relate certain vernacular strategies to specific local climate conditions, and examples mapped. The comparative analysis was established by overlapping the strategies points on specific cartography (as temperature, precipitation and lithology). The graphical analysis allowed understanding the relationship between the purpose of strategies and the surrounding environment.

3.1 GEOGRAPHY AND CLIMATE IN MAINLAND PORTUGAL

Mainland Portugal is located between latitudes 37°N and 42°N in the transitional region between the subtropical anticyclone zone and sub-polar depression zone [109]. Besides latitude, the most important features affecting the climate of the territory are orography and the influence of the Atlantic Ocean [109]. Concerning geographic relief, the highest peaks rise to a height of 1000–1500 m, except for the Estrela Mountains, whose most elevated point is just below 2000 m. Even though the variation in climate factors is rather small, it is sufficient to justify significant changes in air temperature and rainfall [109]. The mainland has a temperate climate – Type C, according to Köppen climate classification [110]. The territory is divided into two sub-types of climate: i) The northern part and almost all of the west coast have a climate sub-type Csb, characterised by rainy winters and hot and dry summers. The annual average mean temperature for the majority of this zone is 15°C, being 10°C in the highest points. The highest values for annual average rainfall are above 2200 mm in the mountain areas of north-eastern Portugal (Serra do Gerês) [110]; ii) inland southern Portugal has a Mediterranean climate, sub-type Csa, hot and dry during summer. In the summer, the mean values for maximum air temperature vary between 32 °C and 35 °C, reaching sometimes maximum temperatures of 40 °C or 45 °C, and July and August are the hottest months. The annual average rainfall is below 500 mm, and July is the driest month (below 5 mm) [110].

3.2 CLIMATE RESPONSIVE STRATEGIES IN PORTUGUESE VERNACULAR ARCHITECTURE

From all the geographical constraints, one of the most relevant is undoubtedly the climate. Nonetheless, in general, it can be stated that the northern part has harsher winter conditions, milder summers and higher annual average rainfall, while the southern part is the opposite, with mild winter, harsh summer conditions and lower values for rainfall [15]. To suit these climatic conditions, Portuguese vernacular architecture developed specific mitigation/adaptation strategies, as shown below.

3.2.1 PROMOTION OF SOLAR HEAT GAINS

From north to south, people knew the importance of taking advantage of a good solar exposure of their buildings. Nevertheless, vernacular strategies to promote solar heat gains are more visible in the northern part of the country, as shown in Figure 3.1. The main reason for this is that winter is the most demanding season in the region. Therefore, considering that the main energy source to heat these buildings was wood, it is easy to understand that all the free heat from the sun is welcome.

These concerns are visible right from the implantation of the urban settlement, frequently implanted in valleys and on south-facing slopes, seeking simultaneously to maximise solar gains and protection from the wind [36]. At the building's scale, the most widespread strategy is the correct solar orientation, with the main rooms facing the south quadrant. However, the strategy that takes more advantage of solar radiation is the glazed balcony. The glazed balconies are a feature of the architectonic identity of the northern interior part of the country (Fig. 3.1b). The balconies are usually facing between south and west so that they can capture in winter the most intense radiation during the highest number of hours of sunshine while affording the best shelter from the prevailing winds [92].

3.2.2 REDUCTION OF HEAT LOSSES / PROMOTION OF OTHER HEAT GAINS

In addition to the previous strategy, buildings usually also used other strategies to face cold winters such as reducing indoor heat losses and promoting other heat gains. As seen before, these strategies are also more concentrated in the northern part, being concomitant in many cases.

To reduce indoor heat losses, buildings in mountainous areas had commonly thatched roofs (Fig. 3.1a). This coating ensures simultaneous protection against rain and some thermal insulation. The straw used for thatching was a waste product from the cultivation of rye, a cereal crop more present in mountain areas. Additionally, such constructions also have a limited number of windows to avoid heat losses, usually very small, and a low ceiling, which allows warming up the indoor air quickly [36].

This concern is also evident in the functional arrangement of the indoor spaces. For example, bedrooms rarely have windows to the exterior and are located next to the kitchen, taking advantage of the heat from the fireplace [36]. In this region, it was also common for cattle to be stabled on the ground floor of the dwelling to take advantage of the animals' body heat.

3.2.3 PASSIVE COOLING / MINIMISE HEAT GAINS

In opposition to the previous strategies, passive cooling strategies are more concentrated in the south of the country, as shown in Figure 3.2. The intense summer heat in the south has forced vernacular buildings to develop strategies to minimise heat gains and to promote cooling (Fig. 3.2). With this purpose, several techniques were developed, and often used together, such as (Fig. 3.3) [16, 29, 40, 111, 112]:

i. Minimising the size and number of windows and doors facing the outdoor environment, to reduce solar gains. The use of small windows, recessed in the façade, also allows that the depth of the openings acts as a shading system (Fig. 3.3a);

ii. The use of high thermal inertia building elements, namely rammed-earth walls and vaulted ceilings, the later increasing the height and thermal stratification (Fig. 3.3b);

iii. The use of light colours for the building envelope, mainly whitewashed surfaces (Fig. 3.2b; 3.3a), reduces heat gains by acting as a radiation reflector, reflecting about 90% of the incident solar radiation [40], [111];

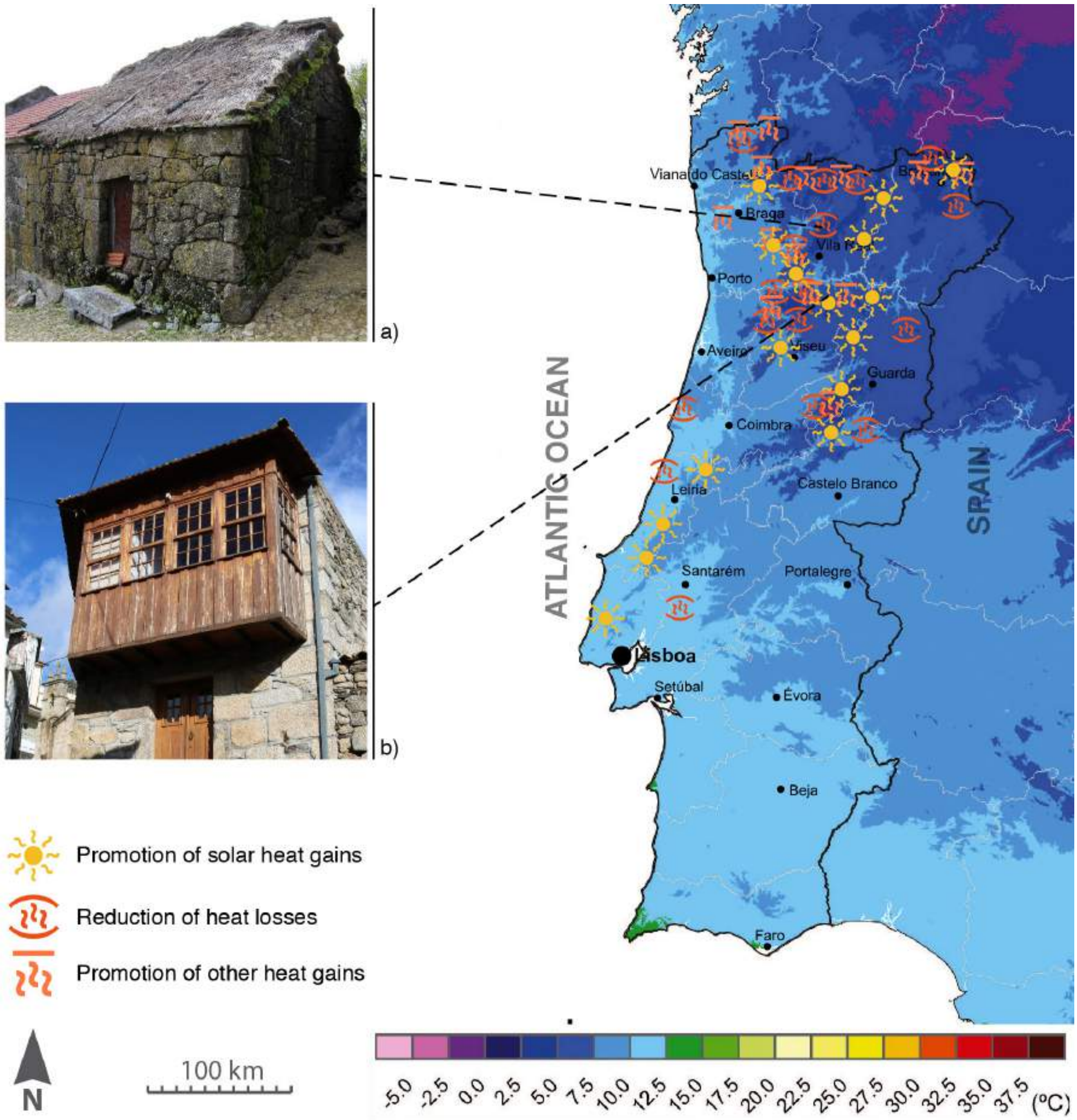


FIGURE 3.1. Map of mean air temperature during the winter season in Portugal, showing the points where strategies for promoting heat gains and reducing heat losses are placed. a) Thatched construction; b) glazed-balcony building. (Adapted from [36], [110]).

iv. Ventilation openings that could be integrated into windows and doors or in the walls, to promote air circulation and night cooling to remove diurnal thermal loads. In some cases, these ventilation openings have gridded shutters, like the mashrabiya. These techniques allow ventilation and shading simultaneously from intense light and radiation without compromising privacy and security (Fig. 3.2c, 3.3c-d);

v. The use of patios (courtyards), usually containing vegetation and/or water, useful to generate a cool microclimate through plants evapotranspiration and water evaporation, respectively (Fig. 3.3e). A study carried out in Évora has demonstrated that during a summer period air temperature in the patio remained lower than those recorded for the city centre, with a maximum difference of around 9°C during heat peaks [16];

vi. Vegetation is also frequently used as a shading system (Fig. 3.3f);

vii. In an urban context, it is also frequent the use of compact and irregular layout with narrow streets, allowing for reducing the surface area exposed to the sun rays and enabling buildings to provide shade for one another, thereby reducing solar gains by the building envelope (Fig. 3.3g-h).

The combination of all these strategies is an interesting feature of this type of buildings, and a great asset to achieving indoor thermal comfort conditions during the summer season by passive means alone [15, 16]. This aspect discloses the advantages of a holistic understanding of the available resources.

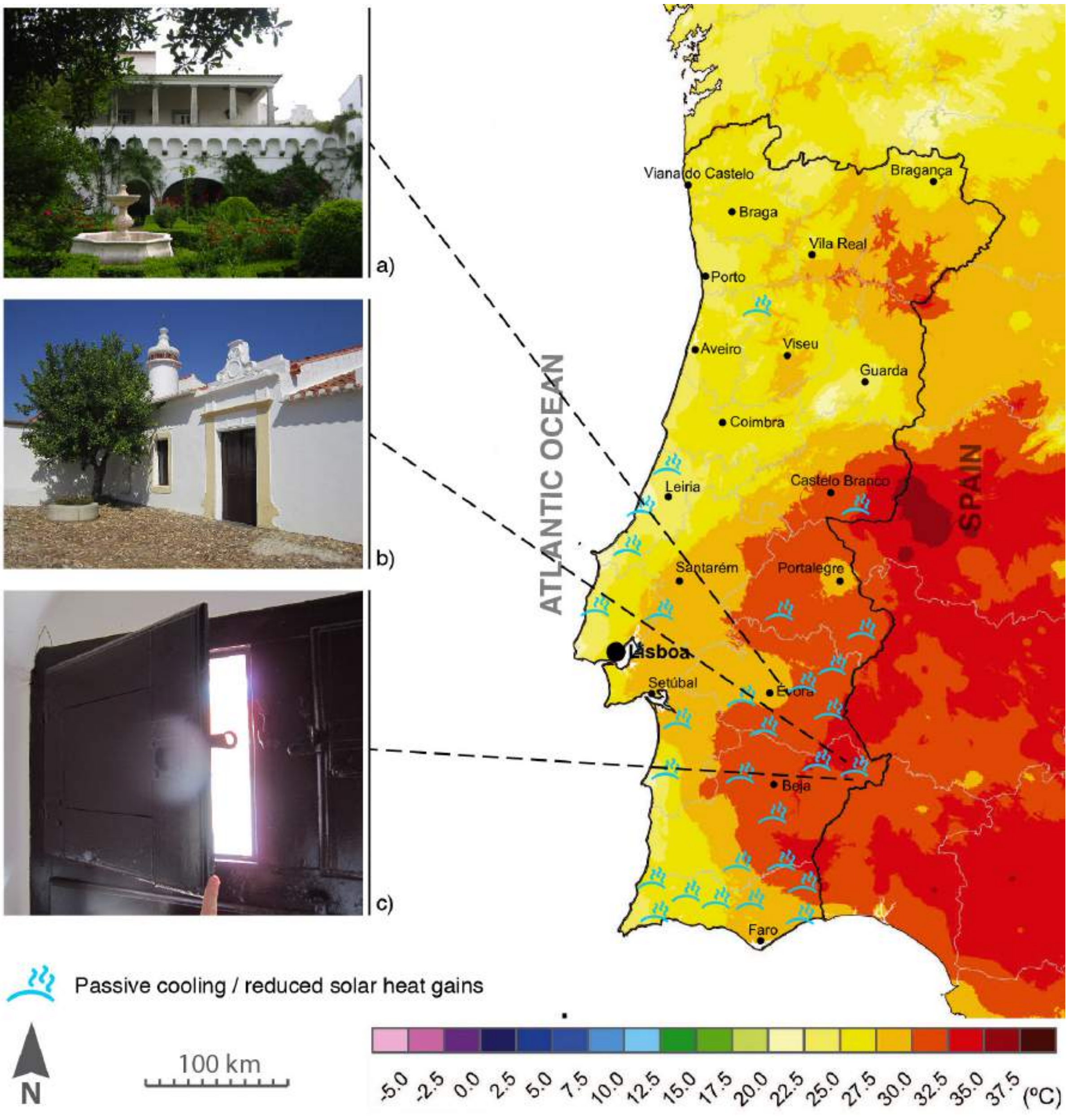


FIGURE 3.2. Map of average maximum air temperature during summer season in Portugal, showing the points where strategies for reducing heat gains and promoting passive cooling are placed. a) building with a courtyard (patio); b) whitewashed rammed-earth building; c) ventilation window. (Adapted from [36], [110]).

FIGURE 3.3. a) Small window recessed in a whitewashed façade; b) vaulted ceiling; c) ventilation shutter integrated into window frame; d) ventilation openings integrated into wall; e) a patio containing vegetation and fountain; f) vegetation shading the façade; g-h) compact layout with shaded narrow streets.

From these strategies, there is one that stands out for being the building element that characterises Portuguese southern vernacular architecture [40, 113]. The heavy walls made of rammed earth are the most widespread vernacular construction technique in the south, and mainly in the Alentejo region (the major area of all the south part of Portugal) [92]. The dense mass and the good heat storage capacity of rammed earth walls allows them to react appropriately to the hot summer of Alentejo, dampening the outdoor thermal wave and keeping indoor temperature and relative humidity stable [15, 31].

The use of rammed earth in the region is ancient, and there are several possible factors to explain it. According to Ribeiro [113], the flat terrain, dry climate and the abundance of clayey material were favourable factors to the use of earthen materials on a large scale. An interesting fact is that in the south, the use of rammed-earth as a building technique has spread beyond the clayey areas and dominated even in areas where stone prevailed [113]. In addition to these, the capacity to dampen the heatwave is another essential factor regarding functionality [40, 92].

These factors are plausible reasons to explain the use of this building technique in the Portuguese territory for over two thousand years, already described by Vitruvius [114], and also by Pliny the Elder, centuries before the arrival of Moors or Arabs to the region [80, 115]. Nevertheless, the Roman and Arab presence and influence in the territory was long and significant, and the latter was probably responsible for spreading the technique in the south of Portugal [113].

The long tradition in applying the abovementioned strategies is, beyond a cultural influence, a consequence of their effectiveness in mitigating the effects of the climate. In this sense, the quantitative study of these passive strategies and their impact on the thermal performance of buildings is useful to the discussion around energy efficiency in buildings, as it will be described and discussed further in this work.

3.2.4 RAINWATER HARVESTING

In Portuguese vernacular architecture, there are multiple examples of rainwater harvesting and use, either for domestic or agriculture purposes. Most of the examples are located in areas where water resources are scarce or difficult to access, as shown in Figure 3.4. The abundance of water in some regions of the country, as in the northwest, can justify the absence of examples (Fig. 3.4). However, this is not always true, as will be explained below. To minimise the lack of water, people developed simple harvesting and water storage systems necessary for their subsistence. In addition to its function, the architectural integration of those systems must be emphasised (Fig. 3.4a).

The Estremadura mountains have the highest levels of rainfall in this region (Fig. 3.4a). A bit similar to what happens in the northwest, the mountain acts as a barrier to the winds from the sea that carry the rain [92]. But, ironically, due to the permeability of limestone soil of this zone, water is here more scarce [92]. To address this problem, the population needed to collect rainwater in cisterns through interesting gutter systems (Fig. 3.4a). The water tank was an essential element of houses in this area.

As an example, the village of Monsaraz due to the fact of being on a top of a cliff has water shortages. This shortage has led to the inhabitants to provide their homes with a gutter system to collect rainwater (Fig. 3.4b) that was conducted into a large cistern below the castle, ensuring the provision for the whole village [92].

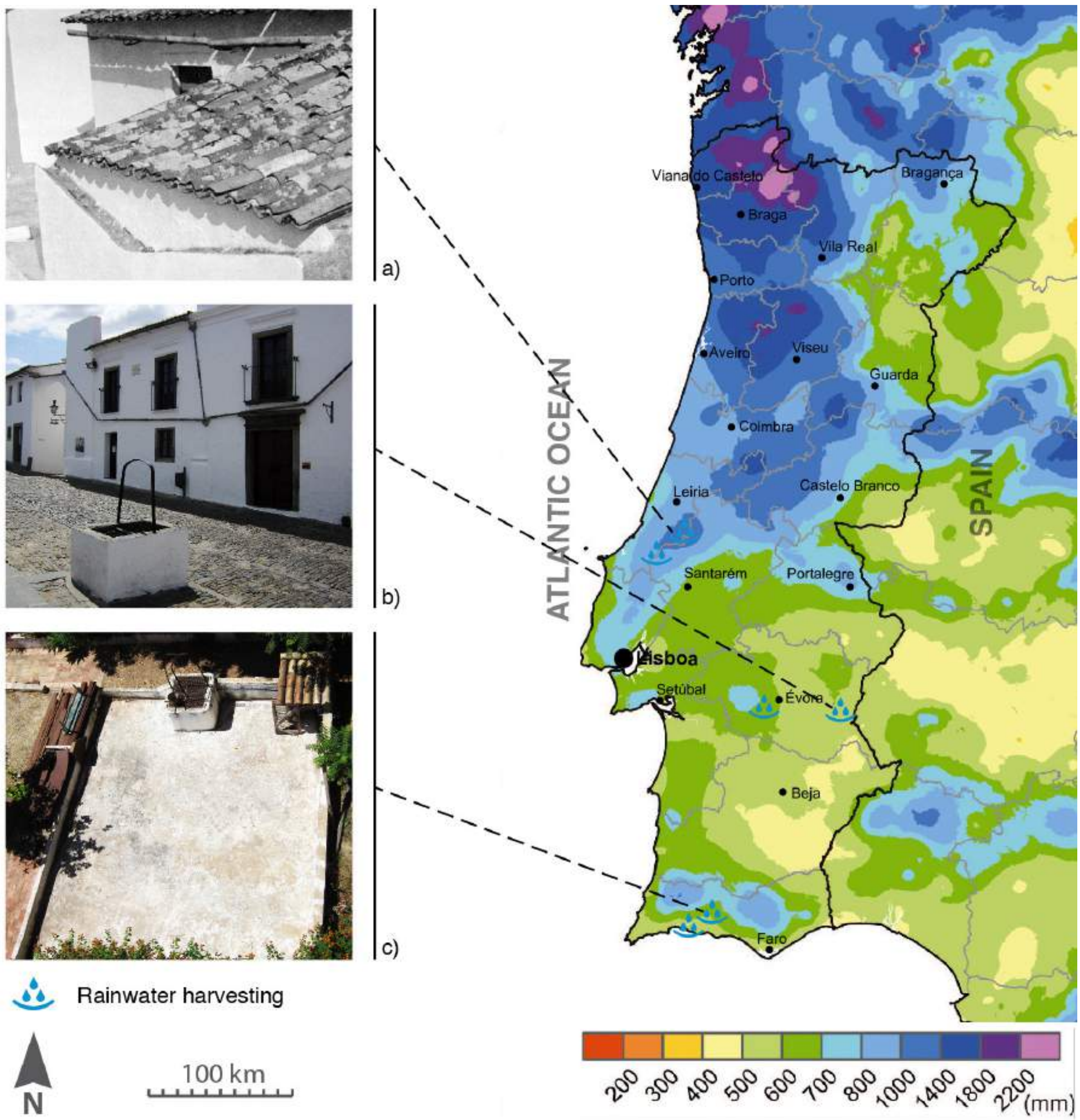


FIGURE 3.4. Map of average total annual precipitation in Portugal, showing the points where strategies for rainwater harvesting are placed. a-b) Gutter system that leads water to a cistern (image "a" source: [92]; c) whitewashed floor for rainwater collection and cistern's access point. (Adapted from [36], [110]).

The low rainfall that occurs in most of the Algarve territory led populations to provide their houses with rainwater harvesting systems for domestic use similar to the previously mentioned. For this purpose, they built gutters under the eaves, or inserted them in the walls, leading the water to a cistern. When the water collected from the roof was not enough, they also resort to the threshing floor to increase the harvest area (Fig. 3.4c). The threshing floor has several slopes that conduct the water to a small hole, which communicates with the cistern, as illustrated by the example in Figure 3.4c. Another point worthy of note is the confinement of the threshing floor by small low walls and the abundant whitewashing of the entire ground surface to nullify the natural acidity of rainwater [92].

Currently, there are already plenty of rainwater harvesting systems developed, but the most significant potential that comes from the vernacular examples is the architectural integration capabilities of these systems. With climate change, it is expected that the frequency of droughts increases, and thus this strategy gains even more relevance.

3.3 USE OF LOCAL MATERIALS AND TECHNIQUES

The use of local materials and techniques is one of the most relevant features of vernacular architecture, being an identity factor of regional differentiation. Broadly speaking, as far as Portugal is concerned, it can be stated that where stone exists people build with this; where there is lack of it, people build with earth, wood or other vegetable materials [40]. The materials used were obtained from the geographical area where the buildings were erected. Even in areas of lithological frontier, the examples of constructions that use stone from the neighbouring region are rare. The scarce economic resources of the population did not allow them to access to materials that were not found locally. Only the wealthiest families, or those with some financial capacity, could bear the costs of transporting materials [92]. The industrialisation brought the habit of using industrially-produced materials, produced far from building sites, which led to the disuse of local traditional materials and techniques [92].

As in climate, Portugal has a considerable lithological contrast between regions. In Figure 3.5 and the following examples, it is particularly noticeable that there is an almost perfect correlation between the distribution of the construction materials used and the lithological characteristics of Portuguese territory. To state this fact, some examples are highlighted, as follows:

1. In the transition zone between schist and granite, constructions reveal the combination of these two materials, either in walls or roofs;
2. In the Montemuro mountains, a region of harsh winters and rye crops, roofs were made of straw

— a waste from cereal production. This coating ensures simultaneous protection against rain and some thermal insulation. The thatch has been used for a long time in regions with this type of crop. It has the advantages of being a natural material, fully biodegradable, low cost, with a good performance against natural elements, such as rain and snow, as well as insulation properties. The disadvantages of straw, mainly in relation to clay tiles insulated with extruded polystyrene are lower fire resistance; and the need for periodic replacement, even considering the reduced cost of this process. In sustainable building design, it is possible to use this material in contemporary applications, and it has good potential for integration with new materials [117]. In Portugal, this technique fell into disuse, yet has good potential to be used in contemporary times, as seen in

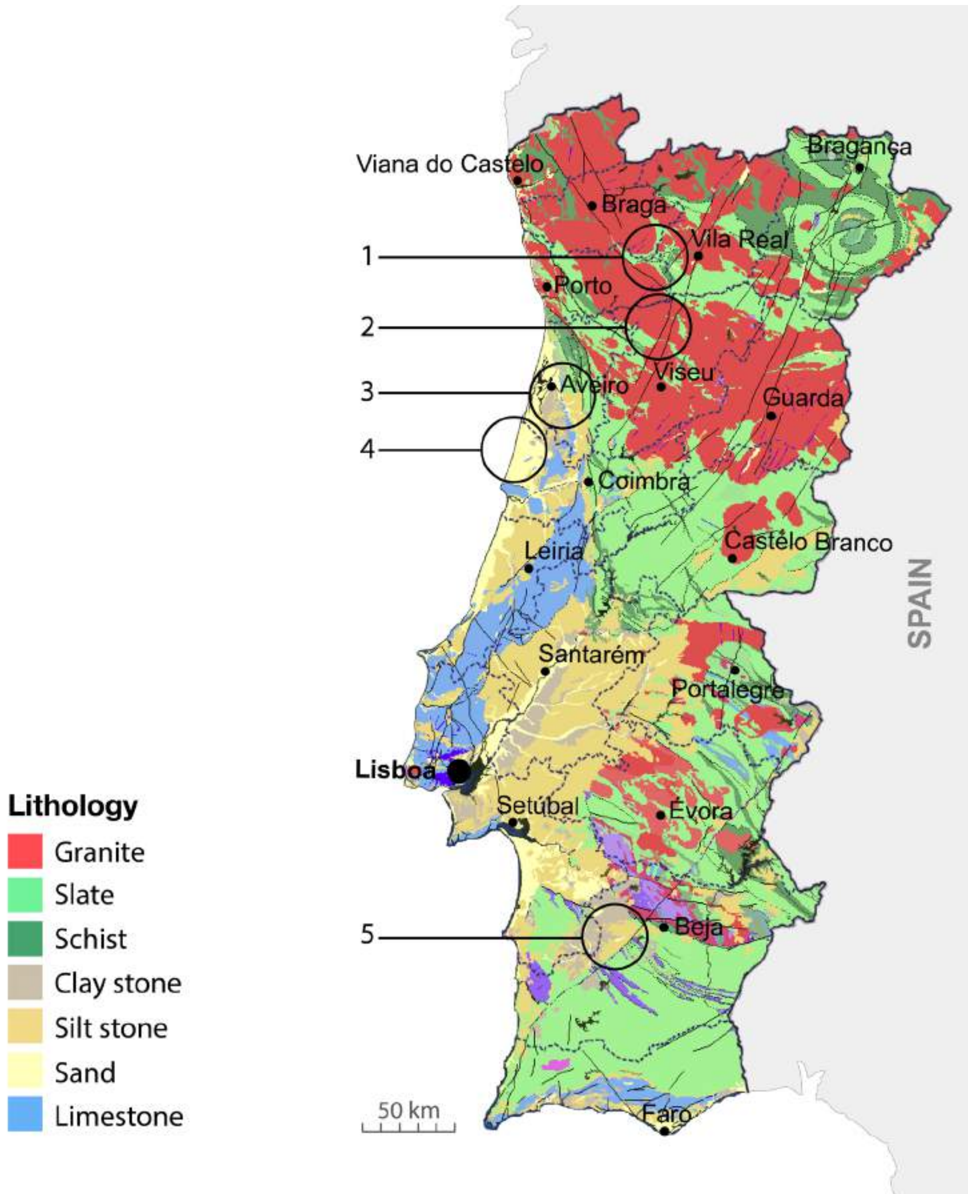


FIGURE 3.5. Lithological map of Portugal (Adapted from [116]) and location of the examples.

examples from other countries (Fig. 3.6).

3. In coastal regions, as the Vouga estuary, where there is no wide availability of stone but where the alluvial soils and clays abound, the buildings are mostly built of adobe;
4. Also in the coast, but particularly in the shoreline (the *palheiros*), timber construction prevails on the sandy soils. Pine forests close to these areas helped to obtain this material and allowed buildings to be almost entirely made of it. This type of construction has a current potential of prefabrication with economical maintenance of their coatings piece-by-piece.
5. Rammed earth is the most widespread construction technique in the Alentejo region. In this area, the good quality of soil for this type of construction technique is reflected in the profuse use of it [92], [118]. The high mass that characterises earthen constructions allows them to respond appropriately to the scorching summer heat of Alentejo.

Analysing the abovementioned examples, it is noticeable that the plurality of the Portuguese territory offers a profuse expression of different vernacular building materials and can be even more if the archipelagos of Madeira and Azores were included. These examples illustrate a close relationship with the characteristics of the sites (lithology, climate, crop and forest cover) where they are used. Materials and techniques used in Portuguese vernacular architecture have the potential for contributing positively to the sustainability of the built environment. So, there is a need to conduct further studies to develop their potential and consequently promote their application.

FIGURE 3.6. (left) Community Market Yusuhara, Japan, completed in 2010 (Architects: Kengo Kuma and Associates) (© Photograph by Takumi Ota [119]); (right) Tåkern visitor centre, Sweden, completed in 2012 (Architects: Wingårdhs) (Photograph by Anna Fuster [120]). The lake´s reeds were used to clad the building.

The contents presented in this chapter are, entirely or partially, published in the following publications:

The importance of vernacular strategies for a climate responsive building design
SBE16 Brazil & Portugal - Sustainable Urban Communities towards a Nearly Zero Impact Built Environment (2016), Vitória, FUES&UM, 429-438.
The potential of vernacular materials to the sustainable building design
Vernacular Heritage and Earthen Architecture: Contributions for Sustainable Development (2013), London: CRC Press, 623-629. doi:10.1201/b15685

CHAPTER 4

MATERIALS AND METHODS

4. MATERIALS AND METHODS

The diversity of the Portuguese territory represents a vast research field on the study of vernacular architecture. According to Orlando Ribeiro [121], the fundamental divisions of mainland Portugal are the North Atlantic, the North Interior and the South, which is a good starting point for the selection of case studies to initiate a set of quantitative analyses on the thermal and environmental performances of Portuguese vernacular architecture.

At this stage, the research work will focus on three areas of the mainland part of the country, different from each other in several local factors (climate, lithology, building techniques, materials, etc.). The selected areas for the study are: 1 — central coastline, 2 — northern interior and 3 — southern interior (Figure 4.1). Therefore, based on the previous carried work [36], vernacular buildings to be considered are 1 — Beira Litoral's timber buildings; 2 — Beira Alta's buildings with glazed balconies and; 3 — Alentejo's earthen buildings.

The study on the environmental performance of vernacular materials will focus on earthen techniques used in the south of the country.

To achieve the proposed goals, the methods adopted in this study are guided by a set of appropriate standards and models, as described below.

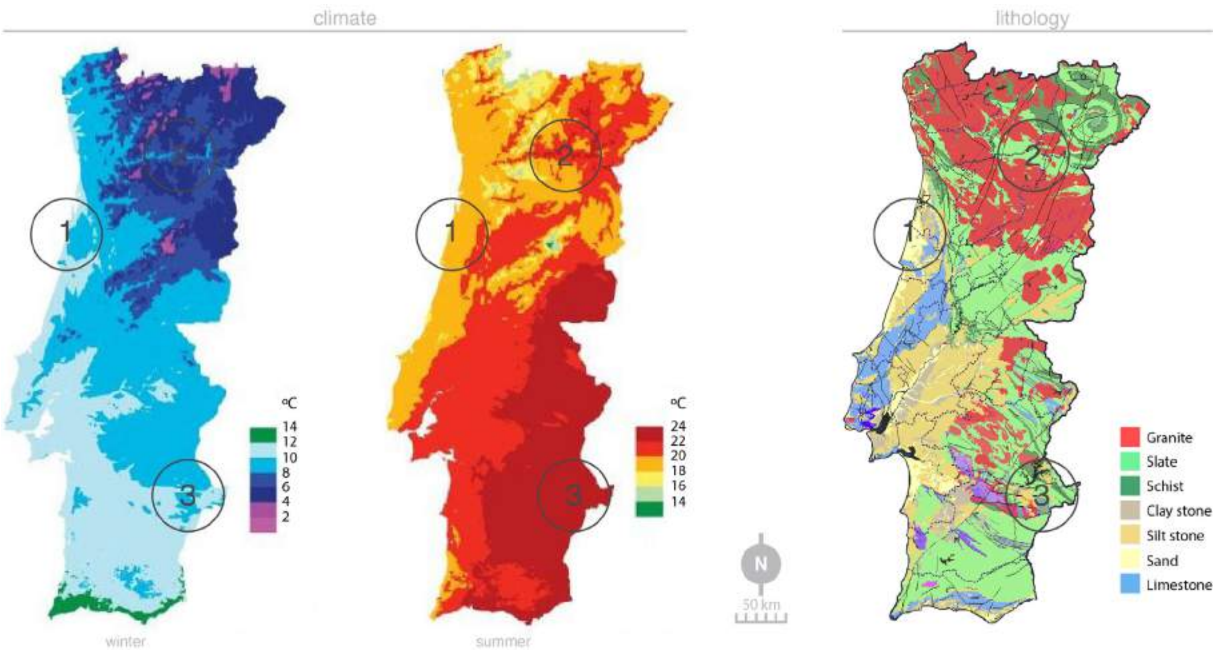


FIGURE 4.1. Climatic and lithologic contrasts of the Portuguese mainland territory and location of the three zones under study. (left) Winter and Summer mean temperatures; (right) Surface lithology. (Maps adapted from [116], [122]).

4.1 THERMAL AND COMFORT MONITORING

To assess indoor thermal performance, *in situ* assessments were divided into short- and long-term monitoring. In these assessments, the hygrothermal parameters that characterise the indoor thermal environment and that affect the body/environment heat exchange (air temperature, relative humidity, mean radiant temperature and air velocity) were measured.

4.1.1 SHORT-TERM MONITORING

Short-term monitoring was carried out at least one day per season and consisted of objective measurements and subjective evaluation:

- Objective measurements - they had the purpose of quantitatively assess the thermal comfort conditions in a room using a thermal microclimate station (model Delta OHM 32.1) that measures air temperature, relative humidity, mean radiant temperature and air velocity (Table 1), in compliance with standards ISO 7726 [123], ISO 7730 [124] and ASHRAE 55 [125]. The measurements were carried out in the room(s) where the occupants stay for more extended periods, and considering that they were seated, as recommended in ASHRAE 55 [125]. The location of the equipment was chosen according to occupants' distribution in the room. The data recorded in these measurements was used to determine the operative temperature (the analysis procedure is explained below in this section).
- Subjective evaluation - it was carried out to assess the occupants' perceived indoor environment quality, using surveys. The survey was based on the "Thermal Environment Survey" from ASHRAE 55 [125] and was used to determine occupants' satisfaction according to ASHRAE thermal sensation scale (Appendix 1).

The results of these two types of analysis were compared.

4.1.2 LONG-TERM MONITORING

Long-term monitoring was carried out to measure the indoor and outdoor air temperatures and relative humidity throughout the measurement period. For this, thermo-hygrometer sensors were installed in the most representative rooms and outdoors (Table 1). The measurements were carried out during different monitoring campaigns for all seasons, in compliance with specified procedures and standards (ISO 7726 [123], ISO 7730 [124], and ASHRAE 55 [125]). The monitoring campaigns were carried out for periods of at least 25 days and with the sensors recording data in periods of 30 min. Results on indoor environmental parameters were correlated with the outdoor parameters. During the measurement period, occupants filled an "occupancy and use profile" table (Appendix 2) where they recorded how they used the building in their daily life, i.e. if they used the heating or cooling systems, promoted ventilation, used shading systems, among others. These occupancy records were useful to understand, for example, sudden changes in air temperature and relative humidity profiles. Local weather data was collected from the nearest weather stations or measured on-site using a portable weather station.

4.1.3 MODEL OF THERMAL COMFORT

An adaptive model of thermal comfort was used in the analysis of thermal comfort conditions since this is the adequate model for naturally conditioned buildings. The chosen model was the Portuguese adaptive model of thermal comfort since it is the most representative of the Portuguese reality [126]. This model is an adaptation to the Portuguese context of the models specified in standards ASHRAE 55 [125, 127] and EN 15251 [128]. It considers the typical climate and ways of living and how buildings are conventionally designed and used. According to this model [126]: i) occupants may tolerate broader temperature ranges than those indicated for mechanically heated and/or cooled buildings; ii) the outdoor temperature has a strong influence on occupants' thermal perception/sensation.

In the application of the proposed model to the case study, the following conditions were assumed: (i) the occupants have activity levels that result in metabolic rates (met), ranging from 1.0 to 1.3 met (sedentary activity levels); (ii) occupants are free to adapt the thermal insulation of their clothing; (iii) air velocity is below 0.6 m/s; (iv) indoor operative temperature is bounded between 10 °C and 35 °C; and (v) outdoor running mean temperature is between 5 °C and 30 °C. The building has no air-conditioning system, or its use is sporadic, and, therefore, in the analysis of the case study, the adaptive model for building without mechanical systems was applied.

Considering that an individual takes approximately one week to be fully adjusted to the changes in outdoor climate, the thermal comfort temperature (operative temperature, Θo) is obtained from the exponentially weighted running mean of the outdoor temperature during the last seven days (outdoor running mean temperature, Θrm). The calculation of the exponentially weighted running mean of the outdoor temperature in the previous seven days was done using Equation (1).

$$\Theta rm = (Tn-1 + 0.8Tn-2 + 0.6Tn-3 + 0.5Tn-4 + 0.4Tn-5 + 0.3Tn-6 + 0.2Tn-7)/3.8 \quad (1)$$

Where:

Θrm (°C)—exponentially weighted running mean of the outdoor air temperature;

$Tn{-}i$ (°C)—outdoor mean air temperature of the previous day (i).

In this model, two comfort temperatures ranges are defined, one to be applied in spaces with active air-conditioning systems and other in non-air-conditioned spaces (areas that do not have an air-conditioning system or where the system is turned off). The operative temperature limits defined in this model are for 90% of acceptability, these limits are up to 3 °C above or below the estimated comfort temperature both for non-air-conditioned ($\Theta o = 0.43\Theta rm + 15.6$) and air-conditioned spaces ($\Theta o = 0.30\Theta rm + 17.9$).

The operative temperature was calculated based on the results obtained in the measurements from the Thermal Microclimate Station (Table 1). With the operative temperature (Θo) and the outdoor running mean temperature (Θrm), it is possible to represent in the adaptive chart the point that characterises the thermal environment condition in the moment of measurement.

4.2 EVALUATION OF THE INDOOR AIR QUALITY

In the buildings monitored, the occupants were the main source of pollution. In this type of buildings, the concentration of carbon dioxide is a good indicator of air quality since it allows verifying whether the building has an adequate ventilation. Thus, if the building does not have an adequate ventilation, it can be also an indicator of the concentration of other pollutants [129].

The air quality was evaluated by measuring the carbon dioxide (CO_2) concentration in the buildings for typical conditions of use/occupation. The measurements were carried out for representative rooms and days in all seasons, in compliance with standard EN15251 [130]. In the case of the heating season, the measurements were carried with the heating devices (combustion) in use to analyse their influence in indoor carbon dioxide concentrations. The equipment used is a multifunction climate measuring instrument with the IAQ probe for CO_2, temperature, humidity and absolute pressure (Table 1).

Case study 2 is located on a granitic area, so in this specific case the radon gas concentration was also measured. In the Portuguese context, and according to national legislation [131], it is mandatory to study and measure the concentrations of radon in granitic sites, as the one where the case study is located (District of Viseu). In this case study, the concentration of radon was measured during the heating season, when the ventilation rate was lower. The living room/kitchen was the room chosen for the measurements since it has the lowest ventilation rates, has granite walls, is located in the ground floor and it sits on a granitic massif. The measurements took place for 28 days, with integration periods of 10 minutes, started after a period of stabilisation of the radon sensor (about 60 days) (Table 1).

TABLE 1. Characteristics and location of the measurement equipment used.

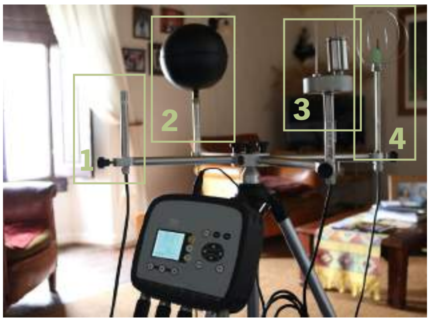
Equipment	Specifications, measurement range and accuracy	Location
Thermal microclimate station (model Delta OHM 32.1) 	Probes installed: 1. Combined temperature and relative humidity probe (range from -10 to 80 °C and 5 - 98% RH); 2. Globe temperature probe Ø 150 mm (range from -10 to 100 °C); 3. Two-sensor probe for measuring natural wet bulb temperature and dry bulb temperature (range from 4 to 80 °C). 4. Omnidirectional hot-wire probe for wind speed measurement (range from 0 to 5 m/s);	Case study 1 Reception Case study 2 Living room/ kitchen and bed-room with balcony Case study 3 Living room
Thermo-hygrometers (Datalogger Klimalogg Pro, TFA 30.3039.IT + Transmitters, TFA 30.3180.IT)  	Datalogger: Temperature accuracy of ± 1 °C and a measuring range between 0 and 50 °C with 0.1 °C resolution; Relative humidity accuracy of ± 3% and measuring range between 1 and 99% with 1% resolution. Transmitters: Temperature accuracy of ±1 °C and measuring range between 39.6 °C and +59.9 °C with 0.1 °C resolu-tion; Relative humidity accuracy of ± 3% and measuring range of 1% - 99% with 1% resolution.	Case study 1 Datalogger: Recep-tion Transmitters: Exhibition room, "dining" room and "school" room Case study 2 Datalogger: Living room/ Kitchen Transmit-ters: Bedrooms, Bath-room Case study 3 Datalogger: Living room Transmitters: Bedroom, alcove (middle) and attic.
Thermo-hygrometers (Testo AG, model Testostor 175-2) 	Temperature accuracy of ±0.9 °C and a temperature measuring range between -10 °C and +50 °C, with 1 °C resolution. Relative humidity measuring ranges from 0 to 100%, with a resolution of 1%.	Case study 1 Outdoor Case study 2 Outdoor Case study 3 Oudoor Indoor: kitchen, old kitch-en and corridor.

TABLE 1 (Cont.). Characteristics and location of the measurement equipment used.

Equipment	Specifications, measurement range and accuracy	Location
Portable weather station 	Probes installed: 1. Pyranometer (solar radiation sensor) CMP3-L, Kipp & Zonen. (range: 310-2800nm; irradiance up to 2000 W/m²; sensitivity 10 µV/W/m²) 2. Air temperature, relative humidity, wind speed and direction, precipitation and absolute pressure sensor (WXT520, Vaisala) Wind speed sensor (range: 0-60 m/s; accuracy: ±0.3m/s); Wind direction sensor (range: 0-360°; accuracy: ±3m/s); Precipitation sensor (intensity range: 0-200mm/h; accuracy: 5%); Absolute pressure sensor (range: 600-1100 hPa; accuracy: ±0.5-1 hPa); Air temperature (range: -52 to +60°C; accuracy: ±0.3° C); Humidity (range: 0-100%; accuracy: ±3% @0-90% to ±5% @ 90-100%) 3. Datalogger (CR800, Campbell Scientific, Inc.) (Operating temperature: -25° to 50 °C) 4. Photovoltaic panel + battery (power source)	Case study 1 Outdoor (Campsite at aprox. 300 meters far from the case study)
Multifunction climate measuring instrument with the IAQ probe for CO_2 and absolute pressure (Testo AG, Testo 435) 	Probe for ambient CO_2: Measuring range from 0 to 10000 ppm. Accuracy ± (75 ppm ± 3% of mv) (0 to +5000 ppm) ± (150 ppm ± 5% of mv) (+5001 to 10000 ppm). Absolute pressure: Measuring range from +600 to +1150 hPa. Accuracy of ± 10 hPa.	All the case studies and all rooms.
Determination of radon content using a portable ATMOS 12 PDX sensor 	Instrument: Measurement operation (Temperature range from 0 to 50 °C; Humidity range from 0 to 90%). Pulse counting ionisation chamber. 10% standard deviation at 800 Bq/m³ and 10 min measurement time. Upper limit for radon gas content detection is 100 000 Bq/m³; Air pump for continuous flow of 1.4 l/min. Airflow through the chamber 1.0 l/min. Memory with capacity for 28 days of time distribution and 20 energy spectra; 10 min interval measurements (it allows 1, 5, 10, 30 minutes and 1, 8, 24 hours).	Case study 2 Living room/ kitchen

4.3 CLASSIFICATION OF THE INDOOR ENVIRONMENT

The indoor environment was evaluated and classified based on the methodology of standard EN15251 [130] to allow the comparison between the performance of the case studies and of other buildings.

In all the case studies the indoor air quality was classified based on the concentrations of carbon dioxide.

In case study 3, the thermal and humidity criteria were also considered to classify the indoor environment. This analysis was developed due to the context in which the AEC professionals in the field of earthen construction argue that the thermal requirements in force are too strict and do not take into consideration other properties of earthen construction. In the analysis of this case study, the classification of the indoor environment was applied individually to representative rooms for the two most demanding seasons (winter and summer). In winter, since heating devices are used (even if not continuously), the values to design heating systems were considered [39]. During summer, since the building is naturally ventilated and has no mechanical cooling system, the adaptive comfort model was applied. In this case, the points that characterise the thermal environment were determined for each day and in relation with the corresponding outdoor running mean temperature [39].

The explanation of each category is presented in Table 2.

TABLE 2. Description of the categories to classify the indoor environment according to the standard EN15251 [130]

Category	Explanation
I	Buildings/spaces for sensitive persons (e.g. for young children and elderly persons) (high level of expectation)
II	New buildings and renovations (normal level of expectation)
III	Existing buildings (moderate level of expectation)
IV	Values outside the criteria for the above categories. This category can be only accepted for a limited part of the year.

4.4 PARAMETRIC ANALYSIS UNDER DYNAMIC CONDITIONS

The energy simulation under dynamic conditions, due to the wide range of options and variables managed, is a useful tool to predict the performance of buildings. In this work, the purpose of using this tool is to compare under the same conditions the impact of different vernacular and conventional strategies/building solutions on the energy performance for heating/cooling.

Since the range of options and variables is wide, modelling and inputs can be very time consuming. Therefore, to simplify the simulation and analysis processes, the method considered was to replicate the case studies and their characteristics (construction systems; operation schedules, etc.) but simplifying and keeping all the variables (e.g. internal heat gains) as stable and unchanged as possible. Nonetheless, in each model specific adjustments were made in order to serve the purpose of each comparison.

All the case studies were modeled and simulated using the DesignBuilder/EnergyPlus software (version 6) (EnergyPlus version 8.9) [132]. The modeling and inputs process had the following steps:

1. Site location: definition of the geographical location and the hourly weather data to be used for each case study. The influence of climate conditions on building performance is significant and thus it is essential to use reliable weather data for energy modelling [133]. In the simulations were used the weather data files from the EnergyPlus weather database [134], since they are more reliable and stable for simulations than other options tested. However, the EnergyPlus weather (EPW) files from this source are only available for few Portuguese locations. For this reason, for each case study, the weather data from the closest location and/or that has similar climate conditions was considered;
2. Building geometry: the model geometry is created based on the dimensional surveys of each case study, including the internal layout and the definition of the thermal zones to be considered in the analysis;
3. Building Model Data: in this step, the data to define the characteristics of the building model and that will be required in each specific section, such as the Activity (usage) of each zone of the building, the properties of the building components such as opaque and transparent envelope, technical equipment, etc. are gathered;
4. Activity data: the data on this section allows defining the activity (usage) of the zones and includes information as zone type, occupancy, internal gains and environmental control. Regarding occupancy, specific details for density, metabolic rate or schedules were not applied in the model since occupancy density is very low in all the case studies and for the study the inputs needed will add unnecessary complexity to the model. However, the influence or action of occupants were integrated in other parameters as the internal heat gains or the schedules for operation of windows opening and shading. The internal heat gains (occupancy, lighting, equipment, etc.) were lumped into a single value and timing schedule to simplify the model. The value considered for internal heat gains was of 4 W/m^2 and 7 W/m^2 for residential and service buildings, respectively, as defined in national legislation [135]. For the environmental control

parameters the heating and cooling setpoint temperatures of 18 and 25°C, respectively, were considered as defined in national legislation on the Energy Performance of Buildings [135];

5. Construction and openings: in this step the construction components to model the conduction of heat through walls, roofs, ground and other opaque parts, and also the openings (windows, doors, etc.) of the building envelope are created. In both opaque and transparent parts, the thermal transmittance values from national technical publications [136, 137] were considered. For other thermo-physical parameters such as specific heat, density, thermal diffusivity, the data from software's components library were considered or edited according to more specific information available;
6. HVAC and natural ventilation: since none of the case studies have a HVAC system, for the comparison purpose of the simulations, the Simple HVAC option was chosen just to allow the quantification of the energy demand for heating and cooling. Although the case studies only have natural ventilation, to simplify the model and to assure an adequate and constant air changes per hour in the buildings, the existence of a mechanical ventilation system was considered. The air change rate considered was 0,6 ach, as defined by the EN16798 standard for new buildings (Category II) [138]. Nonetheless, natural ventilation strategies are very relevant in vernacular buildings, particularly during the summer season. For this reason, in all the building models, the calculated natural ventilation model option was activated, which provided additional data to control the timing and extent of operation of openings. Thus, when the windows and doors are in operation, the air change rate is incremented based on opening size and wind pressure. The details of operation are described in Section 6;
7. Schedules and profiles: these were created to describe the specific operation of each building during all the seasons. Some schedules and profiles were slightly simplified, and the following parameters were considered: internal gains; operation of doors and windows opening and shading; and operation of HVAC.

In all models, the numerical simulation was carried out for one year to quantify the energy performance of each structure under seasonal external environmental conditions (summer, winter, spring and autumn). To establish the comparison between strategies/building solutions, simulations in several models were carried out, including a Base Model (which replicates the original conditions of each case study) and models for alternative scenarios. The scenario models have the same features and conditions as the base model, except for the one that is evaluated in each one (e.g. to assess the influence of the thermal transmittance and inertia of external walls, only this building element is changed between scenarios). The comparison scenarios and simulation conditions considered for each case study are described in detail in the corresponding chapter (Section 6).

4.5 LIFE CYCLE ASSESSMENT

This research work aims to assess the life cycle performance of two earthen materials, namely Compressed Earth Blocks (CEB) and Rammed Earth (RE), in compliance with standard EN15804 [106], i.e. with Product Category Rules (PCR) for Type III environmental product declaration of construction products, based on data collected from a manufacturer of such materials, located in Portugal. Thus, the results of the assessment can be compared with other EPDs for construction materials or other materials assessed according to the same standard. Since the methods considered are related to the PCR and the specificity of each material, the details of the methods are indicated in the corresponding chapter (Section 7).

CHAPTER 5

THERMAL PERFORMANCE AND COMFORT CONDITIONS ANALYSIS OF VERNACULAR BUILDINGS

5.1 CASE STUDY 1 – PRAIA DE MIRA

5.1.1 SITE AND CLIMATE CONTEXTS

The case study is located in the village of Praia de Mira, in Mira's municipality, district of Coimbra, central coast of Portugal (Fig. 5.1). Praia de Mira is part of a territory called Gândara. The human presence in the Gândara territory certainly dates back to the Roman and Arab periods, even Pre-Roman in some parts [139]. The oldest document referring Mira dates back to the 11th century, but only from the 16th century its population had a considerable growth [139]. The occupation of the coastline where Praia de Mira is now is relatively recent, mentioned in a document dating back to 1780 [139]. Nonetheless, fishing activity in this area of Mira (with different configurations of the shoreline) is much older [139].

In ancient times this part of the territory did not exist, and the ocean extended to Mira (about 7 km from the current coastline). In the last thousand years, the position and form of the coastline have suffered considerable changes [139]. Between the 7th and 12th centuries, the shoreline would be very close to the current location of Mira, and the village was a trading port [139] (Fig. 5.2). From the 13th century the sea started to retreat until the current shoreline landform. The result of this phenomenon was the formation of a vast territory of dunes, in constant change, described by some authors [139, 140] as a desert without plants or birds. The meaning of Gândara, i.e. unpopulated land and unproductive or barren sandy soil [141, 142], is by itself a description of the territory. Nevertheless, the inland part of Gândara is historically described as having extensive forests [139]. Therefore, due to the reasons mentioned, but particularly due to being inhospitable, the permanent occupation of the coastline is more recent.

FIGURE 5.1. Case study's location. (left) country context; (right) Case study position in Praia de Mira's current urban layout.

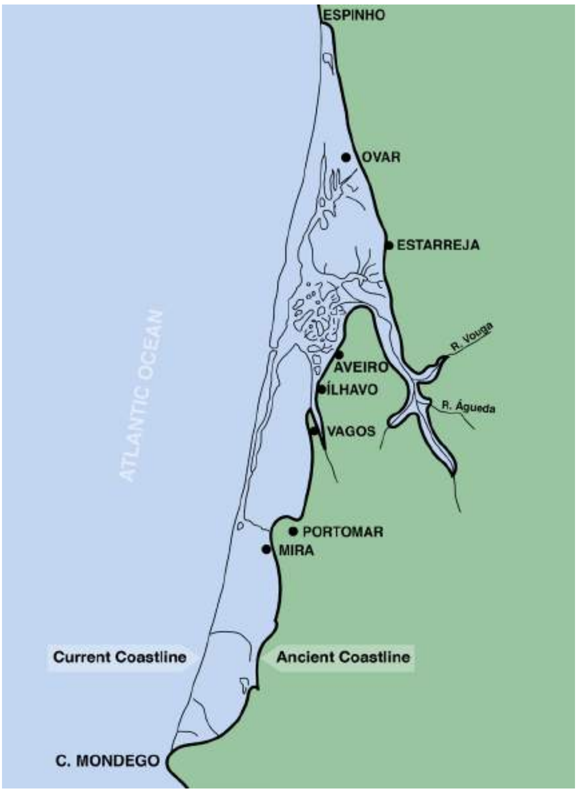


FIGURE 5.2. Ancient coastline between Espinho and Cape Mondego according the geological map of Delgado and Choffat (adapted from [139]).

The village of Praia de Mira, as other coastline settlements from the 19th century, had at first a seasonal occupation of fishermen during the fishing season (from Spring to Autumn) [143]. According to Soeiro de Brito [143], the first births occurred in 1835 and the population settled permanently around 1860/70. At this time, all the inhabitants were dedicated to the fishing activity [139, 143]. Nonetheless, and despite the difficulty of the soil, the permanent occupation led the population to start cultivating the surrounding wet sandy soils [139, 143], as will be explained further in this section.

The original name of the village was "Palheiros de Mira" and received this name due to type of constructions that existed there, the *palheiros*. The first occupants brought this type of timber construction. In a zone of dunes and pine forests, where stone does not exist and timber abounds, the *palheiro* was the temporary dwelling needed for fishermen from other locations during the fishing season [40, 113, 139]. These palafitic buildings were adjusted to humid environment and an unstable landscape of dunes constantly changing by the action of wind [40, 92, 144]. The elevation of the building allowed the sand pushed by the wind to flow beneath, avoiding accumulation of sand on the walls [40, 92, 113, 143, 145]. The designation of *palheiro* is related to the material originally used to roof the building, i.e. straw from a plant found in abundance in coastal sands (estormo –

Ammophila arenaria) [40, 113, 143].

The village was strategically implanted next to a freshwater lagoon and sheltered by the dunes from north and west quadrants (Fig. 5.3). These two natural phenomenon conditioned the urban structure and two main nucleus were formed [143]: i) one in the northern part of the village, implanted at the southeast of a big dune called the "medo grande" and spreading to north, interrupted by the road to Mira; ii) the other, at south of the "medo grande" and spreading south protected by the dunes. The only constructions exposed to the winds coming from the sea and the north were for storing and fishnets repairing and for the living stock [143].

The village of Praia de Mira is an interesting case study since from all the shoreline settlements it was the one where timber construction had its best expression, not only for the dimension of the settlement but also the dimension of the buildings (reaching three storeys high in some cases) [113, 143]. Even Ernesto Veiga de Oliveira and Fernando Galhano [146] used the classification of "Type of Mira" to define the construction technique used in the coastline between Costa Nova and Leirosa. In this type, the plumbs of the structure were built on a frame or a grid of beams, that in turn was on a dense mesh of pillars inserted in the soil (Fig. 5.4).

However, it was also here that this type of construction has seen the fastest decline. In the late 1940's, the approval of the urbanization plan for Praia de Mira, considering that these do not comply with modern requirements of hygiene, prohibited the construction and conservation of timber

FIGURE 5.3. Plan of Palheiros de Mira in 1949 (adapted from [143]).

FIGURE 5.4. Timber dwelling from Praia de Mira (anonymous author).

buildings, which contributed to their systematic and accelerated destruction [143, 147]. The plan also considered the fishing activity as interfering with the touristic activity and the connotation of the constructions with poverty and underdevelopment was clear, which led to the change of the name from “Palheiros de Mira” to “Praia de Mira” [143]. This prohibition contributed to foster the use of industrial materials in the village and to the replacement of timber constructions by conventional constructions of concrete and clay bricks, making this type of traditional construction gradually disappear [40, 143]. This process was probably inevitable, since with the construction of the road to Mira the access to clay tiles replaced thatch [40, 143]. In the end of the 1940’s, the geographer Orlando Ribeiro already mentioned that other types of construction started to break the uniformity of the village [113, 143]. Nowadays, concrete buildings are the rule, invading even the seafront, and there are few existing timber examples and most of them in poor condition, in some cases completely constrained between concrete buildings (Fig. 5.5 and 5.6).

Regarding the land use capability, most of the area surrounding the village is not suitable for agriculture, with some exceptions in the terrains close to the lagoon and to the narrow canal connecting to the Ria de Aveiro estuary (Fig. 5.7a). The condition of unproductive or barren sandy soil that defines the Gândara region is confirmed at geological and type of soils levels. The area is dominated by sand and the soil group of the Regosols. These soils are very weakly developed mineral soils in unconsolidated materials, characterised by a low moisture holding capacity and therefore requiring frequent irrigation [148] (Fig. 5.7bc). The common land use is low volume grazing [148]. Although these adverse features, the need and the persistence of the population were able to convert barren sandy soil in cultivated land through abundant fertilisation [143] (Fig. 5.8). The land chosen to cultivate was the most humid, near the lagoon and the canal, and the fertilisation was

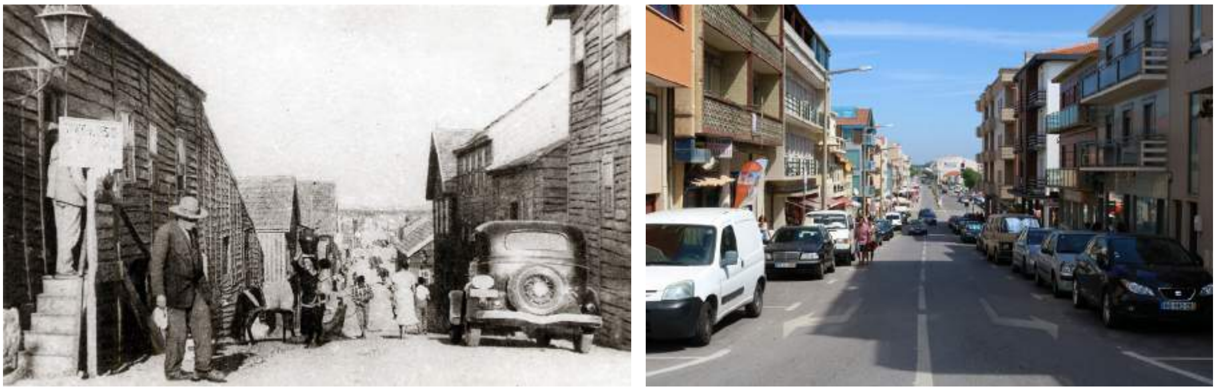


FIGURE 5.5. (left) Main street in the 1950's (anonymous author). (right) Main street in 2016.

FIGURE 5.6. *Palheiros* constrained between taller concrete buildings.

possible by using seaweeds and crabs from the lagoon, and fish waste [143, 149].

Concerning climate context, the central coast region has a temperate climate – Type C, sub-type Csb (temperate with dry or temperate summer), according to Köppen-Geiger Climate Classification (Fig. 5.9a) [110]. The annual average mean temperature is below 15 °C [110]. The average mean temperature in winter is 10 °C, while in summer it is 20 °C (Fig. 5.9b) [110]. Winter is the most demanding season in this area. Summer is mild with an average maximum temperature below 25°C [110] (Fig. 5.9d). In the case of the coast, the influence of the Atlantic Ocean is an important feature affecting local climate parameters, as moderating temperature variation, higher relative humidity values, precipitation and wind speed [121]. Thus, in the case of Praia de Mira, a lower annual thermal variation than in other zones of the country (Fig. 5.9bc), an higher average relative humidity (79%) and higher wind speed and more frequent than in inner areas of the territory are visible [153].

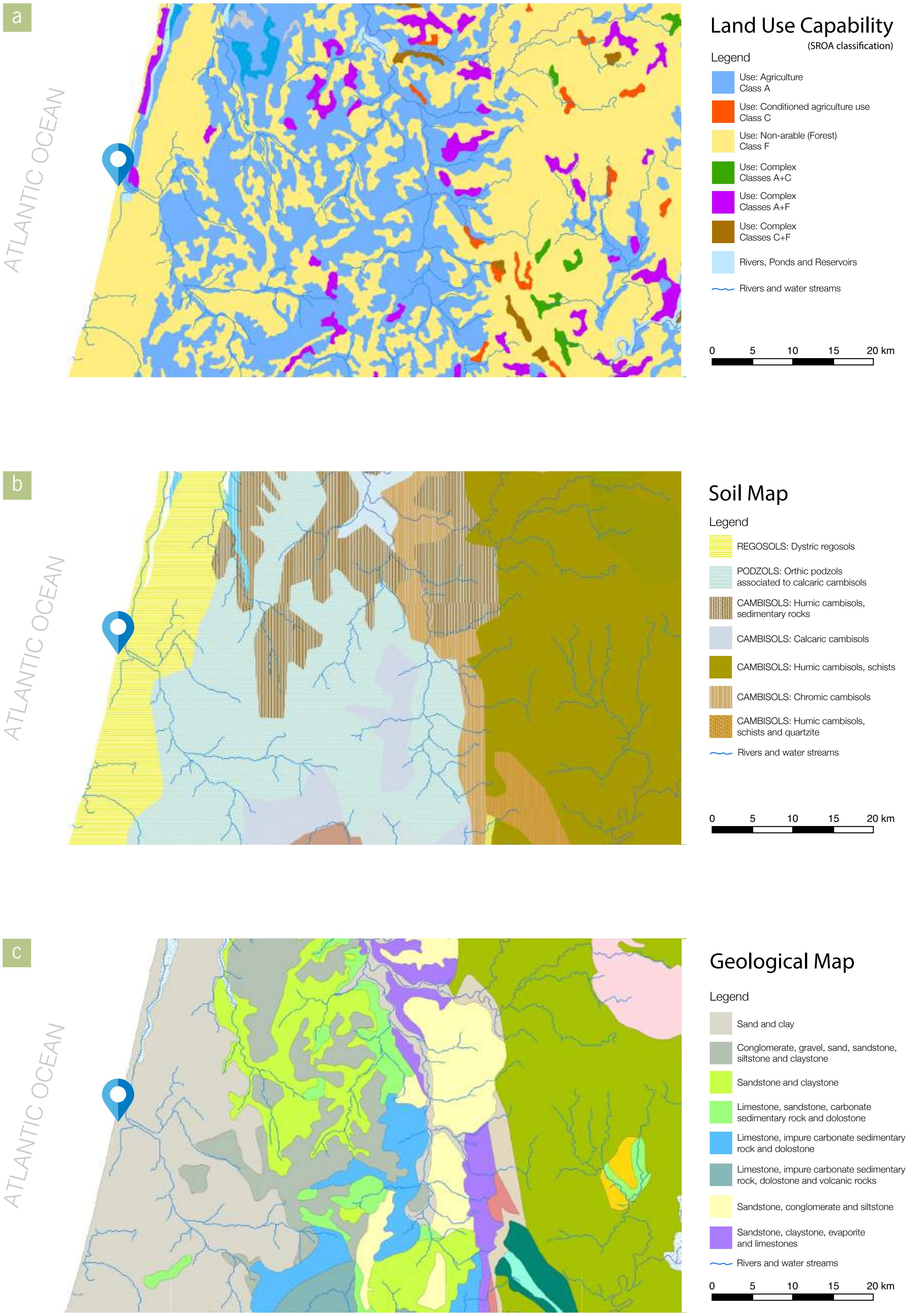


FIGURE 5.7. (a) Land Use Capability Map of Praia de Mira area (adapted from [150]); (b) Soil Map of Praia de Mira area (adapted from [151]); (c) Geological Map of Praia de Mira area (adapted from [152]).

FIGURE 5.8. Agriculture field near Praia de Mira surrounded by trees and bushes for wind protection.

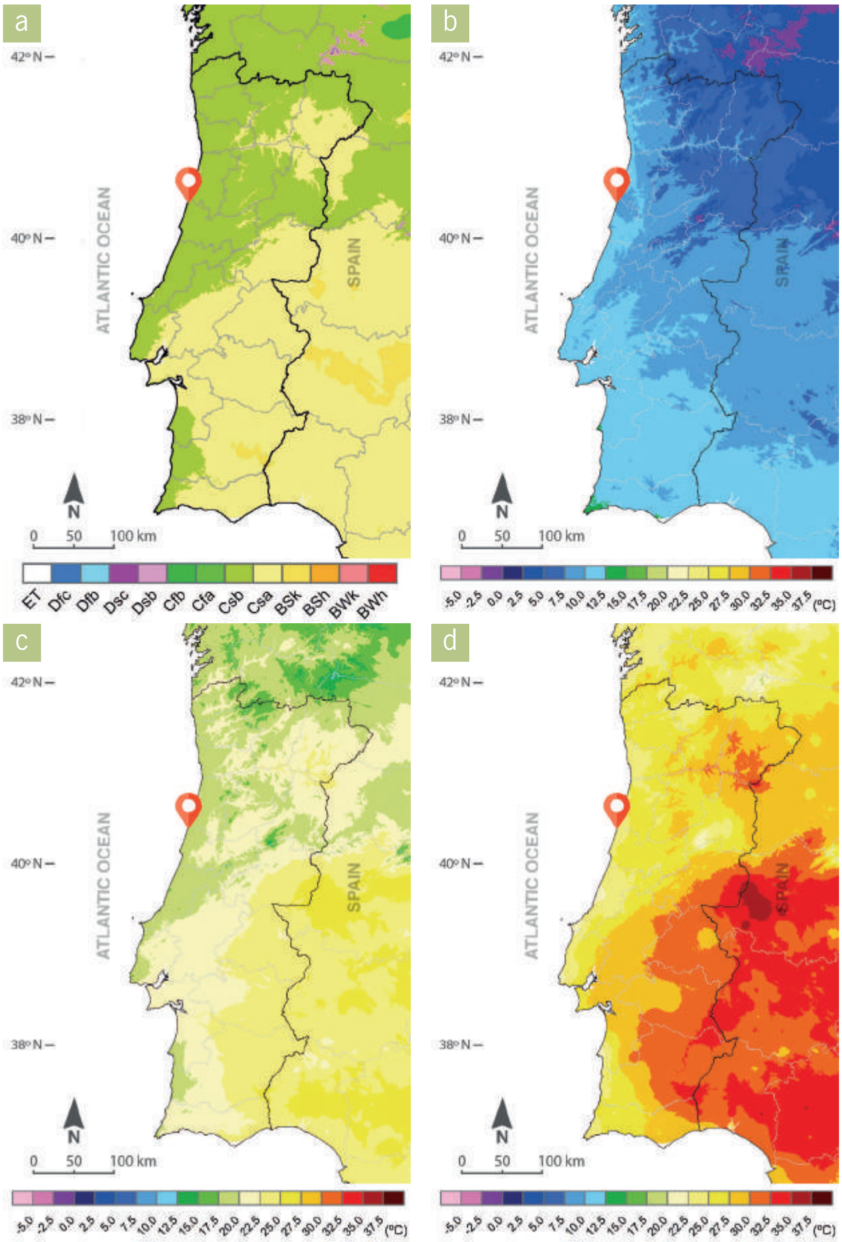


FIGURE 5.9. (a) Köppen-Geiger Climate Classification for Portugal; (b-c) Average mean temperature in winter and summer; (d) Average maximum air temperature in summer (adapted from [110]).

5.1.2 CASE STUDY BUILDING

Nowadays, the number of wooden buildings in Praia de Mira is scarce and just a few are in a good condition. The case study is one of those and is representative of vernacular wooden architecture of Portuguese central coast. The building was built in 1997 to function as the Ethnographic Museum and Tourist Office of Praia de Mira (Fig. 5.10). The building was designed with the purpose of preserving the memory of timber construction in Praia de Mira, but also to show the potential of this type of construction and to alert to the need for its maintenance and conservation, as mentioned in the technical description of the project. In this sense, the building replicates the construction techniques used (palafitic and almost entirely with timber) and the most common internal arrangement of the rooms (with some slight differences).

The case-study is implanted near the lagoon and in an isolated position to emphasise its presence due to its function (Fig. 5.1). It has main and rear façades facing west (street) and east (lagoon), respectively (Fig. 5.10). The gross floor area is approximately 340 m^2 divided into two storeys. On the ground floor, next to the entrance, is the tourist office, and the remaining area is for the exhibition of content related to the daily work of the population in the sea, the lagoon and agriculture (Fig. 5.11 and 5.12), ressembling the activities that normally occupied the ground floor of a dwelling with this size. On this floor, a water closet was added hidden beneath the stairs and only for the staff. This type of space did not exist in the traditional buildings. On the upper floor, the type of dwelling is represented with the kitchen, the dining room and the bedrooms, and an additional room to show how a classroom was in the 1950's (Fig. 5.11 and 5.12).

FIGURE 5.10. External views of the case study. (left) north and west façades; (right) south façade.

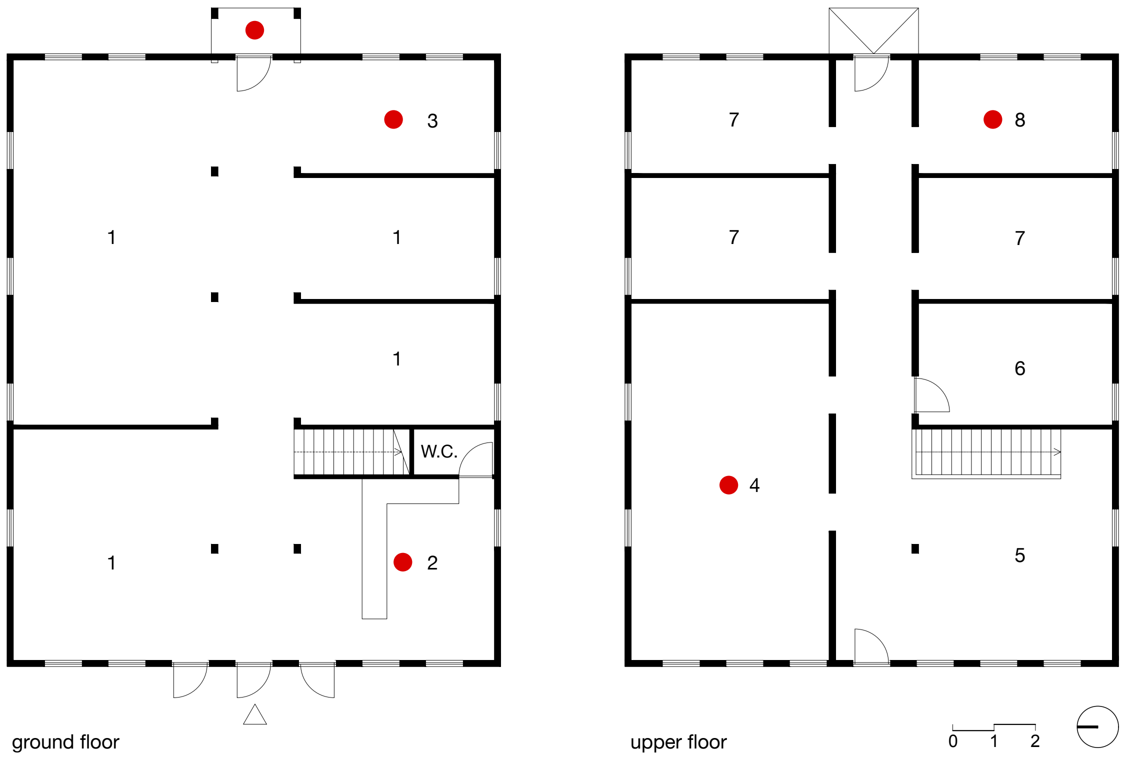


FIGURE 5.11. Floor plans showing the location of measuring instruments (1— Exhibition rooms; 2—Reception; 3— Exhibition room (monitored); 4— “Dining room”; 5— “Kitchen” room; 6—Storage room; 7— “Bedroom”; 8— “School” room).

FIGURE 5.12. (a) Reception view; (b) “Kitchen” view; (c) “Bedroom” view; (d) “Dining” room view; (e) View from under the building of the pillars and pavement; (f) “School” room.

Regarding the construction techniques, as mentioned, the building replicates the techniques that characterised the *palheiros* from Praia de Mira, namely, i) the palafitic foundation to rise the building above the soil/water; ii) built entirely in timber structure; iii) dark coloured wooden siding with planks laid out horizontally, and overlapping (to ensure better protection from the wind, sand and rain [144]); iv) small balconies; and v) white wooden sash windows. Despite the respect for the traditional techniques, measures to improve safety and comfort were implemented, namely the adjustment of the structure to support higher loads, the placement of thermal insulation in walls, floor and ceiling, and improvement of windows to reduce air leaks. The building envelope has the following characteristics (Fig. 5.13):

- Exterior timber structure cavity wall made of overlapping wooden planks (1.5 cm); air gap (7 cm); thermal insulation (3 cm extruded polystyrene - XPS) and indoor timber plank (1.2 cm);
- Pitched roof (2 slopes, 20° angle), roofed with clay tiles, separated from indoor space by a horizontal timber slab made of mineral wool (3 cm), air gap (20 cm) and timber plank (1.2 cm), under ventilated space;
- Ground floor timber slab, over the exterior, made of timber planks (3 cm), thermal insulation (3 cm XPS), air gap (22 cm) and indoor timber floor (3 cm);
- Solid timber doors (4 cm);
- Single glazed timber frame sash windows (without solar protection in the upper floor and with indoor curtains in the ground floor).

Table 3 lists the thermal transmittance coefficient (U-value) of the building envelope. The building has no mechanical system for heating and cooling. The use of portable heating equipment is restricted to the reception area and only during the heating season.

TABLE 3. Characteristics of the building envelope

Envelope element	Materials	U-value (W/(m^2.°C))
External Walls	Insulated timber structure cavity wall with 3cm of extruded polystyrene (XPS)	0.81 [136]
Ceiling (in contact with ventilated roof)	Insulated timber structure cavity ceiling with 3 cm of mineral wool	0.84 [136]
Floor (in contact with outdoor)	Insulated timber structure cavity floor with 3 cm of extruded polystyrene (XPS)	0.61 [136]
Doors	Solid timber	3.0 [136]
Windows (ground floor)	Single glazed timber frame sash windows, indoor translucent curtains	4.3* [136]
Windows (upper floor)	Single glazed timber frame sash windows (no solar protection)	5.1 [136]

*U_{wdn} - day/night heat transfer coefficient, including the contribution of shading systems.

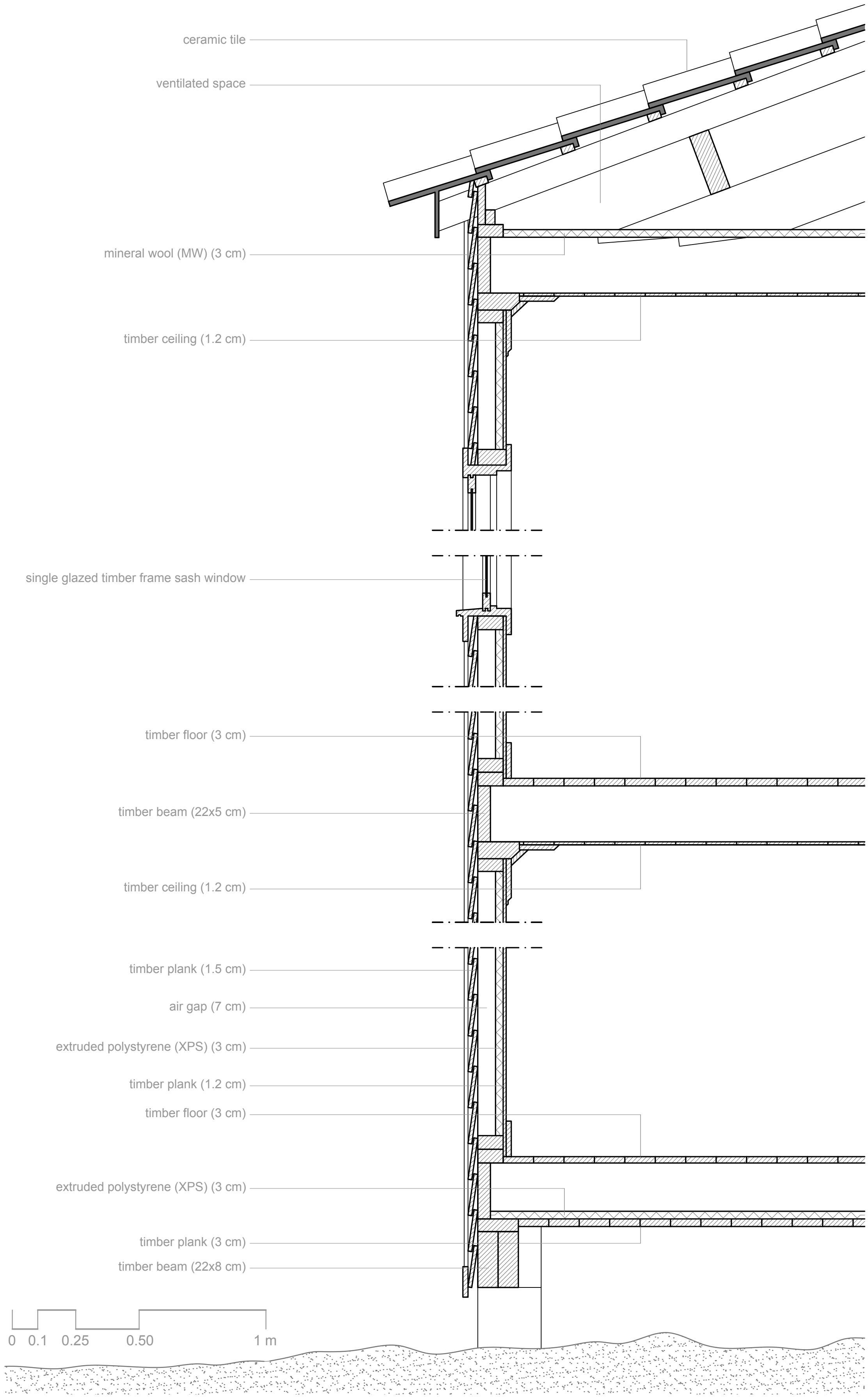


FIGURE 5.13. Detailed section of the building.

5.1.3 SITE-RESPONSIVE STRATEGIES

In the central coast of Portugal, specific local conditions as the absence of stone, the unstable sand landscape and the availability of wood were the main factors that conditioned the type of construction. These conditions determined that timber construction had its best expression in Praia de Mira. Besides, a mild climate characterised by high relative humidity and windy environment also contributed to defining a set of strategies to respond to all these constraints, as the following:

- The material used, i.e. timber, was the most suitable and viable in this context. It is a reflection of several constraints, namely the scarcity of materials as stone and earth (e.g. adobe, rammed earth), but also of the difficulty to build with these materials in areas of alluvium and sand. In the Portuguese context, this type of construction is common to other fishing settlements, and it appears associated with the riverside (e.g. the Avieiros in the Tagus river) and coastal areas [40], [92, 154], confirming the experience and the viability of this specific context. Although the ethnologists Oliveira & Galhano [40] say that this preference is also due to the lower construction cost, the constraints of the site seem to overcome the cost. Whatever the construction date is, timber is the only material that remains in all buildings, from the foundations and structure to the cladding elements [155]. In the case of Praia de Mira, the suitability is demonstrated by the use of a material that was not also available nearby. When the village was formed, the timber used to build the first *palheiros* came from the inner areas of Gândara, between Mira and Cantanhede (≈10-20 km far from Praia de Mira), and not from the pine forests that exist today in the vicinity of the village. These pine forests have their origin at the beginning of the 20th century as a way to contain the advance of sand over arable and productive land [140, 156]. Although the higher distance, when compared with other vernacular materials, the versatility of timber and ease of transport were advantages [155];
- The lightweight of timber construction favoured adaptability to sandy soil and dunes morphology [92]. Due to this feature, the buildings were raised above the ground on peers, which allow the sand dragged by the wind to flow underneath the building, preventing its accumulation on the walls [40, 92, 145] (Fig. 5.14). Moreover, when needed, the building could be lifted higher and the peers pulled or added or even moved to another place [92];
- Regarding the external coating, as a rule, the wooden boards were laid out horizontally, overlapping as scales to ensure better protection from the wind, sand and rain [144]. The structure of the walls, reinforced at the corners by diagonal struts, was characterised by the large number of

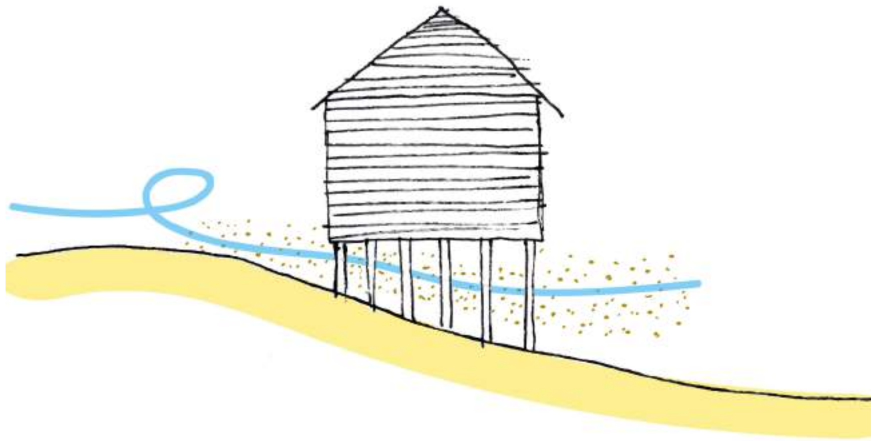


FIGURE 5.14. Wind blowing beneath the palafitic timber building.

plumbs that allowed the boards to be arranged horizontally (in some cases with a rabbet joint) [146]. Although this technique seems more basic and simpler than the system of vertical boards with joint seal (which has fewer infiltrations), it allows better repelling water and sand by gravity;

- The possibility of maintenance and replacement piece-by-piece is an interesting feature of these buildings [34, 36]. Although the timber construction works correctly in relation to the sandy ground and salty sea moisture [92], because it is an organic material its durability is influenced by atmospheric agents and the action of insects and fungi, beyond being susceptible to combustion [155]. It was possible to overcome this apparent weakness with periodic maintenance of the foundations and coating. After construction, the outer coating timber was impregnated with *sil* (sardine oil, produced locally) that together with the sea air, saturated with salt, made it extraordinarily resistant [157]. The *sil* had an unpleasant smell that eventually disappeared and, unlike any other oil used in the preparation of paints (linseed oil was the most common), it did not need a drying agent, although it took a long time to dry [157]. After painting, the operation was usually only repeated after three years [154]. Later, they start to use burned oil from the boat's engines instead of *sil* [143]. In the case of the pillars, to prevent or delay their degradation due to contact with soil's moisture, they were sometimes coated with asphaltic bitumen (named *piche*) [143]. Regarding the replacement of pieces or parts, the fact that the building has several independent parts makes it easy to disassemble and thus to perform individual replacement of the degraded pieces. In the "Type of Mira", the distance between the pillars is higher than that of the plumbs, these could be easily replaced when rotten or when it was necessary to lift the building due to the movement of dunes [155];
- The moisture buffering capacity of timber structures [158, 159] and the relatively low thermal

conductivity of pine wood (0.18 W/(m.°C) [136]) were adequate responses to local climate (sea moisture, moderate temperature and wind speed) and had a positive effect in indoor environment quality;

- The promotion of natural ventilation is particularly relevant in a humid environment. These buildings, as the case study, frequently had windows in opposite façades, which favours cross-ventilation and healthy indoor air quality;
- The urban layout, although not planned, shows an intention of a structured organisation and a purpose of shelter, with the buildings implanted around the lagoon and sheltered from the wind by the dunes, as mentioned before (Fig. 5.3). Moreover, the warehouses for storing fishnets and other fishing tools were implanted facing the sea, which besides being easier to support fishing, would certainly work as a barrier against the wind, protecting the dwellings. The permanent dwellings were implanted in the sheltered slope of the dunes, and most of them with their back facing the sea (Fig. 5.15).

The set of strategies presented reflects people's ingenuity and necessity to adapt to a hostile environment. These timber constructions, built with creative building techniques, low-tech and based on local resources, are an example of ecological buildings. They used local renewable resources, biodegradable, and their impact on the land was almost none since they can be dismantled or moved. Regarding indoor thermal comfort, Brito [143] mentioned that during winter, both timber and concrete buildings were uncomfortable, but that concrete houses had additional moisture problems. To carry out the present work, conversations were held with former timber builders and inhabitants of the *palheiros* that live now in concrete houses. When asked about what type of homes they felt better in, everyone indicated the *palheiros*, mainly due to the warmer touch of timber and also because there was less perceptible relative humidity (the latter with a considerable influence on thermal sensation).

Timber construction has some advantages in the context of sustainability as it is a renewable

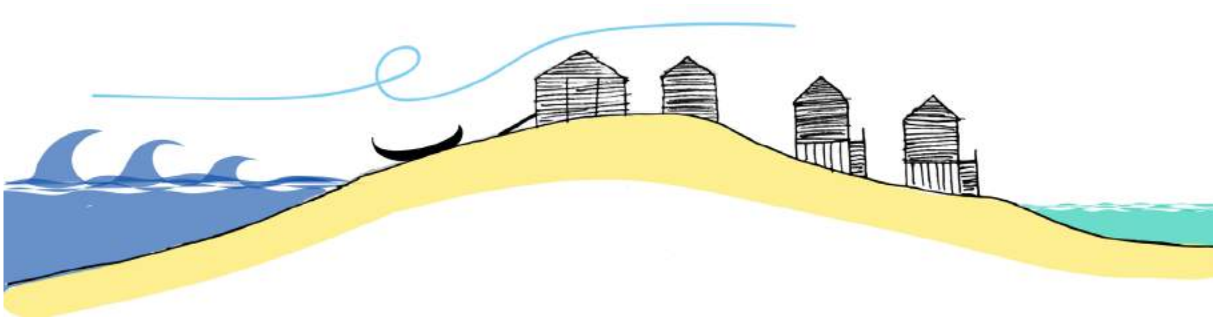


FIGURE 5.15. Warehouses in the seafront protecting the dwellings from the wind.

resource but also because it has a potential for prefabrication, piece-by-piece maintenance [36] and the portability inherent to the lightweight characteristics of this type of construction [155]. However, nowadays, there are only a few examples of this type of construction left in Praia de Mira. Thus, it is relevant to understand whether this type of construction could have potential in this regional and climatic context. In the following sections, the thermal performance of a case study and the effectiveness of this type of construction in mitigating the effects of this specific climate are analysed.

5.1.4 OCCUPANCY AND USE PROFILE

The thermal performance of a building is directly influenced by the actions of its occupants [125]. In this case, since the building houses the tourist office and an ethnographic museum, beyond the permanent workers, the occupancy profile is variable upon the season. Nonetheless, to better understand how the building is used, operation routine/daily habits that influence thermal comfort were recorded by the occupants. Since the building is open to the public, its main entrance is frequently open regardless of the season, affecting ventilation rates and indoor temperature. Due to the proximity to the sea, during autumn and winter, in some days a portable dehumidifier is used to reduce moisture content indoors. During the monitoring, the building was kept in a free-running mode most of the time. The main activities reported by the occupants are synthesised in Table 4.

TABLE 4. Building occupancy and use profile

Season		Use and description
Winter	heating/cooling	Heating (for all season). The pattern is two oil-filled radiators in the reception (9-5 p.m.).
	ventilation	Windows and doors closed. The main entrance door is sporadically opened when visitors enter/exit the building.
	shading	The curtains were usually closed in the ground floor. The upper floor has no curtains.
Spring	heating/cooling	Sporadic use of heating in spring cool days (1 oil-filled radiator).
	ventilation	Main entrance door and reception window open during the day (9 a.m. – 5 p.m.), particularly from May forward (sporadically closed in cool days).
	shading	The curtains were usually closed in the ground floor. The upper floor has no curtains.
Summer	heating/cooling	No cooling system was used.
	ventilation	Main entrance door and reception window open during the day (9 a.m. – 5 p.m.)
	shading	The curtains were usually closed in the ground floor. The upper floor has no curtains.
Autumn	heating/cooling	Heating (more frequent from middle October forward). The pattern is: One oil-filled radiator in the reception (9 a.m.-5 p.m.). Occasionally, two.
	ventilation	Windows and doors closed. The main entrance door is sporadically opened to enter/exit the building.
	shading	The curtains were usually closed in the ground floor. The upper floor has no curtains.

5.1.5 THERMAL MONITORING AND INDOOR COMFORT EVALUATION

The thermal performance monitoring and indoor comfort evaluation were carried out for all seasons. The monitoring data is presented for approximately 30 representative days of each season.

5.1.5.1 WINTER

The Winter monitoring was carried from 21st December 2014 to 19th March 2015. During the representative period analysed (21st January to 21st February 2015), the outdoor mean air temperature was 10 °C (Table 5). The daily maximum and minimum values were very irregular, in which the maximum was often below 15 °C and minimum usually around or below 5 °C, reaching on some days nearly 0 °C (Fig. 5.16a). The daily temperature variation was frequently around 10 °C.

Indoors, the temperature profiles show an irregular daily variation following the outdoor trend (Fig. 5.16a). In the reception, it is possible to see several peaks of the maximum temperature values, in some days considerable higher than in the other rooms, due to heat gains by occupation, office equipment and, mainly, because of the use of heating devices (Oil-filled radiators). Since the reception is not an enclosed room, i.e. it has no doors dividing it from the exhibition rooms, it is difficult to achieve stable temperature values above 18 °C during the day, even with two radiators. In most of the days, the peak temperature is around or below 18 °C, showing a low quality of the thermal environment. The other rooms have similar temperature profiles, in which the "dining" room has the lowest mean and minimum values but at the same time the highest maximum right after the reception. This condition is due to the fact that this room has a higher floor and glazed areas (almost the double), it has façades facing north and west and no sun-protection devices, being at the same time exposed to the coldest part of the en-

TABLE 5. Comparison between outdoor and indoor air temperatures and relative humidity values during Winter.

WINTER					
	Outdoor	Reception	"Dining" room	Exhibition room	"School" room
Temperature (ºC)					
Mean	10.0	14.0	12.4	13.2	13.3
Maximum	17.0	20.7	19.9	18.4	18.8
Minimum	-0.3	6.6	5.5	6.4	6.4
Relative Humidity (%)					
Mean	76.3	62.6	68.5	66.3	66.7
Maximum	94.5	79.0	74.0	77.0	79.0
Minimum	32.9	37.0	54.0	53.0	50.0

velope and receiving direct solar radiation at the end of the day. The other rooms, "school" (upper floor) and the exhibition room (ground floor), have the same orientation (East and South) and a similar thermal behaviour (slighter better than the "dining" room due to a better solar exposure). During the night period, when the building is not occupied, the indoor temperature of all rooms is low (minimum values < 10 °C). Nevertheless, minimum values are considerably higher than the minimum outdoor values.

The low thermal inertia of the building elements, together with single-glazed windows with no external solar protection, are the main reasons to explain the considerable indoor daily thermal variation.

In what relative humidity is concerned, maximum outdoor values were high and frequently around 90% (Fig. 5.16b), with a mean value of 76.3%. Indoors, the relative humidity profiles are similar for all rooms, being relatively stable (with mean values below 70%) and with low daily variation, except for the reception (Fig. 5.16b). The reception, due to heating during opening hours of the museum but also for being in contact with the main entrance, shows a higher daily variation.

Even though it is a museum, the collection does not require special humidity limits. Thus, taking into consideration the design criteria for the humidity in occupied spaces recommended by EN 15251 standard, the values recorded are most of the time within limits for an existing building (Category III – 20-70%),

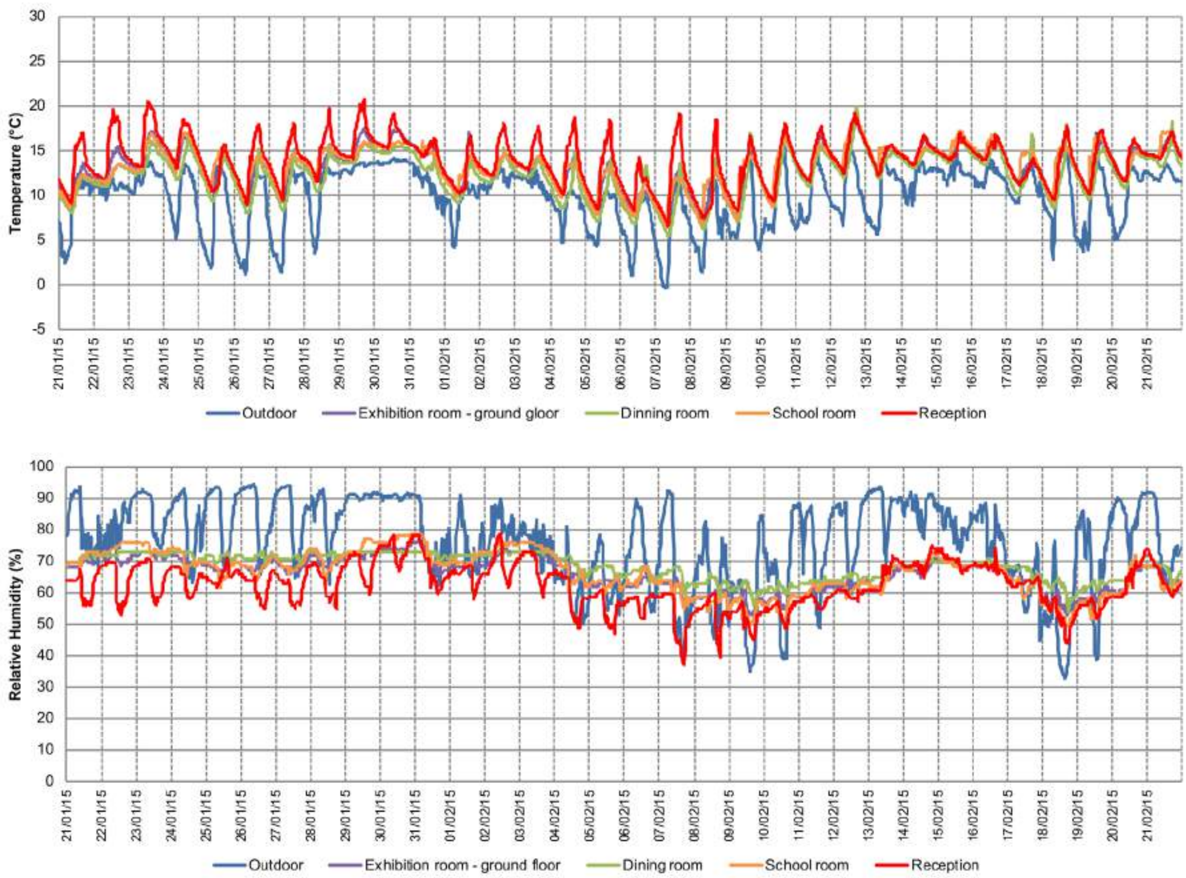


FIGURE 5.16. Winter: (a) indoor and outdoor air temperature profiles; (b) indoor and outdoor relative humidity profiles.

or close, and considerably below the outdoor values.

Concerning thermal comfort, during the measurement, the occupants were using the oil-filled radiators to heat the room. The results showed low thermal comfort conditions in the reception, below the lower limit (Fig. 5.17). In the context of a cold week (ϴrm of 7.6 °C), even when the heating system was on, it was not possible to reach adequate thermal comfort conditions. From the measurements, it was also possible to conclude that the other rooms were also below the thermal comfort limits.

In the survey, one occupant answered as being "cold" (1.2 met; 1.62 clo) and one as being "slightly cool" (1.6 met; 1.19 clo). Although without the same thermal sensation, the two occupants describe a condition of thermal discomfort, therefore confirming the objective measurements. The considerable difference between the two occupants may be justified due to the fact that the occupant who answered has was "cold" has a physiological reason (hyperthyroidism), beyond the different metabolic rate and clothing insulation, which could condition his thermal sensation. This can explain the high level of clothing insulation (including a scarf and a blanket) this occupant had.

From the results for the winter, it is possible to conclude that the building has a low thermal quality, even with thermally insulated elements, and a heating system is required to achieve thermal comfort conditions during the winter season. The use of the two oil-filled radiators is not enough since they do not have the calorific power to rapidly increase air temperature to thermal comfort levels in the reception. Though not an energy-efficient equipment, the occupants use the radiators close to them to minimize the sensation of discomfort. Moreover, the non-continuous use of heating and the lack of thermal inertia of the building elements do not allow the indoor temperature to be more stable and within the comfort limits.

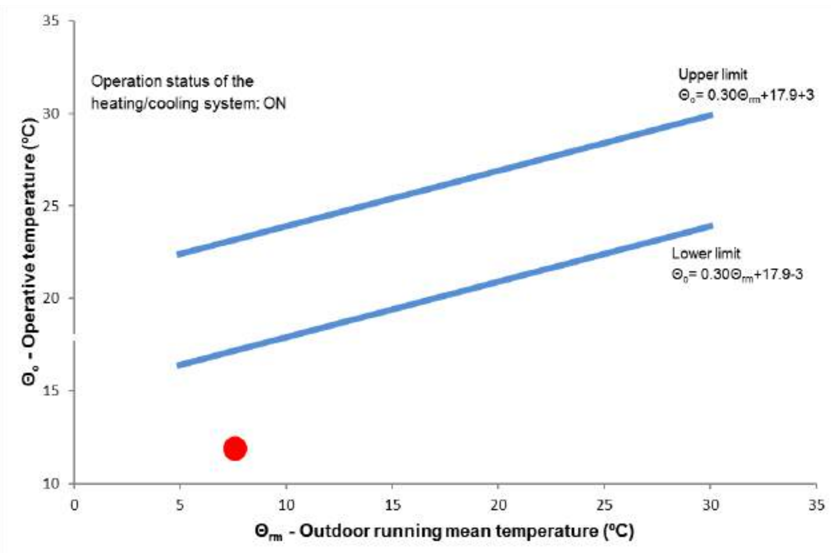


FIGURE 5.17. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the reception during one representative Winter day.

5.1.5.2 SPRING

The Spring monitoring was carried from 21st March to 20th June 2015. During the representative monitoring period analysed (15th April to 16th May 2015), the outdoor mean air temperature was about 15.7 °C, with maximum values often around 18 °C and minimum values frequently above 10 °C (Table 6; Fig. 5.18a).

The indoor air temperature profiles for all rooms are very similar, with a mean temperature around 19 °C and almost the same daily variation (≈ 4 °C) (Fig. 5.18a; Table 6). Indoor temperature variation follows the outdoor temperature curve but with higher minimum and maximum values. From the Spring further, since heating it is no longer used, the reception has a profile similar to the other rooms. During the analysed period, the percentage of time with the temperature above 18 °C in all rooms was between 73-82% and the "dining" room had the lowest value.

Regarding relative humidity, the outdoor day/night variation was high (≈40%), frequently with maximum values around 90% and minimum between 50% and 60% (Fig. 5.18b; Table 6). Indoors, the relative humidity profiles for all rooms are more stable than outdoors, showing almost no daily variation. The mean values are similar for all rooms and around 65%. During the analysed period, the percentage of time with relative humidity values between 20-70% (Category III) in all rooms was higher than 80%, not exceeding by far the upper limit.

The thermal comfort assessment was conducted on two different days, one in mid-April and the other in mid-May. The results show different comfort conditions between the two parts of the monitoring, where in the first part the reception had a thermal comfort condition below the lower limit of the comfort range, and in the second part had a condition in the centre of the comfort range (Fig. 5.19). In the survey carried out in mid-April, two occupants answered as being "neutral" (comfortable) (1.2 and 1.6 met; 1.21

TABLE 6. Comparison between outdoor and indoor air temperatures and relative humidity values during Spring.

SPRING					
	Outdoor	Reception	"Dining" room	Exhibition room	"School" room
Temperature (ºC)					
Mean	15.7	19.1	19.0	19.1	19.6
Maximum	22.6	23.5	23.9	22.3	22.8
Minimum	7.7	14.9	14.4	15.2	14.5
Relative Humidity (%)					
Mean	77.2	64.6	66.2	65.5	65.1
Maximum	92.2	80.0	73.0	75.0	79.0
Minimum	92.2	80.0	73.0	75.0	79.0

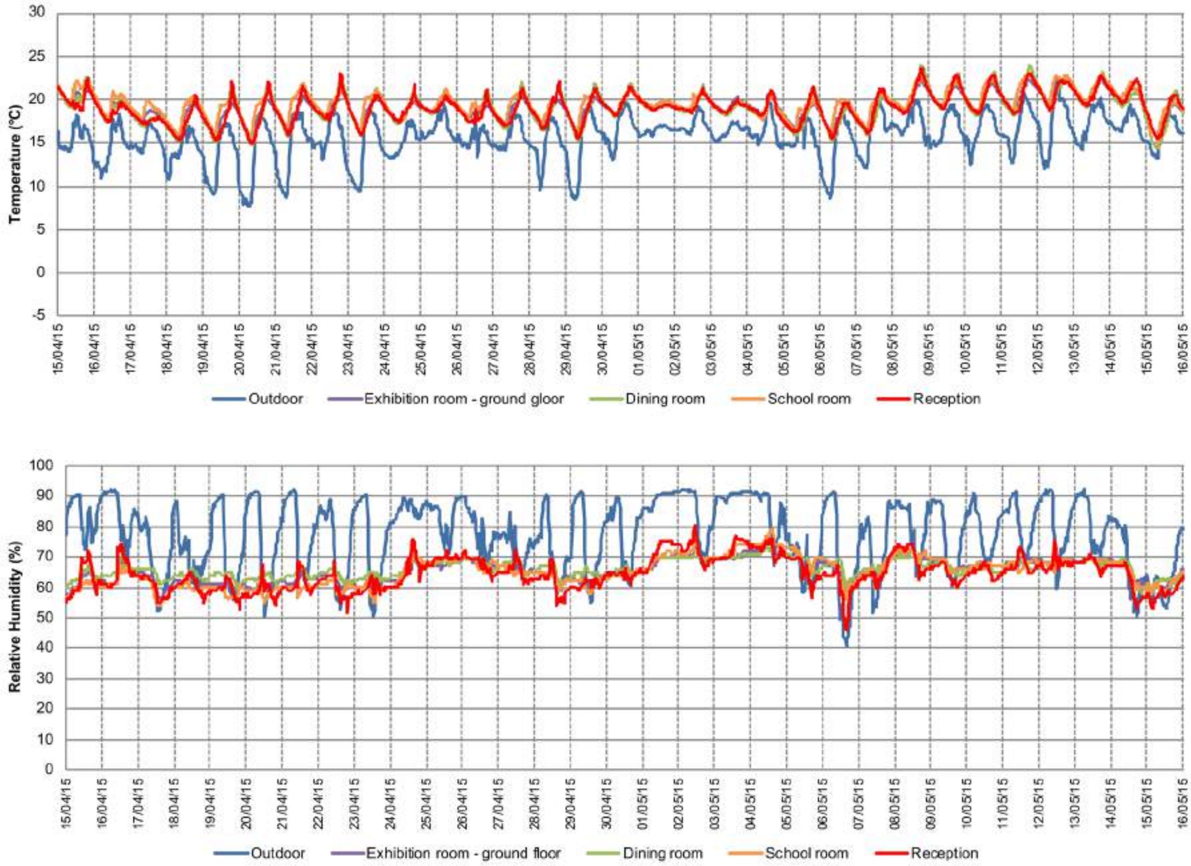


FIGURE 5.18. Spring: (a) indoor and outdoor air temperature profiles; (b) indoor and outdoor relative humidity profiles.

and 0.69 clo, respectively) and one as being "cool" (1.20 met; 1.42 clo). In this measurement, the occupants feeling "neutral" had differences in metabolic rate and clothing insulation, where the occupant with less clothing had the highest metabolic rate, and vice versa. The occupant feeling "cool", as in the winter measurement, had higher clothing insulation and a significantly different thermal sensation. As during winter, the physiological factor influenced the perceived thermal comfort of this occupant. It must also be noted that even with an operative temperature of 18 °C, the thermal condition measured (Fig. 5.19-left) is below the lower limit of the comfort boundaries. It confirms that this limit is not always sufficient to assure a comfort condition and that it also depends on external conditions.

In the other survey (mid-May), three occupants answered as being "neutral" (comfortable) (1.2-1.6 met; 0.43-0.47 clo) and one as being "slightly cool" (1.2 met; 1.04 clo). The adaptive comfort chart (Fig. 5.19-right) showed a good thermal comfort condition in the centre of the comfort range. The results from the subjective evaluation showed occupants' "neutrality", which confirm the results from the objective measurements. As in previous monitoring, the occupant feeling uncomfortable had higher clothing insulation (the double) and a considerable different thermal sensation, confirming the influence of the physiological disorder on the perceived thermal sensation.

In this season, the difference between the two parts of the monitoring was visible in the significantly different thermal conditions, where the increase of the outdoor running mean temperature was less than 2 °C but indoors the operative temperature increased more than 4°C. This difference was due to the increase in the number of hours with incident solar radiation and with more intensity in the month of May.

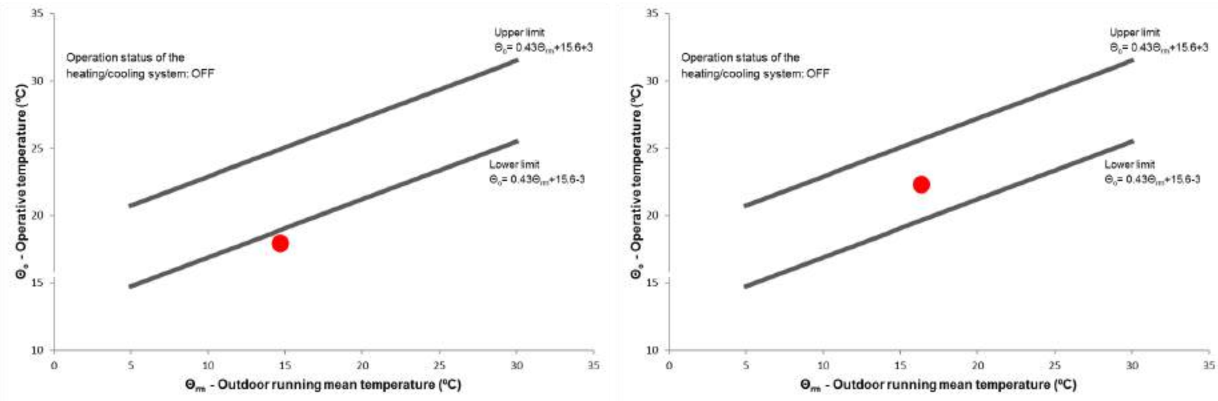


FIGURE 5.19. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the reception during two representative Spring days – (left) mid-April; (right) mid-May.

5.1.5.3 SUMMER

The Summer monitoring was carried from 21st June to 20th September 2015. During the representative monitoring period analysed (15th July to 16th August 2015), the outdoor mean air temperature was about 19 °C, with maximum values often around 22-23 °C and minimum values frequently above 15 °C (Table 7; Fig. 5.20a).

Regarding indoor temperature, as in previous seasons, the mean, maximum and minimum values were very similar for all the monitored rooms (Table 7). The mean temperature was around 23-24 °C, and often there was a daily variation of 4-5 °C (Table 7; Fig. 5.20a). The "school" room had the highest mean temperature, while the "dining" room had the highest and lowest maximum and minimum temperature, respectively (Table 7). The solar exposure of the two rooms influenced these values. The "school" room has façades and windows facing east and south, receiving solar radiation during the morning and part of the afternoon. The "dining" room has façades at north and west, and it is the room with the highest number of windows (two at north and three at the west, ≈ 1 m^2 each window) and highest mean daily temperature variation, having at the same time a façade receiving intense direct solar radiation during all the afternoon and a "cooler" façade with windows that almost does not receive direct solar radiation in this season. The reception had the lowest mean temperature record and an average daily temperature variation (around 4.5 °C) similar to the that of the "dining" room. In the reception, this variation was due to the direct contact with the outdoor environment and ventilation through the always-open entrance door during the opening hours.

During the analysed period, all the rooms were always above 18 °C and below 25 °C for 85-90% of the time.

For the relative humidity, as in previous seasons, outdoor profile had a high outdoor day/night variation (about 20-30%), where the mean was 80% and maximum and minimum values often around 90%

TABLE 7. Comparison between outdoor and indoor air temperatures and relative humidity values during Summer

SUMMER					
	Outdoor	Reception	"Dining" room	Exhibition room	"School" room
Temperature (ºC)					
Mean	19.2	22.9	23.0	23.2	23.6
Maximum	27.3	27.2	27.8	26.6	27.2
Minimum	10.7	18.6	18.2	18.9	18.9
Relative Humidity (%)					
Mean	79.9	65.8	66.0	66.1	65.8
Maximum	92.3	76.0	70.0	71.0	71.0
Minimum	37.1	56.0	60.0	60.0	58.0

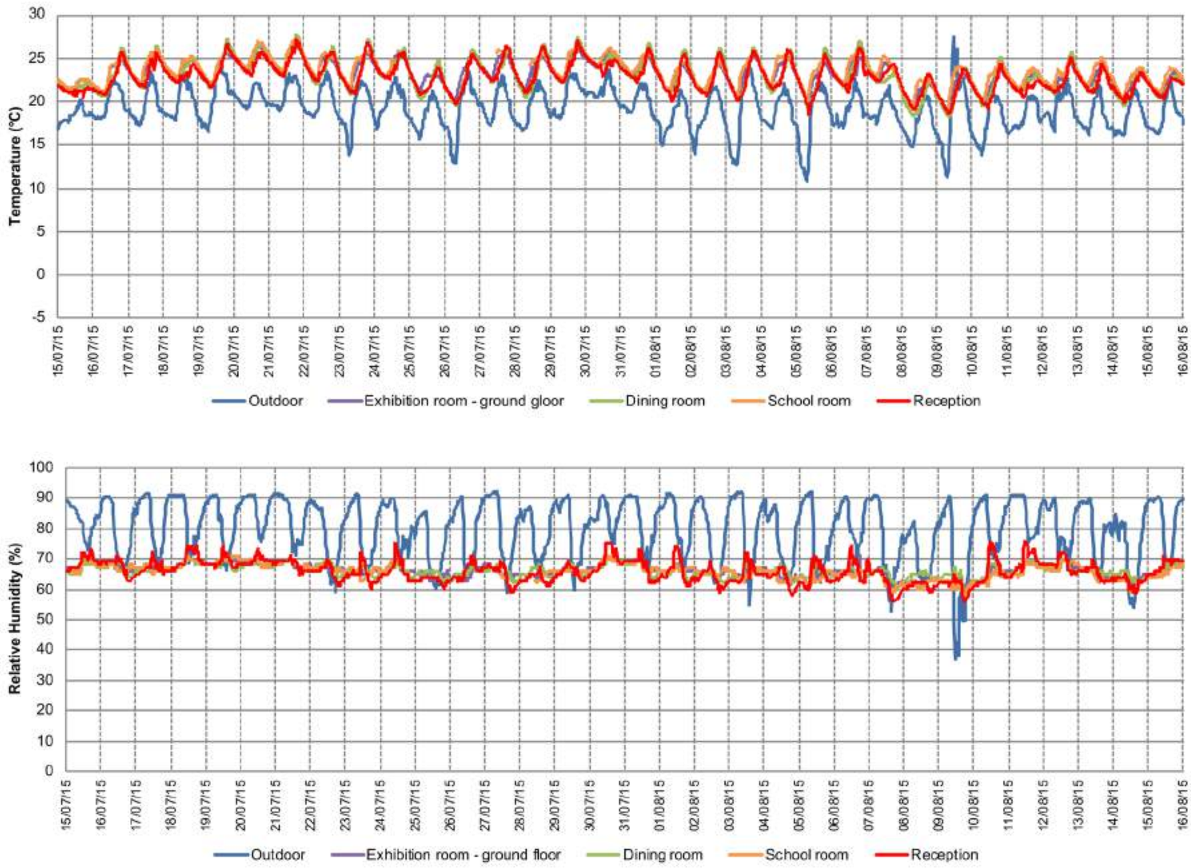


FIGURE 5.20. Summer: (a) indoor and outdoor air temperature profiles; (b) indoor and outdoor relative humidity profiles.

and 70%, respectively (Table 7; Fig. 5.20b). In contrast, indoor rooms had more stable relative humidity profiles, with slight fluctuations and mean values around 66%. In the reception, it is possible to see some fluctuation peaks in the profile that match the opening hours of the museum. Nevertheless, during the analysed period, the percentage of time with relative humidity values between 20-70% (Category III) in all rooms was higher than 85% (in some rooms more than 95%), not exceeding by far the upper limit. It must be highlighted that even without the portable dehumidifier, indoor relative humidity profiles were very stable, within acceptable values, and below outdoor values.

Regarding the thermal comfort assessment, the results for this season show that the reception had a thermal comfort condition in the centre of the comfort range (Fig. 5.21). In the survey, the two occupants answered they were "neutral" (comfortable) (1.2 met; 0.44 and 0.46 clo), and these results confirmed the objective measurement. In this measurement, the occupant who has a physiological disorder was not present, and therefore it was not possible to verify the existence of differences in the thermal sensation.

From the results for this season, it was possible to see that the building showed good comfort conditions without the use of any cooling system. Taking into consideration that the building has a lightweight construction, i.e., with less capacity to regulate the influence of outdoor thermal variations in indoor environment, as shown in Figure 5.20a, the fact of being in a zone with a mild summer climate (often max. ≤25 °C and min. ≥15 °C) allowed the building to have good thermal conditions in a free-running mode. Additionally, the low density of occupants, office equipment and lighting, represented low internal gains and did not affect the thermal environment considerably. Besides, the promotion of natural ventilation, due to the permanent opening of the entrance door, also allows removing thermal loads.

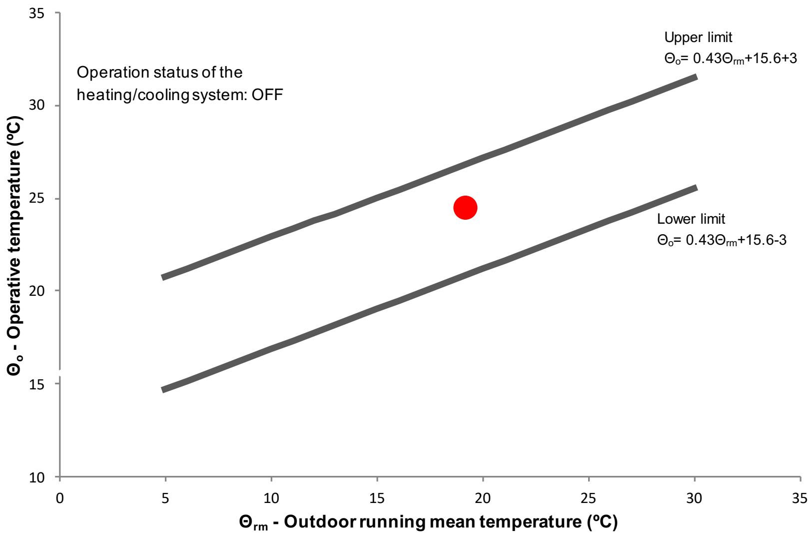


FIGURE 5.21. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the reception during one representative Summer day.

5.1.5.4 AUTUMN

The Autumn monitoring was carried from 21st September to 20th December 2015. During the representative monitoring period analysed (15th October to 16th November 2015), the outdoor mean air temperature was 16.5 °C (Table 8). In this season, maximum and minimum values are very variable throughout the days, but the maximum was often above 20 °C and the minimum frequently between 10 °C and 15 °C (Table 8; Fig. 5.22a). The difference between the first and the second parts of the analysed period is visible, with maximum and minimum temperature values decreasing in the second half.

As in previous seasons, indoor temperature profiles were very similar for all the monitored rooms (Table 8; Fig. 5.22a). Indoor temperature fluctuation followed the outdoor trend, being the maximum daily values close to outdoor, while the minimum daily values were always higher (around 6 °C) (Fig. 5.22a). The difference between the first and the second parts of the analysed period is visible, with maximum and minimum temperature values decreasing in the second half, both indoors and outdoors. The mean indoor temperature was between 18.8-19.7 °C (Table 8). During the analysed period, all rooms were always below 25 °C and above 18 °C for 70-81% of the time.

Regarding relative humidity, the outdoor day/night variation was more regular during the second part of the analysed period (≈20%), frequently with maximum values around 90% and minimum between 60% and 70% (Fig. 5.22b; Table 8). Indoors, the relative humidity profiles for all rooms are more stable than outdoors showing slight daily variations. In the first half of the monitoring, a sudden decrease in indoor values is visible, following the decrease during two days in outdoor relative humidity. After this event, outdoor relative humidity went back to typical values but indoors it took almost five days to increase to previous values around 70%. The mean values are similar for all rooms and around 70% (Table 8). In the case of the reception, some higher peaks are visible, which coincide with the opening

TABLE 8. Comparison between outdoor and indoor air temperatures and relative humidity values during Autumn

AUTUMN					
	Outdoor	Reception	“Dining” room	Exhibition room	“School” room
Temperature (ºC)					
Mean	16.5	19.3	18.8	19.3	19.7
Maximum	25.8	24.4	25.4	24.3	25.6
Minimum	8.5	14.8	14.3	15.0	14.9
Relative Humidity (%)					
Mean	80.3	69.0	68.3	68.2	69.1
Maximum	93.3	80.0	72.0	76.0	81.0
Minimum	34.1	50.0	57.0	53.0	51.0

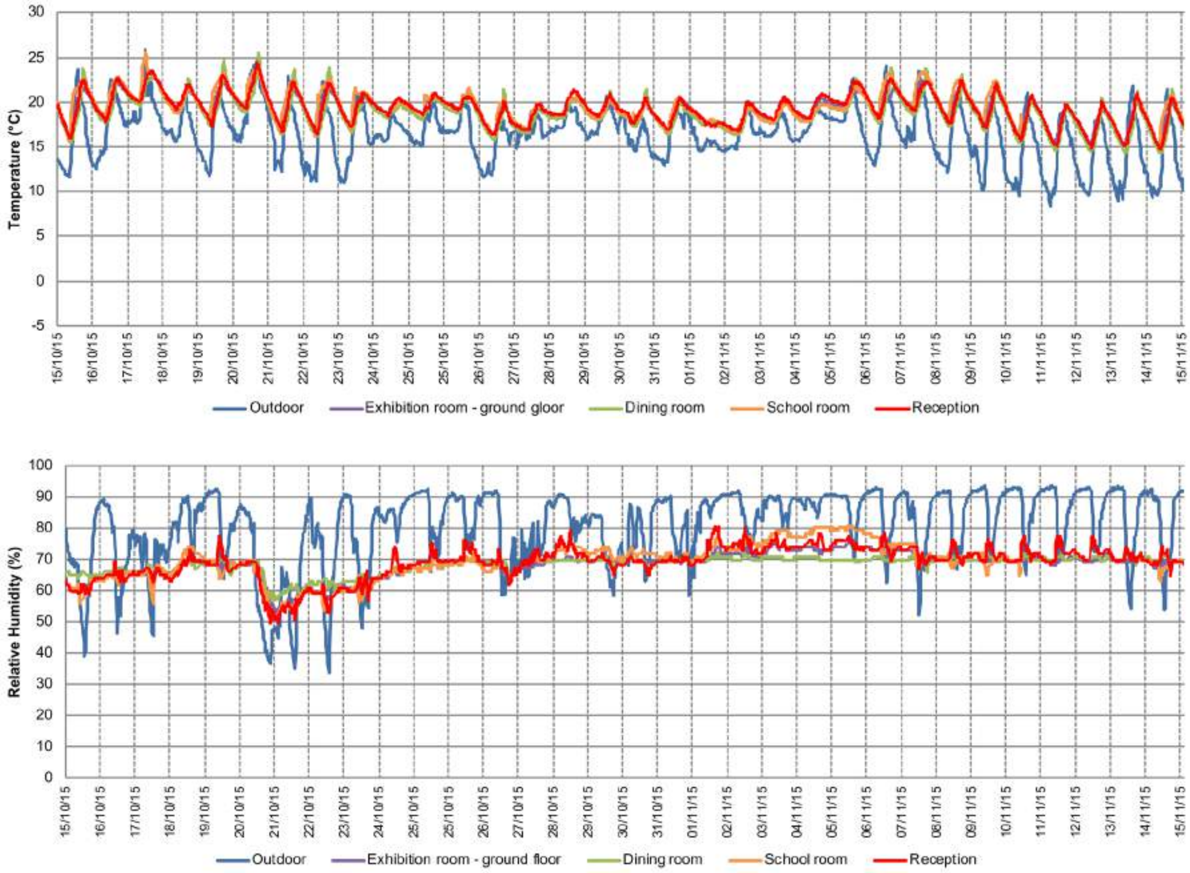


FIGURE 5.22. Autumun: (a) indoor and outdoor air temperature profiles; (b) indoor and outdoor relative humidity profiles.

period of the museum. During the analysed period, although the percentage of time with relative humidity values between 20-70% (Category III) in all rooms was around 50-60%, the upper limit was not exceeded by far. Nevertheless, it has to be highlighted the relative stability of indoor moisture, due to the capacity of timber structures to regulate the moisture (i.e. ability to absorb and release humidity) [1, 158].

In the thermal comfort assessment, the results for Autumn show that the reception had a thermal comfort condition below, but close to, the lower limit of the comfort range (Fig. 5.23). In the survey, the two occupants answered they were "neutral" (comfortable) (1.2-1.6 met; 0.86 and 0.69 clo, respectively). Although the survey results do not confirm the objective measurement, the thermal condition point is close to the limit. The inversely proportional relationship between the metabolic rate and the clothing insulation of the two occupants has influenced their thermal sensation, showing the adaptation of the two to satisfy their comfort needs. A decrease of one of these variables could have been sufficient to change their answers. In this measurement, the occupant who has a physiological disorder was not present. Additionally, as in Spring, it must be also noted that even with an operative temperature of 19.6 °C, the thermal condition measured (Fig. 5.23) was below the lower limit of the comfort boundaries. This condition shows that the design value of 18 °C for heating (Category III) is a minimum and that it is not always sufficient to assure a comfort condition, being dependent on external conditions.

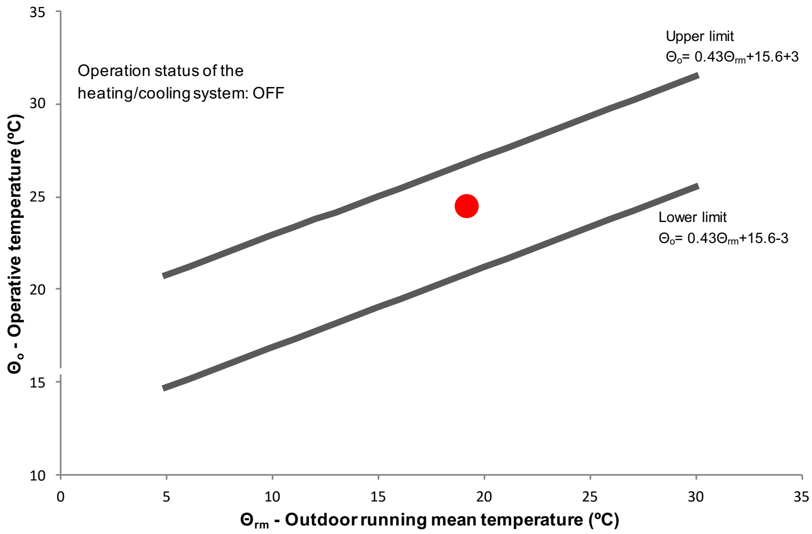


FIGURE 5.23. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the reception during one representative Autumn day.

5.1.6 INDOOR AIR QUALITY MONITORING

In buildings where occupants are the main source of pollution, as in this case study, air quality can be evaluated by measuring the carbon dioxide concentration [130]. Although it is a non-residential building (museum), it has a low occupation density, and it was not possible to carry the measurements when it was fully occupied, as recommended by standard EN 15251 [130]. The carbon dioxide (CO_2) concentration in the case study was evaluated and classified according to the categories defined by EN 15251 [130]. The carbon dioxide concentrations were measured in different occupied rooms during a representative day of each season.

From the measurements, it was verified that the differences between outdoor and indoor carbon dioxide concentrations were very small and can be due to the low occupation density of the building and to the natural ventilation and infiltration rate. In the case of the winter monitoring, when it was expected to have higher values indoors because the main entrance door is much of the time closed, the results showed better values indoors than outdoors. However, the differences are small and can be due to punctual higher outdoor pollution from traffic or a restaurant nearby. Nevertheless, the results show that CO_2 concentration levels were within the design values for Category I (high level of expectation and the most demanding category) (Table 9) for all seasons.

TABLE 9. Classification of the indoor air quality in representative rooms for all seasons

CARBON DIOXIDE (CO_2) CONCENTRATION					
Season	Place/room	Concentration (ppm)	Difference above outdoor	Category	Pressure (hPa)
Winter	Outdoor	470			1027
	Reception	466	-4	I	
	Exhibition room	455	-15	I	
	"Dining" room	448	-22	I	
	"School" room	450	-20	I	
Spring	Outdoor	378			1030
	Reception	402	24	I	
	Exhibition room	420	42	I	
	"Dining" room	402	24	I	
	"School" room	402	24	I	
Summer	Outdoor	365			1025
	Reception	392	27	I	
	Exhibition room	420	55	I	
	"Dining" room	419	54	I	
	"School" room	420	55	I	
Autumn	Outdoor	417			1012
	Reception	445	28	I	
	Exhibition room	445	28	I	
	"Dining" room	446	29	I	
	"School" room	435	18	I	

5.1.7 CONCLUDING REMARKS

In what thermal-hygroscopic performance is concerned, the case study presented showed interesting results. Regarding thermal behaviour, although the building does not have a high thermal inertia to stabilise indoor temperature variation, the mild local climate favoured the thermal performance of the case study and it had satisfactory comfort conditions during almost all year without using a heating/cooling system. During all seasons, minimum values for indoor temperature were always above the ones recorded outdoors. However, in winter, comfort conditions were poor. The lack of an efficient heating system, the low thermal inertia and the fact that it is a public building, in which the entrance door is frequently opened, increasing heat losses by convection, are some of the reasons to explain the poor thermal performance during the winter. Although the case study building has already an improved timber structure (when compared with traditional buildings), its thermal performance could be improved by using adequate thermal insulation thicknesses, double glazing windows, increase air tightness/reduce air leaks (e.g. implementing a buffer zone at the entrance).

Concerning relative humidity (RH), taking into consideration that high values of humidity characterise local climate during all year, it must be highlighted that the case study has indoor RH values more stable and considerably lower than outdoors, even during winter. This behaviour is due to the hygroscopic properties of timber. Timber structures are very hygroscopic, and thus they have the ability to exchange water vapour with the surrounding air continually, i.e. gaining and losing moisture until reaching an equilibrium point (equilibrium moisture content – EMC) [158, 159]. The EMC is influenced by relative humidity and temperature, and any change in these parameters forces the material to adjust to a new equilibrium point [159]. In the study of Silva *et al.* [158], from the three softwood species analysed, Maritime Pine (Pinus Pinaster) had the highest EMC (12.8%) and also the lowest ability to shrink and swell. Taking into consideration the most frequent indoor conditions recorded in the case study (during all seasons), and using the values for the dependence of the EMC of wood on temperature and relative humidity, estimated by the U.S. Forest Products Laboratory [160], for an indoor range of 10-25 °C and 60-70% the EMC values are within 11-13.4%. Thus, the type of wood is adequate for local environmental conditions. This moisture buffering quality has a positive effect on indoor environment quality since it improves health, comfort and reduces problems and degradation caused by excessive humidity as moulds and fungi [1, 159, 161]. This passive feature of timber structures is an advantage in this type of climate since they can tolerate and regulate moisture more than other materials. For example, concrete structures take more than twice as long to dry out as it does a timber wall [1], and light-weight timber structures reveal to have constant and stable moisture fluctuations during different seasons [162]. Moreover, moisture buffering has the benefits to improve the perceived acceptability of indoor air, and of saving energy by reducing the requirement for mechanical ventilation (when needed to control indoor humidity) [163].

Therefore, the thermal-hygroscopic performance of the case study shows that timber construction, if correctly designed, has a great potential for the coastline environment, i.e. for the specific climate and landscape. Regarding the latter, in a context in which the susceptibility and potential impacts of coastal erosion and flooding due to sea level rise are known [164], this type of construction would be better suited to respond to coastal landscape morphodynamics, with fewer impact, using local materials and with the possibility of being moved or disassembled and relocated. Studies on coastal vulnerability and flooding assessment due to sea level rise [164, 165] have concluded that it is evident that inland waters will be the most affected areas, as the Ria de Aveiro estuary (in which an arm connects to the Praia de Mira lagoon). These studies evaluated the risk for 2025, 2050 and 2100 with different sea-level scenarios and different extreme event return periods (Fig. 5.24), and in all, there is a large area with an increasing probability of flood. However, the authors mention that the present scenarios for the coast shoreline (with wave setup) are underestimated since the digital terrain model of the actual coastal morphology does not represent the expected future erosion effect and coastline retrieving [164]. As mentioned by the authors, the Ria de Aveiro estuary will be one of the most affected areas, corresponding also to an area with a high level of exposure of people and buildings [164, 165]. In Figure 5.24, it is possible to see that the area of Praia de Mira is not an exception, showing high risk in some parts as early as in 2025 and increasing considerably in the scenarios for 2050 and 2100.

The vulnerability and the risk of coastal areas represent considerable potential negative social and economic impacts [165]. Therefore, the implementation of timely adaptation measures is needed to minimise the effects and the exponential costs associated, since the time required to study, design and implement these measures will be considerable. The resettlement of populations from some areas of the Portuguese coast is one of the measures expected. In this sense, this type of palafitic timber construction would have allowed for a simpler (and probably cheaper) process of disassemble > transfer of place > reassemble and with less impact than the demolition of concrete structure buildings, that were built on the coastline in the last 70 years.

Beyond these site-specific advantages, there are also other general advantages of timber construction, like the ones regarding environmental impacts. The advantages of timber construction nowadays, which were already visible in the vernacular examples, lies in the fact that it is a renewable, biodegradable and reusable/recyclable resource fitting into a "cradle to cradle" life cycle approach, that requires low processing to be used in construction and that allows prefabrication - which contributes to optimising manufacture and construction processes and thus to reducing construction waste. Depending on the construction method, it can be considered that it also allows for economical and more efficient maintenance with the possibility of replacing part-by-part. However, the raw material must come from local sources, in order not to hinder its environmental performance due to transportation.

Due to the advantages mentioned above, timber construction should be promoted, especially for the sites and climates where it is adequate. In contrast to what happened in the middle of the last century in Praia de Mira, with the depreciation and prohibition of the conservation of timber buildings, today this type of construction should be encouraged. It has the features to contribute to achieving sustainable/regenerative buildings, and it can contribute to the sustainable management of the national forest. The measures to promote timber construction and consequently sustainable management of the Portuguese forest, in addition to the environmental benefits, can contribute to the decentralisation of economies and the redistribution of wealth, namely by creating jobs in the various areas related to these.

The *palheiro*s of Praia de Mira are an example of the interaction between the construction and the site. Still, it is necessary not to forget that they were developed to suit the specific conditions of a territory and a way of life that have changed over time. Therefore, nowadays, the step forward should not mimic this type of construction but to interpret it and, if possible, sustainably and coherently improve it.

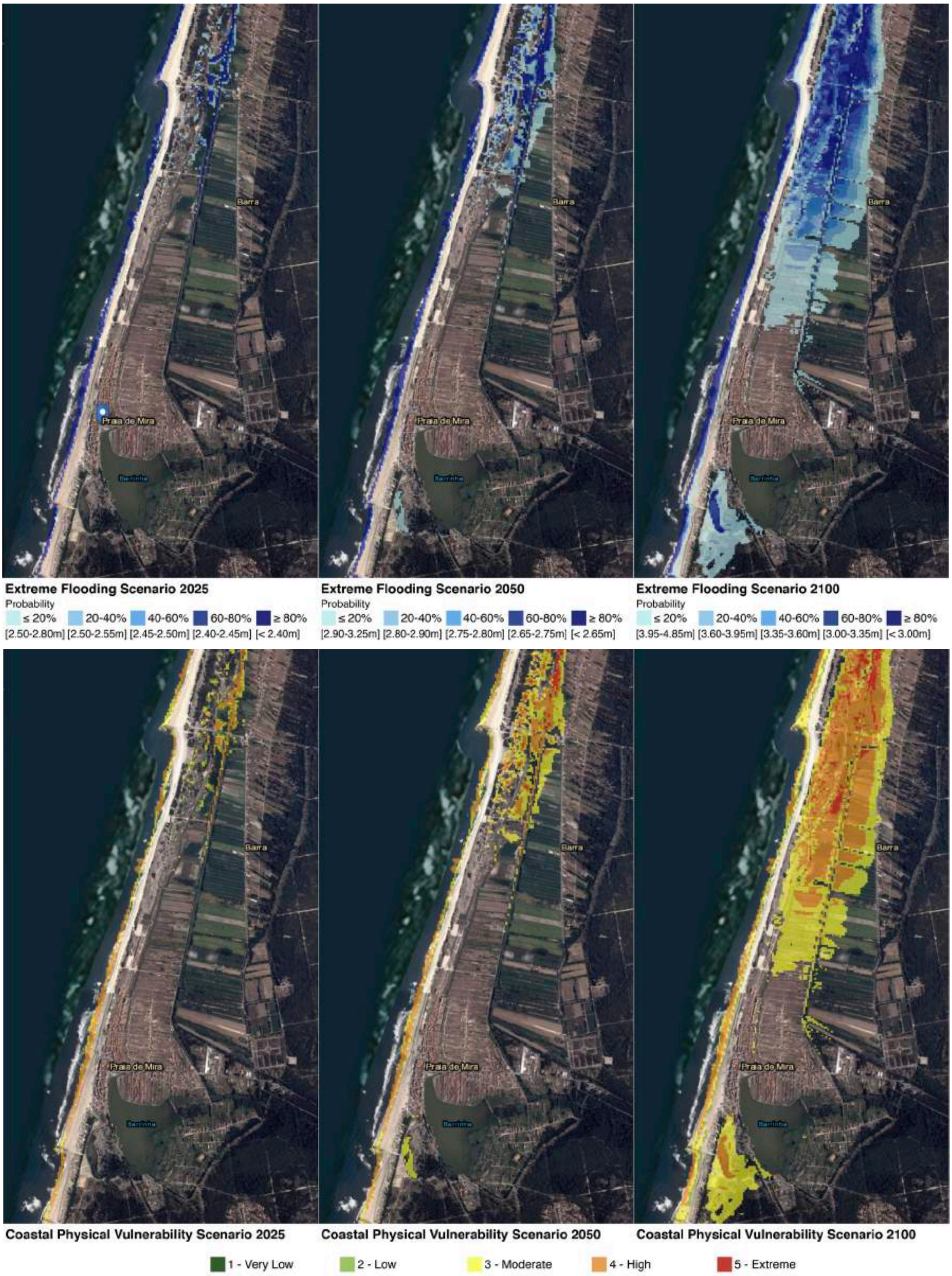


FIGURE 5.24. (above) Extreme Coastal Flood Scenarios due to the rise of sea level; (below) Coastal Physical Vulnerability Mapping of Extreme Coastal Flood Scenarios relative the rise of Mean Seal Level; for 2025 (baseline scenario), 2050 and 2100, in accordance with the requirements of Directive 2007/60/wEC (adapted from [166]).

5.2 CASE STUDY 2 – GRANJA DO TEDO

5.2.1 SITE AND CLIMATE CONTEXTS

The case study is located in the old village of Granja do Tedo, in the municipality of Tabuaço, district of Viseu, Northern Portugal (Fig. 5.25). The Granja do Tedo territory has an ancient history, with a rich medieval past and some archaeological remains dating back to the Romans (as the bridge over the river Tedo) [167]. The village's name has its origin in D. Thedon, a knight that conquered this territory from the Moors in the 11th century and decided to settle there a farm and his home. For this reason, the place was named literally as D. Thedon's Farm (Granja do Thedon and after Granja do Tedo) [168]. The village is strategically implanted in the lower part of a valley, next to the confluence between the river Tedo (that flows to the river Douro) and of two other streams. It is divided by the river in the lower and upper parts (Fig. 5.26). The implantation favours a good solar exposure to the south (particularly in the upper part of the village located on a south-facing slope), and the surrounding mountains offer protection against the wind (Fig. 5.27). The implantation in the valley also provides a more favourable microclimate, warmer than the one of the higher areas of the territory. The village is surrounded of areas of conditioned agriculture use and forest (Fig. 5.28a). Nevertheless, the area is dominated by the soil group of the Cambisols, i.e. soils that make good agricultural land, characterised by the absence of a layer of illuviated clay, organic matter, aluminium and/or iron compounds but with high content of weatherable minerals (favourable for plants) [148]. The Dystric Cambisols, though less fertile, are suitable for arable farming and as grazing land [148] (Fig. 5.28b). At geological level, the area is dominated by granitoids of different types and ages (Fig. 5.28c), confirming the abundancy of this resource and its use in the village as the primary building material.

The village has a compact urban layout with narrow and winding streets, and most of the built area is implanted on a rocky massif (Fig. 5.25 and 5.26), sparing the fertile agriculture land near the watercourses (Fig. 5.27). These features are common in mountain settlements. Also common was the communitarian sense of living, expressed in constructions as the community oven, threshing floor and mills (olive oil, wine and cereals).

The village is mostly composed of two, and three-storey buildings, where the ground floor is commonly used to store goods and/or livestock, and the upper floors are for human occupancy. The wooden balconies (open or glazed) is a frequent feature in the buildings of the village. Due to the sun exposure, these were spaces used to dry grains and fruits and also for sewing. Additionally, like other constructions in regions with cold winters, buildings have very few and small openings to avoid heat losses. The compact layout and form

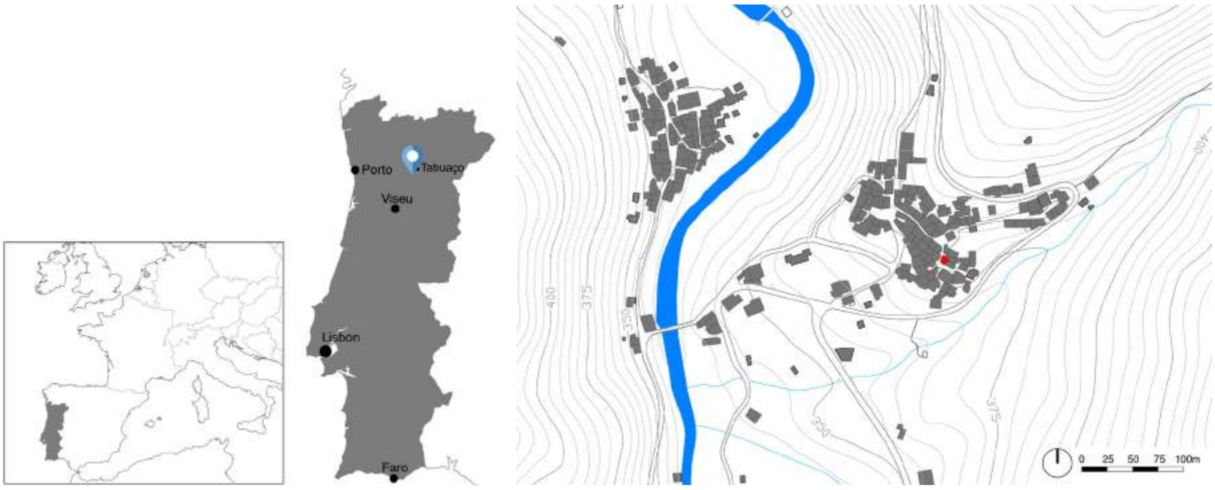


FIGURE 5.25. Case study's location. (left) country context; (right) Case study position in Granja do Tedo's current urban layout.

FIGURE 5.26. Granja do Tedo. (left) Upper part, seen from West; (right) Lower part, seen from East.

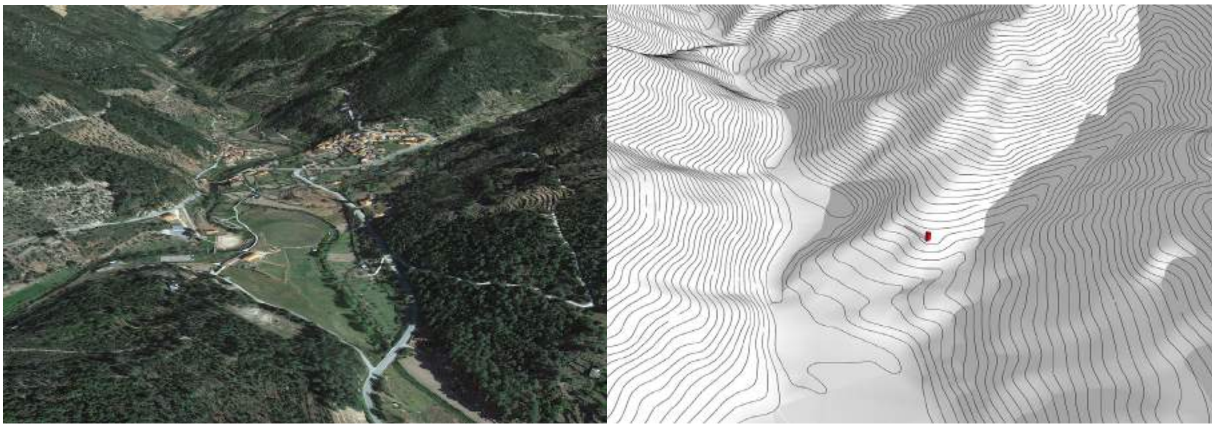


FIGURE 5.27. Granja do Tedo's context. (left) Aerial view with terrain relief (Google Earth); (right) Tridimensional model of the terrain showing the solar exposure at 9:30am on the winter solstice (case study location marked in red).

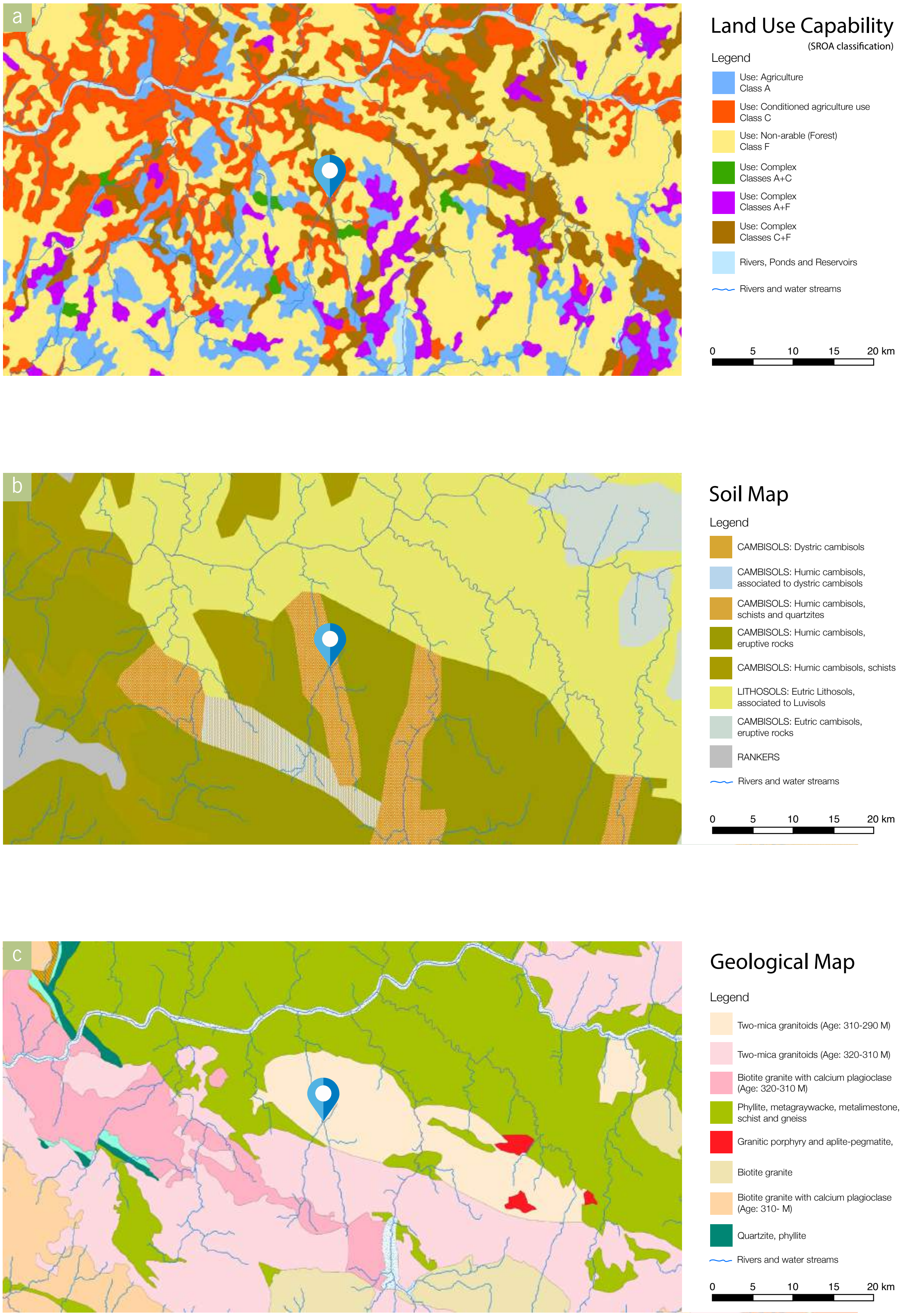


FIGURE 5.28. (a) Land Use Capability Map of Granja do Tedo area (adapted from [150]); (b) Soil Map of Granja do Tedo area (adapted from [151]); (c) Geological Map of Granja do Tedo area (adapted from [152]).

also allow for reducing heat losses through the building envelope.

The Douro Valley region has a temperate climate – Type C, according to Köppen-Geiger Climate Classification, co-existing the sub-types Csa (temperate with hot and dry summer) and Csb (temperate with dry or temperate summer) (Fig. 5.29a) [169]. Granja do Tedo is located in a narrow valley connected to the river Douro valley, and in the transition between the two climate subtypes [169] – the Csa in the valley and the Csb in the higher altitude areas. The annual average mean temperature is 17.5 °C. The average mean temperature in winter is 10.0 °C, while in the summer it is between 22.5 and 25.0 °C (Fig. 5.29b-c) [169]. Winter is the harshest season in this area. Excluding the valley, the mean temperature in winter is 7.5°C. The average maximum air temperature in winter varies between 12.5 °C and 15.0 °C, while the average minimum air temperature is 5.0 °C [169]. In winter there are 10 to 20 days with a minimum temperature below or equal to 0 °C (Fig. 5.29d), whereas the surrounding area has around 40 days [169].

5.2.2 CASE STUDY BUILDING

The selected case study is a representative glazed-balcony building of Northern Portugal vernacular architecture [92], presenting a set of strategies to promote heat gains and reduce heat losses. The construction date is unknown, but considering the ages of neighbour buildings, and according to the owners, the case study is probably from the 18^{th} century.

The building is a semi-detached single-family house, integrated into the urban mesh (Fig. 5.30). It has an irregular floor plan and the main façade with the balcony is facing southwest, while the others are facing northeast, southeast and west (Fig. 5.31). As other constructions in regions with cold winters, and apart from the balcony that has the purpose of harvesting solar gains, the building has only two windows to avoid heat losses (one to the west, facing the street, a small one facing southeast and none at the north quadrant). Also common in this type of climate is to have the ground floor of the dwelling to store goods and cattle (taking advantage of animal's body heat), while the upper floor, with better solar exposure, was for human occupancy. The gross floor area is of approximately 50 m^2 divided into two floors.

The building was renovated in 2005. During this intervention, some changes were introduced in the layout and use of some rooms. Some improvements were also implemented, such as the installation of a bathroom, renovation of windows and doors, the ground floor was paved, renovation of the timber balcony structure and fitting thermal insulation to the ceiling. In the renovation, the ground floor was converted into a kitchen and living room (Fig. 5.32a), and the upper floor layout was reorganised to accommodate two bedrooms and a bathroom (Fig. 5.32b). In this modification of the floorplan, the par-

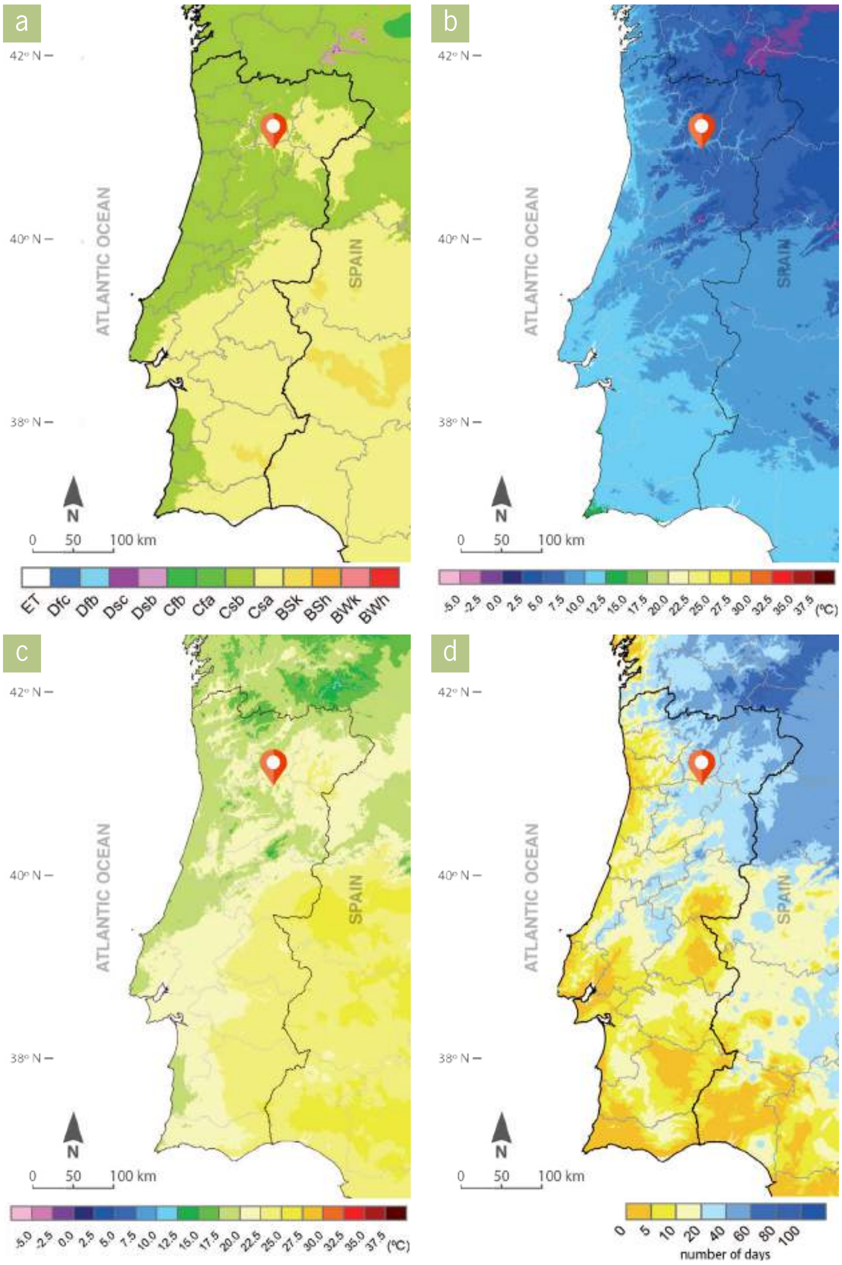


FIGURE 5.29. (a) Köppen-Geiger Climate Classification for Portugal; (b-c) Average mean temperature in winter and summer; (d) Average number of days with minimum temperature ≤ 0 °C in winter (adapted from [169]).

tition wall of the balcony and other walls were removed to increase the floor area of the bedrooms and bathroom (Fig. 5.32c).

The building envelope consists of granite walls (50-55 cm thick) with a pitched roof, wooden doors and wooden framed single glazed windows. Indoors, the partitions walls in tabique (earth-filled timber frame walls) were replaced by plasterboard walls. The ground floor is now paved with clay tiles, and the upper floor has a hardwood flooring on a timber frame. Table 10 lists the thermal transmittance coefficient (U value) of the building envelope. The building has no cooling system, and the heating system is a closed wood-burning fireplace (Fig. 5.32d).

FIGURE 5.30. External views. (left) southwest and southeast façades; (right) northeast and west facades.

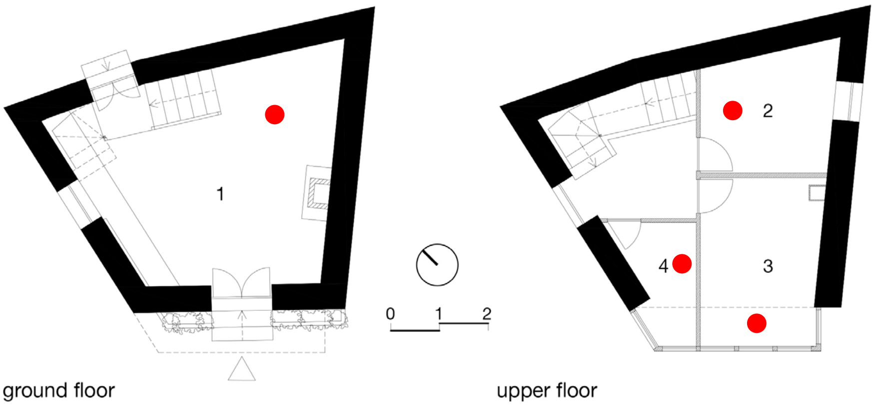


FIGURE 5.31. Floor plans showing the location of measuring instruments (1 - living room / kitchen; 2 bedroom; 3 - bedroom with balcony; 4 - bathroom).

FIGURE 5.32. (a) Kitchen view; (b) Bathroom view; (c) Bedroom with balcony; (d) Closed wood-burning fireplace; (e) Removable ventilation net; (f) Smoke exhaust through the roof.

TABLE 10. Characteristics of the building envelope

Envelope element	Materials	U-value (W/(m².°C))
External Walls	Granite (50-55 cm)	2.87 [137]
Ceiling (in contact with ventilated roof)	Ceiling with timber structure with 4 cm of extruded polystyrene (XPS)	0.84 [136]
Floor balcony (in contact with outdoor)	Timber floor (4cm) on timber structure	2.38 [136]
Doors	Solid timber	2.15 [136]
Windows	Single glazed timber frame sash windows, indoor wooden shutters	3.40* [136]
Windows (balcony)	Single glazed timber frame sash windows, indoor opaque curtains	4.30* [136]
Balcony (lower part)	Timber frame (double wooden panel) (10 cm)	1.70 [136]

*U_{wdn} - day/night heat transfer coefficient, including the contribution of shading systems.

5.2.3 PASSIVE STRATEGIES

In the inland Northern part of Portugal, to respond to a climate of harsher winter conditions and milder summers, vernacular architecture developed specific mitigation strategies. These had, in general, the purpose of increasing solar gains and reducing heat losses during winter, like the ones found in this case study:

- Balconies are an architectonic feature and identity of Northern Portugal vernacular architecture. It has to be taken into consideration that most of these buildings had low daylight levels and comfort conditions. Therefore, balconies were spaces used to enjoy the sun, work with daylight and to heat the adjacent areas, particularly in sunny winter days. The glazed balcony is an improved version of a balcony, that acts as a sunspace, allowing harvesting solar gains and reducing heat losses (Fig. 5.32c). In the case study, the larger area of the balcony is facing southwest, with parts facing southeast and west. Thus, in winter, the balcony is exposed to a higher solar radiation level during a larger number of sunshine hours. Although this strategy is aimed for the heating season, the cantilevered volume of the balcony and the possibility to keep windows open without compromising security also allow proper operation during the cooling season (Fig. 5.32e), by shading the walls and promoting natural ventilation (Fig. 5.33);
- To reduce heat losses, only a few windows (upper floor) face directly outdoors. In the original configuration of building the balcony acted as buffer space and only some indoor rooms connected directly to outdoors (Fig. 5.32c); additionally, and although it was not possible to verify whether was the case of this building, to reduce heat losses by ventilation sometimes, buildings did not have chimneys, and the exhaust of smoke was done through the roof, as it is still visible in a neighbour-

ing building (Fig. 5.32f);

- The use of high thermal inertia building elements, namely the massive granite walls and the massif rock where the building is laying, gives the building the capacity to stabilise indoor temperature;
- The functional arrangement of the indoor spaces in this type of buildings (as it was the case of this building before the renovation), can also reduce the heating needs. In this type of architecture, bedrooms rarely had exterior windows and were located next to the kitchen, taking advantage of the heat generated by the fireplace;
- The storage of the livestock on the ground floor was also a heating strategy. After the renovation, this strategy is mimicked by the closed wood-burning fireplace;
- The organic and compact urban layout, suited to the topography, can also be considered a passive strategy since the compactness of constructions allows minimising the area of the envelope exposed to outdoor conditions and therefore reducing heat losses. The narrow and winding streets allow reducing wind speed, and in some places, the streets form small "public patios" sheltered from the prevailing winds (Fig. 5.25 and 5.26).

The combination of all these passive strategies has the primary purpose of achieving the best possible indoor thermal comfort conditions. The range of strategies highlights the poor living conditions and the need to understand and use the available resources the best possible way.

The dissemination of the abovementioned strategies in the region highlights their usefulness in mitigating the effects of the cold climate, as shown in previous studies [170, 171]. Therefore, the quantitative study of the effectiveness of these passive strategies on the thermal performance, particularly of the glazed balcony, is useful to the discussion about the energy efficiency of buildings in this region. This is described and discussed in the following sections.

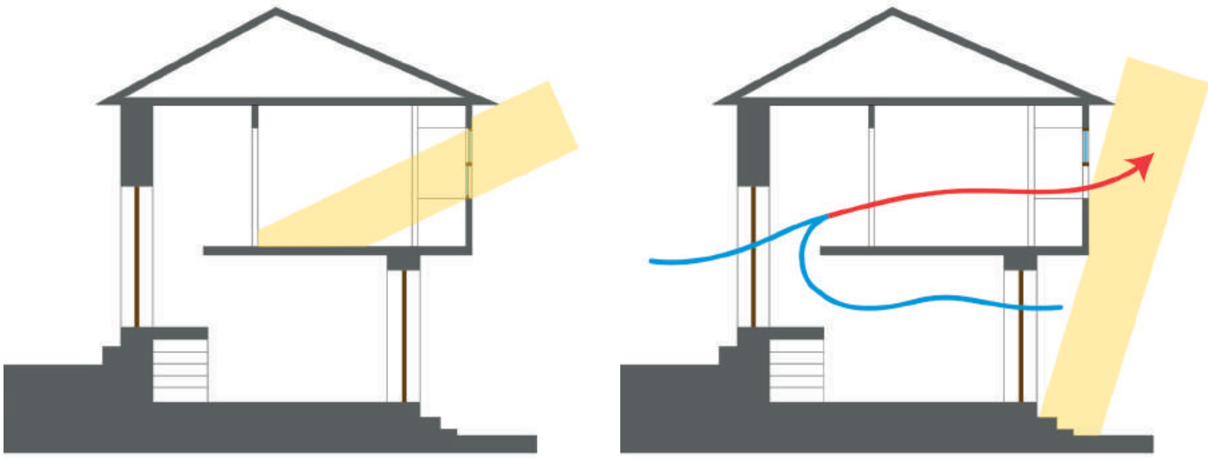


FIGURE 5.33. Schematic section of the glazed balcony operation. (left) Winter solstice; (right) Summer solstice.

5.2.4 OCCUPANCY AND USE PROFILE

It is essential to know the building occupancy profile since the daily occupants' habits have a direct influence on the thermal performance of the building [125]. The studied building is a holiday house, mainly used for weekends and holidays. During the summer period (vacations), it is occupied continuously during one or two months. The building is only used sporadically during the remaining of the year. Table 11 summarises the main activities reported by the occupants (during the occupancy period) that may influence the thermal performance of the building. It is important to refer that the building was unoccupied during most of the winter monitoring period.

TABLE 11. Building occupancy and use profile

Season		Use and description
Autumn	heating/cooling	The closed wood-burning fireplace was in operation
	ventilation	The windows remained closed.
	shading	The curtains were usually opened in the morning (around 9:30 a.m.) and closed at night
Winter	heating/cooling	The closed wood-burning fireplace was in operation from 6:00 p.m. until 12 p.m.
	ventilation	Sporadic opening of windows for ventilation
	shading	The curtains were usually opened during the day and closed during the night.
Spring	heating/cooling	No cooling system was used.
	ventilation	Daily opening of the window for ventilation (8:30 a.m. to 6:30 p.m.).
	shading	The curtains were usually opened during the day and closed during the night.
Summer	heating/cooling	No cooling system was used
	ventilation	The windows were open day and night. Mosquito nets were placed in the windows to allow for ventilation during night-time.
	shading	The bedroom/balcony curtains remained open in the morning only until the direct sun passes through the window (around 1:00 p.m.).

5.2.5 THERMAL MONITORING AND INDOOR COMFORT EVALUATION

The thermal performance monitoring included the assessment of the air temperature and relative humidity. Additionally, the indoor comfort conditions in the main rooms of the case study were characterised. These parameters were evaluated for one year, and the data here presented are for 30 representative days of each season.

5.2.5.1 AUTUMN

During Autumn monitoring (from 8th November to 8th December 2014), the outdoor mean air temperature was of about 10.6 °C (Table 12). The daily maximum and minimum outdoor air temperatures had some variations during the monitoring period. In the second half of the monitoring period, starting from 23rd November (Fig. 5.34), these variations were more frequent and significant.

Figure 5.34a shows that indoor temperature remained stable in the rooms with a smaller glazing area, with a mean temperature of 12.1 °C in the living room/kitchen and 11.5 °C in the bedroom (Table 12). The reduced glazed area and the high thermal inertia of the building envelope allow stabilising the indoor temperature in these rooms. In the 7th of December, when the outdoor temperature reaches a minimum value of 1.2 °C, it is possible to observe how building occupants can take correcting measures to improve the indoor thermal comfort conditions. The increase of the indoor temperatures in the living room/kitchen and bedroom (Fig. 5.34a) is due to the use of the heating system (closed wood burning fireplace). According to Table 12 and Figure 5.34a, in these rooms, the maximum temperatures were always below the comfort temperature range.

In the rooms where the glazing area is predominant, bedroom/balcony and bathroom, it was observed that the indoor temperature was not stable as it is strongly dependent on the outdoor climate conditions. The maximum temperature recorded in the bedroom/balcony was 18.9 °C while in the bathroom it was 16.4 °C (Table 12). In these rooms, during the day, the indoor temperature followed the trend of the outdoor temperature (Fig. 5.34a). The temperature profiles in both rooms were quite similar, but since the bedroom/balcony has a larger glazed area than the bathroom, it presented higher temperatures. The bedroom/balcony had the highest indoor temperature throughout the monitoring period, reaching

TABLE 12. Comparison between outdoor and indoor air temperatures and relative humidity values during Autumn

AUTUMN					
	Outdoor	Kitchen/Living room	Bedroom/balcony	Bedroom	Bathroom
			Temperature (ºC)		
Mean	10.1	12.1	12.6	11.5	11.5
Maximum	24.6	14.3	18.9	15.2	16.4
Minimum	-0.3	9.2	6.5	8.5	6.6
			Relative Humidity (%)		
Mean	84.1	75.7	72.5	78.9	77.9
Maximum	96.8	79.0	79.0	82.0	85.0
Minimum	32.3	67.0	60.0	69.0	70.0

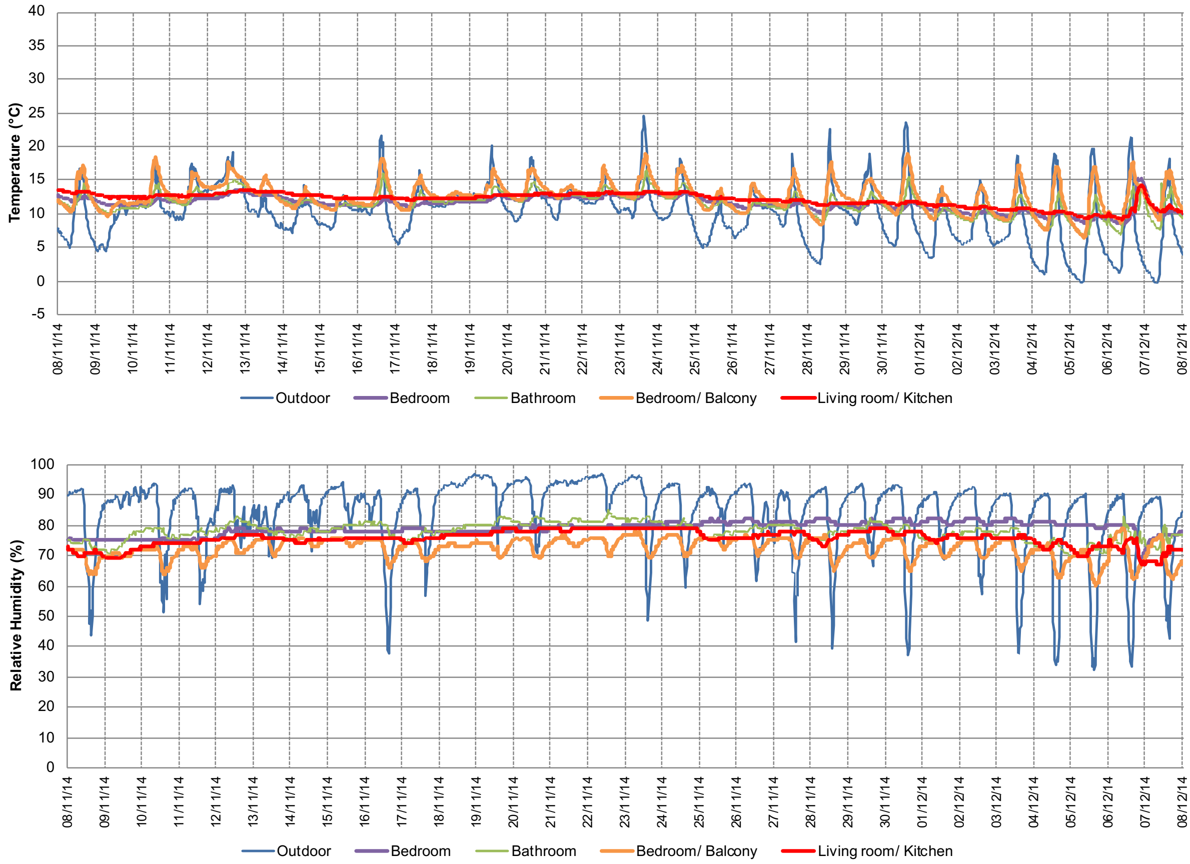
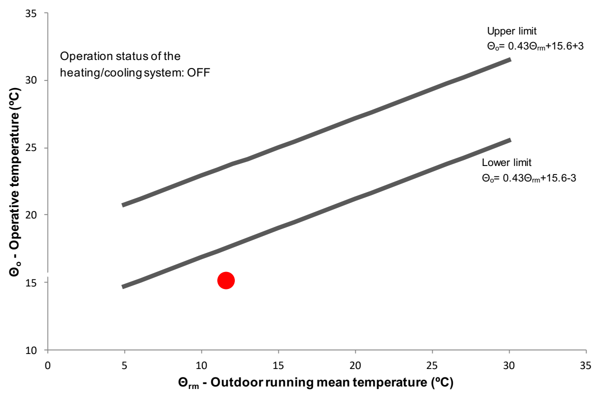


FIGURE 5.34. Autumn: (a) indoor and outdoor air temperature profiles; (b) indoor and outdoor relative humidity profiles.

temperatures close to the comfort threshold temperature. These results highlight the effect of the glazed balcony as a strategy to capture solar gains.

Concerning the outdoor relative humidity, it was found that there was a high daily variation, reaching values of around 90% during the night and lower values of 32.3% during the day (Table 12). The average outdoor relative humidity value was also high, 84.1% during the monitoring period (Table 12). In contrast, almost all indoor rooms had stable relative humidity profiles with small daily variations. The exception was the bedroom/balcony, where the fluctuations were slightly higher than in the other rooms, due to higher solar radiation, but much lower than the variations outdoors. The indoor relative humidity values were high (about 70-80%), higher than those recorded outdoors during the day, but smaller than those verified outdoors during the night. The reduced ventilation rate of the rooms, due to the lack of occupancy, might be the main reason for the high indoor relative humidity levels. During the occupancy period (from 7th to 8th of December 2014), there was a slight decrease in the relative humidity level in the living room and bedroom (Fig. 5.34b) due to the use of the heating systems. However, due to the low outdoor temperatures, the ventilation was minimised to reduce heat losses.

Regarding the assessment of the thermal comfort, the measurements in the living room/kitchen and bedroom/balcony were carried out when the heating system was not used. The influence of the curtains on the thermal comfort in the bedroom/balcony was also evaluated. In autumn and without the use of the heating system, the results showed that the thermal comfort conditions in the living room/kitchen were below the lower comfort limit (Fig. 5.35a). In the survey, the two inhabitants answered they were "slightly cool" (1.0 met; 0.91 clo) and one "cool" (1.0 met; 0.95 clo), confirming the objective measurements. In what concerns the assessment of the thermal comfort conditions in the bedroom/balcony, it was possible to verify the influence of the glazing area. In this room, when the curtains were closed, the comfort conditions were within the thermal comfort limits, but close to the bottom threshold (blue dot in Fig. 5.35b)). In the survey, the two occupants answered they were "neutral" (comfortable) (1.0 met; 0.91-0.95 clo), i.e. the results were in line with the objective assessment. When the curtains were open, the solar gains increased the operative temperature, and thermal conditions were above the upper thermal comfort threshold, showing an overheating period (red dot in Fig. 5.35b).



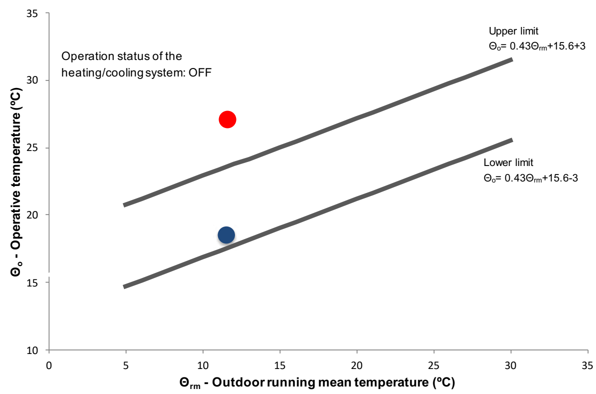


FIGURE 5.35. Adaptive comfort chart during a representative autumn day: (a) Thermal comfort temperature (operative temperature) in the living room/kitchen; (b) Thermal comfort temperature (operative temperature) in the bedroom/balcony for open curtains (red dot) and closed curtains (blue dot).

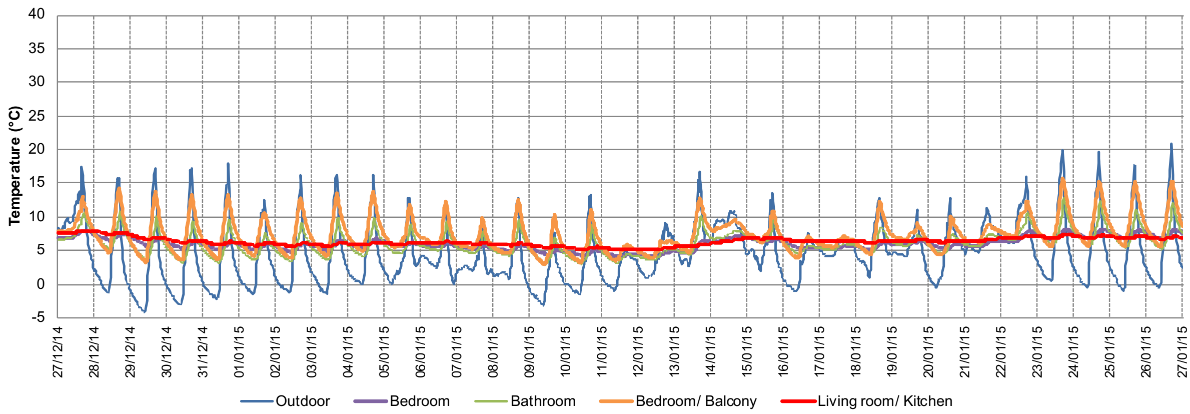
5.2.5.2 WINTER

The winter monitoring was carried out between 27th December 2014 and 27th January 2015. In this period, the minimum outdoor temperature was very low, reaching a minimum value of -4.0 °C (Table 13), being around 0 °C most of the days. The maximum outdoor temperature reached 20.9 °C (at the end of the monitoring period), and the mean temperature did not exceed 4.6 °C.

From the analysis of Figure 5.36a, it is possible to conclude that the living room/kitchen and the bedroom (the rooms with the smaller glazed area and not in contact with the glazed balcony), showed a stable profile with low daily thermal variation and a mean temperature of 6.0 °C and 6.4 °C, respectively (Table 13). Beyond the reduced glazed area, the thermal inertia of the envelope is the main reason for this steady behaviour. The fact that the building was not occupied during this period of the monitoring campaign explains the lower temperature values and its uniformity since there was no human action to achieve thermal comfort conditions (i.e. active heating to increase the indoor temperatures). Although considerably below the comfort limits, even in a free-running mode, it has to be highlighted that indoor mean temperature was always higher than outdoors.

TABLE 13. Comparison between outdoor and indoor air temperatures and relative humidity values during the Winter

WINTER					
	Outdoor	Kitchen/Living room	Bedroom/balcony	Bedroom	Bathroom
Temperature (ºC)					
Mean	4.6	6.4	7.4	6.0	6.1
Maximum	20.9	8.0	15.7	8.2	12.8
Minimum	-4.0	5.2	3.0	4.2	3.1
Relative Humidity (%)					
Mean	77.8	75.5	68.8	79.4	74.5
Maximum	95.2	80.0	76.0	83.0	85.0
Minimum	14.7	68.0	58.0	77.0	63.0



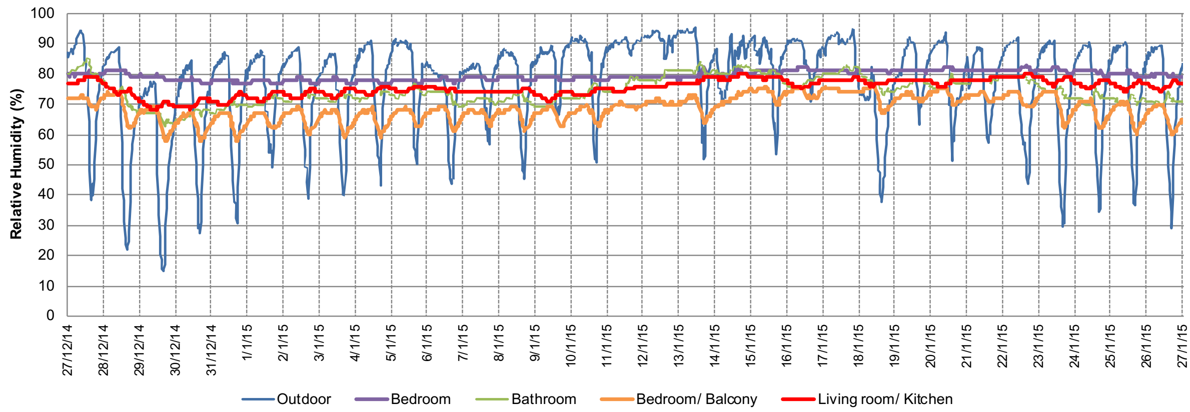


FIGURE 5.36. Winter: (a) indoor and outdoor air temperature profiles; (b) indoor and outdoor relative humidity profiles.

Both in the bedroom/balcony and the bathroom, it was observed that temperature profiles were not stable and followed the outdoor temperature variation during the day (Fig. 5.36a). The maximum indoor temperature recorded was 15.7 °C in the bedroom/balcony and 12.8 °C in the bathroom, both in days with higher outdoor temperatures. Due to the large glazed area of the balcony, the effect of sunny days is visible in temperature peaks close to the thermal comfort boundary, even with this strategy not being used to its full potential. Since the opaque curtains were closed, part of solar radiation was reflected. Consequently, in days with more incident radiation and if the curtains were open, it is expected that temperature would reach or be much closer to the comfort boundaries (similar to the condition measured during autumn and shown in Fig. 5.35a), where active heating was only necessary as a backup). Nevertheless, there is also a drawback resulting from the greater glazed area, since these rooms also have more heat losses and therefore the minimum temperature recorded is lower than in the ground floor (Table 13). Moreover, the lack of thermal mass to store the heat gained during the day is a disadvantage, since the rooms have lightweight wooden floor and walls (as the original earth-filled timber frame walls – tabique - were replaced by plasterboard walls).

Considering that the glazed area is an important strategy to harvest solar gains, it was expected that these rooms had temperatures close to the comfort conditions, but the mean temperature during the monitoring period was very low (7.4 °C) (Table 13). The non-occupation of the building and the use of the internal shading curtains during all monitoring period are the aspects that explain this behaviour.

Additionally, the temperature differences between ground and upper floors show how well the functional distribution of the rooms was before the building renovation. Originally, the ground floor was conceived for storage and not for human occupancy, and in the first, stable and lower temperatures were an advantage.

The outdoor relative humidity had a significative daily variation, reaching values close to 96% during the night and a minimum of 14.7% during the day (Table 13). The average relative humidity of 77.8% is also high (Table 13). In general, the rooms have stable relative humidity profiles with little daily fluctuations. The rooms with smaller glazing area are the ones with the most stable temperatures. The bedroom/balcony showed the highest daily variation among the studied rooms, of about 8.0%, being most of the monitoring period between 60% to 70%.

Regarding the assessment of the thermal comfort (Fig. 5.37), the measurement of the thermal environment conditions was performed during a typical winter day, in the bedroom/balcony and the living room/kitchen. In the living room/kitchen, the analysis was carried out for two situations: i) when the heating system was not in operation (Fig. 5.37a), and ii) when the heating system was in operation (Fig.5.37b). The results showed that, when the heating system was not in operation, the thermal environment was very uncomfortable (Fig. 5.37 left). The influence on the thermal comfort of using the closed wood-burning fireplace is quite evident since when the heating system was in operation, the living room/kitchen had a comfortable thermal environment (Fig. 5.37 right). In the survey, the occupants also expressed their thermal sensation for the same two situations. When the heating system was not in operation, one occupant (1.0 met; 1.48 clo) answered he was “cool” and the other (1.0 met; 0.92 clo) “cold”. When the heating system was in operation, one occupant (1.0 met; 1.48 clo) answered he was “neutral” and the other (1.0 met; 0.92 clo) “slightly cool”. These results confirm the ones from the objective measurements. The differences between the answers of the two occupants are related to the different clothing insulation levels, which influenced their thermal sensation.

In the bedroom/balcony, the measurements were carried out only when the heating system was not in operation. The thermal comfort conditions in this room were outside the comfort boundaries (Fig. 5.38). Although the operative temperature was outside the comfort limits, it was very close to the lower comfort threshold. It is likely that the regular building occupation and, consequently, the appropriated use of the glazed balcony, would lead to an operative temperature within the comfort limits. It must be noted that during the measurements, the sky was cloudy, and thus solar gains were low. In the survey, the two occupants answered they were “slightly cool” (1.0 met; 0.92 - 1.48 clo), which confirms the objective measurements.

5.2.5.3 SPRING

During this monitoring campaign (carried out from 14th April to 14th May 2015), the outdoor mean air temperature was about 16.0 °C, the maximum temperature was often below 20.0 °C, and the minimum values varied between 5.0 °C and 10.0 °C (Table 14 and Fig. 5.39). The outdoor air temperatures had significant daily variations during the period, with maximum and minimum values having a slight increment in the last days of the period (Fig. 5.39). The maximum temperature recorded was 34.2 °C, while the minimum was below 4 °C (Table 14).

In spring, a relevant difference was observed between the indoor air temperatures of the rooms located on the ground floor and those on the upper level. Concerning the ground floor, the living room/kitchen had a very stable indoor temperature during the monitoring period, with a mean air temperature of 15.2 °C (Table 14). In the upper floor, it was observed that the indoor temperature was less stable, particularly in the rooms in the glazed balcony. The increase in the outdoor temperature and the number of hours of solar radiation had a strong influence on the temperature of these rooms. The bedroom had a more stable temperature profile since it has fewer solar gains through the windows and higher thermal inertia due to the granite walls. The bedroom/balcony had the highest indoor temperature in the building during the monitoring period. The maximum temperature in the bedroom/balcony always remained below the outdoor temperature, since

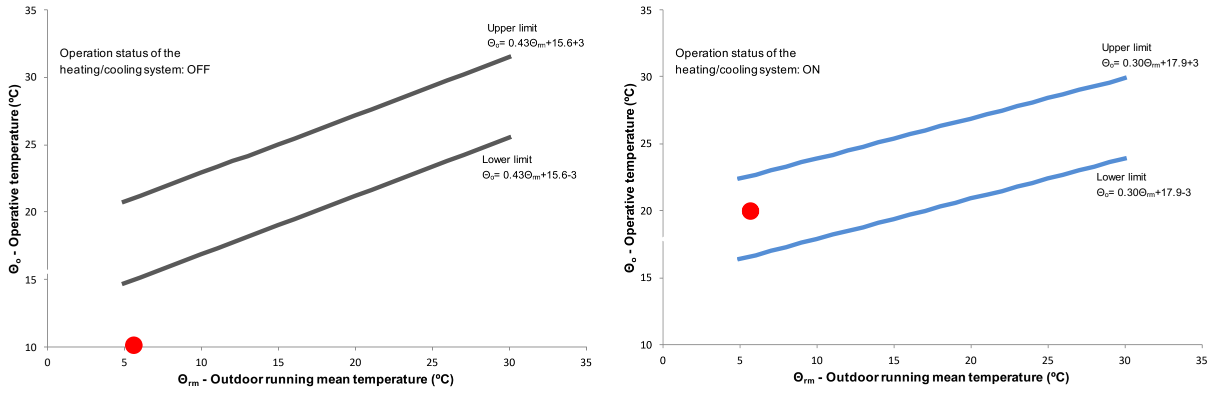


FIGURE 5.37. Adaptive comfort chart during a representative winter day: (a) Heating system OFF - Thermal comfort temperature (operative temperature) in the living room/kitchen; (b) Heating system ON - Thermal comfort temperature (operative temperature) in the living room/kitchen.

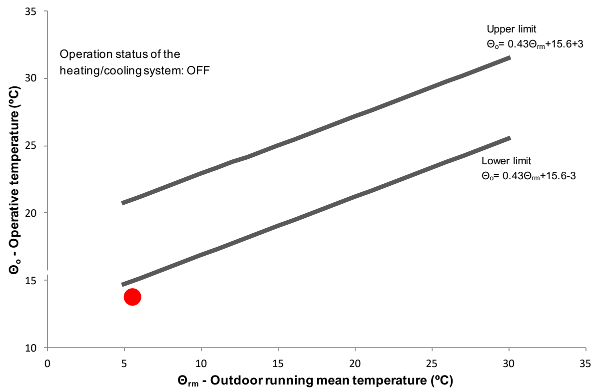


FIGURE 5.38. Adaptive comfort chart during a representative winter day. Thermal comfort temperature (operative temperature) in the bedroom/balcony.

during the monitoring period the curtains were closed. Nevertheless, from May onwards, when the outdoor temperature begins to rise, closing the curtains is the right decision to reduce solar gains. However, since the glazed area is protected by an inside shading device (opaque curtains), it is difficult to avoid overheating both in the bedroom/balcony and in the bathroom, as shown in Figure 5.39a.

Regarding the outdoor relative humidity, it was found that there is a high daily fluctuation, reaching values near 93% during the night and minimum vales of 11.3% during the day (Table 14). Indoors, the values were stable, with daily variations around 10%. The bedroom/balcony and the bathroom showed higher daily variation, and the mean relative humidity was around 60% (Table 14). The relative humidity is within the recommended levels for human health and comfort [130]. The living room/kitchen and the bedroom also had a very stable relative humidity profile, with mean values around 70% (Table 14).

The thermal comfort assessment was carried out both in the bedroom/balcony and the living room/kitchen, without the heating system in operation. From the analysis of the adaptive comfort charts, it is possible to conclude that the thermal comfort conditions in the living room/kitchen are below the lower comfort limit (Fig. 5.40 left), even with an operative temperature of 18.9 °C and an outdoor running mean temperature above 20 °C. The low heat gains and mainly the high thermal inertia of the envelope are the main factors affecting these results. In the survey, the two occupants (1.0 met; 0.44-0.58 clo) answered they were “slightly cool”.

TABLE 14. Comparison between outdoor and indoor air temperatures and relative humidity values during the Spring

SPRING					
	Outdoor	Kitchen/Living room	Bedroom/balcony	Bedroom	Bathroom
Temperature (ºC)					
Mean	16.0	15.2	18.1	17.2	17.9
Maximum	34.2	19.2	28.9	24.0	28.7
Minimum	3.8	13.2	11.0	13.5	12.4
Relative Humidity (%)					
Mean	65.9	70.3	59.6	67.4	60.4
Maximum	92.8	78.0	72.0	77.0	74.0
Minimum	11.3	62.0	46.0	47.0	43.0

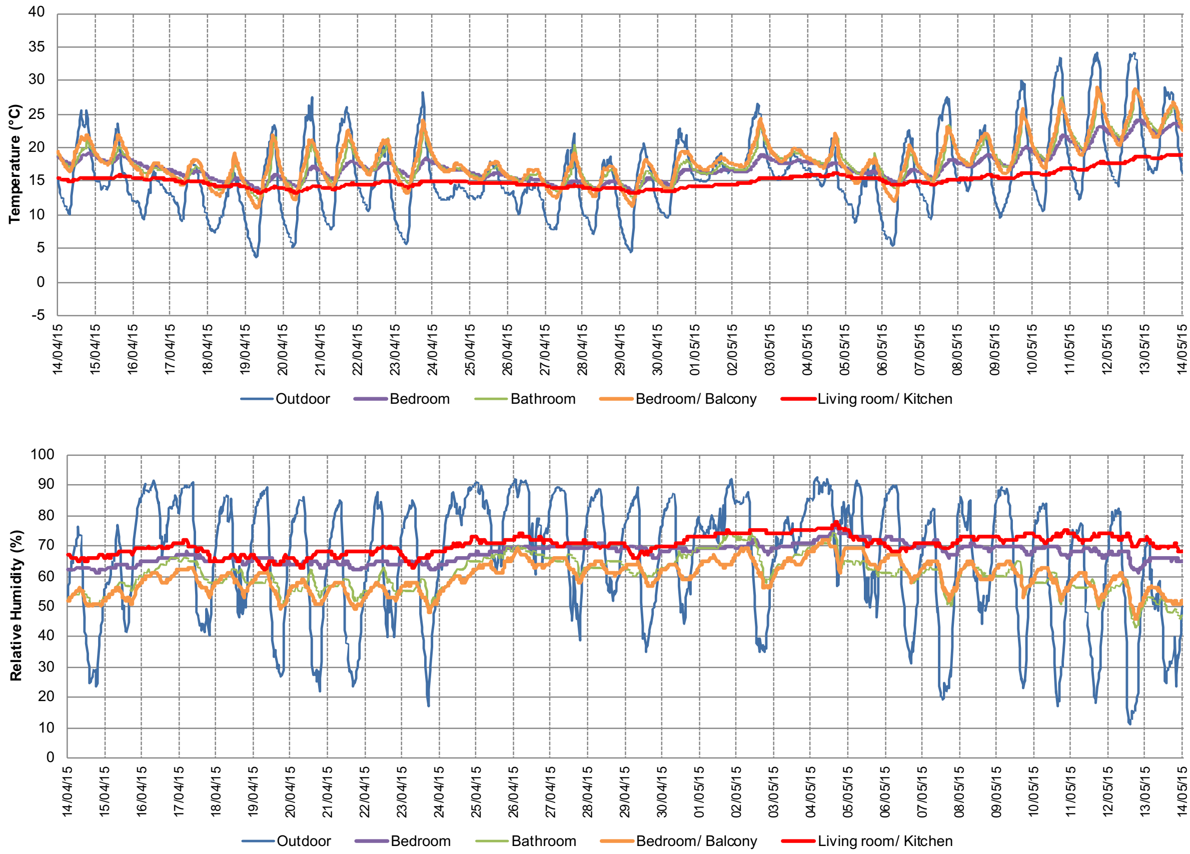


FIGURE 5.39. Spring: (a) Indoor and outdoor air temperature profiles; (b) Indoor and outdoor air relative humidity profiles.

In contrast, the bedroom/balcony had a thermal condition within the comfort range (Fig. 5.40 right). The operative temperature was higher than on the ground floor due to the heat gains provided by the glazed balcony. In the comfort survey, the two occupants (1.0 met; 0.44 and 0.58 clo) answered they were “neutral”, which confirms the measurements.

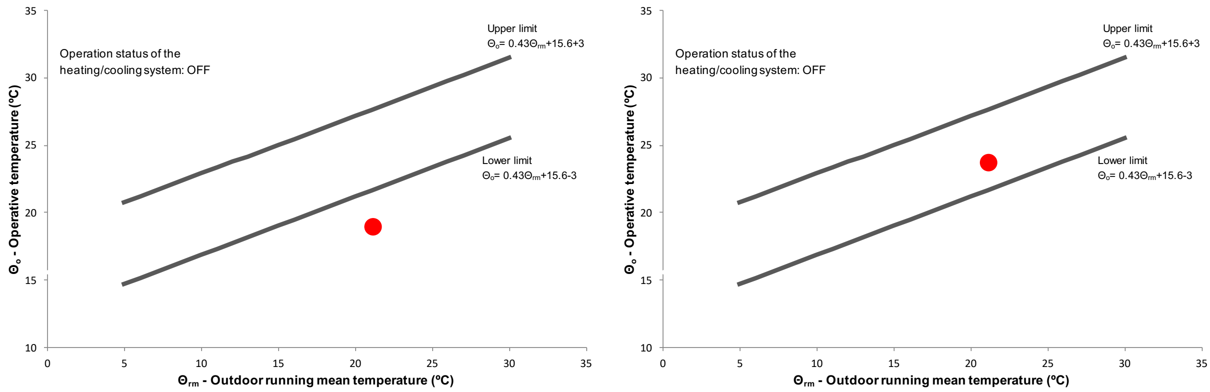


FIGURE 5.40. Adaptive comfort chart during a representative spring day: (a) Thermal comfort temperature (operative temperature) in the living room/kitchen; (b) Thermal comfort temperature (operative temperature) in the bedroom/balcony.

5.2.5.4 SUMMER

The summer monitoring was carried out from 18th July to 18th August 2015. In this period, the mean outdoor temperature was 24 °C, there was a high daily thermal amplitude, with several days reaching most of the time maximum values around 35.0 °C (and a peak of 39.1 °C), and minimum values around 15.0 °C (Table 15).

From the analysis of Figure 5.41, it is possible to conclude that the living room/kitchen had the most stable temperature profile, with a mean temperature of 24.1 °C (Fig. 5.41 and Table 15). This is due to the higher thermal inertia and lower direct solar gains of the room. As mentioned before, this room was initially for storage and thus, during summer, it had the advantage of keeping the temperature stable. In its current use, during summer, it is the room with the best thermal comfort conditions.

In the upper floor, the bedroom is the room with the most stable air temperature profile with slight day to night temperature variations (usually around 3 °C). The reason for the small differences in this room can be related to the higher thermal inertia than the other rooms on the upper floor. Nevertheless, when it was unoccupied, and therefore without ventilation, the maximum air temperature in this room was around 30 °C.

Regarding the rooms in the balcony, as in the seasons previously presented, it was observed that the indoor temperature had significant daily variations. In these rooms, the indoor temperature follows the outdoor temperature profile during the day (due to both solar gains and heat losses through the glazing area). The minimum mean indoor temperature stabilises around 25 °C, while the minimum outdoor temperature was usually 10 °C lower (Table 15 and Fig. 5.41). The larger glazed area of these spaces, facing southwest, is the reason why these rooms have higher temperatures due to the solar gains.

TABLE 15. Comparison between outdoor and indoor air temperatures and relative humidity values during the Summer

SUMMER					
	Outdoor	Kitchen/Living room	Bedroom/balcony	Bedroom	Bathroom
Temperature (ºC)					
Mean	23.7	24.1	26.8	26.8	27.1
Maximum	39.1	26.2	35.0	31.0	35.2
Minimum	12.4	21.4	19.6	22.7	21.5
Relative Humidity (%)					
Mean	54.1	51.8	46.0	48.1	46.5
Maximum	89.4	63.0	64.0	60.0	65.0
Minimum	13.8	35.0	27.0	30.0	28.0

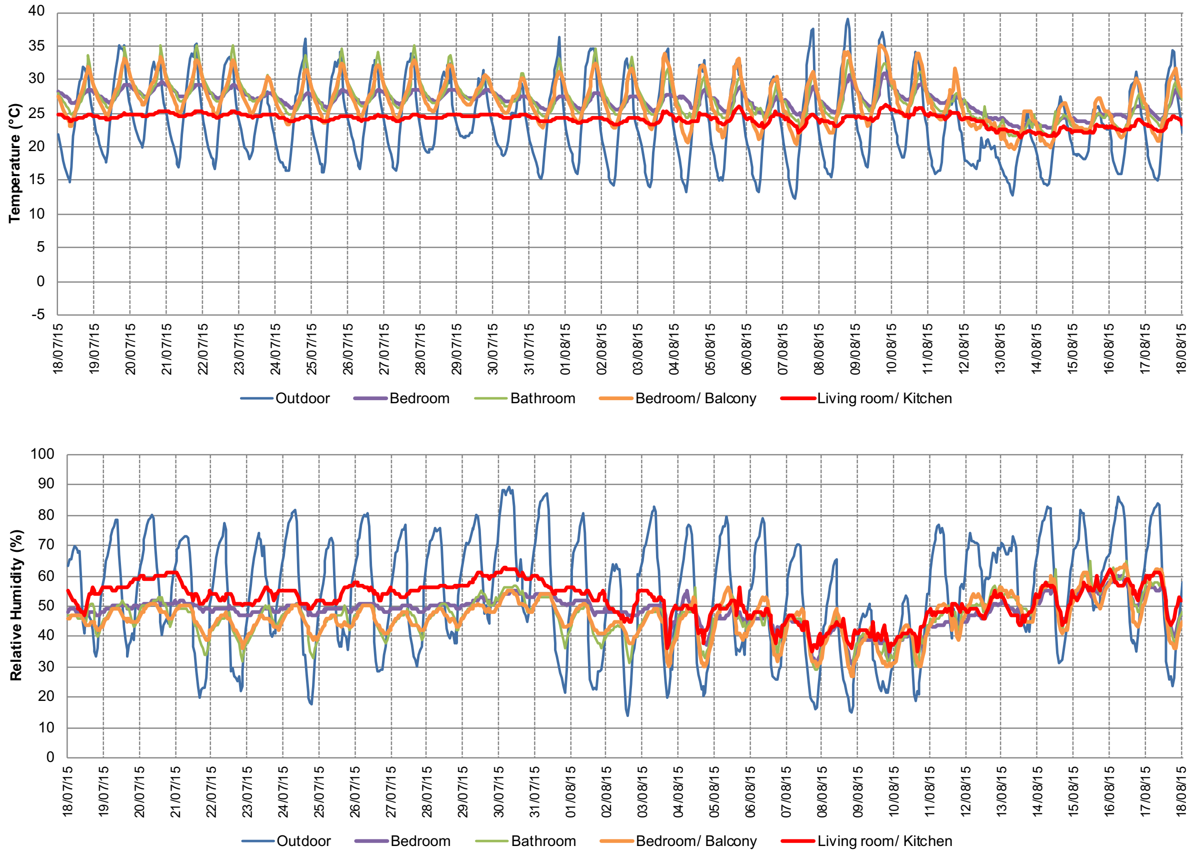


FIGURE 5.41. Summer: (a) Indoor and outdoor air temperature profiles; (b) Indoor and outdoor air relative humidity profiles.

In this season, the building was occupied during the entire month of August. From the moment the building began to be occupied, it was expected that the promotion of natural ventilation would change the indoor temperature profile, but this is not noticeable in the graphs (Fig. 5.41a). The maximum temperature in the rooms remained similar (Fig. 5.41a) since the flow of warmer air from outdoors into the building during the day does not favour its cooling. On the other hand, during the night, the minimum temperature slightly dropped due to the ventilation since the outdoor air temperature was lower during the night. During the occupation period, the inhabitants closed the curtains during the morning to avoid solar gains (usually until 2 p.m.). However, since there are no external shading devices in addition to the fact that windows were kept open for ventilation, it is not easy to control the solar gains through the glazed area of the balcony.

Nonetheless, the airflow in the building can improve occupants' thermal sensation by increasing convective heat losses from their bodies. The most recommended solutions to avoid solar gains in the cooling season is to use an external shading device and to use night ventilation to remove diurnal thermal loads. At this point, it is worth mentioning that if the balcony had its original configuration (i.e. if it was a space separated from the indoor rooms by a wall), it would influence in a much positive way the thermal behaviour of the building during this season. The reasoning for this is that it would act as a buffer space between outdoor and indoor rooms and would work as a shading device of the openings that existed in the demolished wall.

Regarding the outdoor relative humidity, it showed significant daily variations, with maximum values around 70-80% and sometimes near 90% during the night, and minimum values varying from near 40% to minimum values of 14% during the day (Table 15). The mean value is around 55% (Table 15). The indoor relative humidity has lower daily variations and is relatively stable (Fig. 5.41b). The rooms with the most stable relative humidity profiles are the living room/kitchen and the bedroom. In general, the relative humidity decreases during the day due to the warmer dry air and increases during the night due to the cooler outdoor humid air that flows into the building. This is particularly visible in the rooms with the balcony, where daily variations are higher.

The period of occupation (starting on 4^{th} of August) influenced indoor relative humidity profiles, increasing the daily humidity variation, even in rooms with stable profiles. This reduction in relative humidity values is related to the ventilation and circulation of hot air from outdoors. The relative humidity slightly raised during some rainy days and then decreased again.

In the thermal comfort assessment, the living room/kitchen and the bedroom/balcony showed a thermal environment within the comfort range (Fig. 5.42 left). The operative temperature in the living room/kitchen is more stable due to the higher thermal inertia, and therefore this room had a better thermal condition during the summer. The results of the survey confirmed the measurements since the two occupants (1.0 met; 0.27 - 0.43 clo) answered they were “neutral”.

In the bedroom/balcony, the operative temperature was close to the upper comfort limit, mainly due to the solar gains through the glazed envelope (Fig. 5.42 right). In the survey, one occupant (1.0 met; 0.43 clo) answered he was “slightly warm” and the other (1.0 met; 0.27 clo) “neutral”. The difference between the answers is mainly related to the different clothing insulation levels.

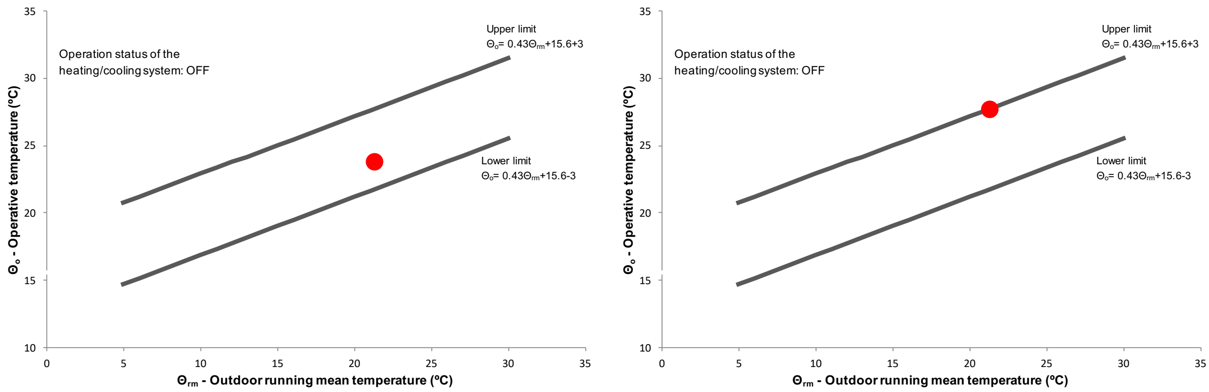


FIGURE 5.42. Adaptive comfort chart during a representative summer day: (a) Thermal comfort temperature (operative temperature) in the kitchen/living room; (b) Thermal comfort temperature (operative temperature) in the bedroom/balcony.

5.2.6 INDOOR AIR QUALITY MONITORING

5.2.6.1 CARBON DIOXIDE CONCENTRATION

In this section, the carbon dioxide (CO_2) concentration in the case study is evaluated and classified according to the categories defined by EN 15251 [128]. The CO_2 concentrations were measured in different rooms during a representative day of each season. During the winter, the measurements were carried out in two situations, i.e., with and without the closed wood-burning fireplace in operation, to verify the influence of the fireplace use in the CO_2 concentrations. From the measurements, it was verified that the use of the fireplace slightly increased the CO_2 concentrations. Still, they did not exceed the design values for category I (high level of expectation) (Table 16). The small differences between outdoor and indoor carbon dioxide concentrations are due to the low occupation density of the building, to the natural ventilation and infiltration rate, and the efficiency of the closed fireplace exhaust system. In the records, two values correspond to category III. A possible explanation for this situation is that those two rooms were closed until the beginning of the measurements, and therefore the CO_2 concentrations were higher. Although the case study is an old building, the results showed that the CO_2 concentrations are, most of the time, within the boundaries of the most demanding category.

TABLE 16. Classification of the indoor air quality in representative rooms for all seasons

CARBON DIOXIDE (CO_2) CONCENTRATION					
Season	Place/room	Concentration (ppm)	Difference above outdoor	Category	Pressure (hPa)
Autumn	Outdoor	496			975.3
	Kitchen/Living room	797	301	I	
	Bedroom/balcony	725	229	I	
	Bedroom	1210	714	III	
	Bathroom	686	190	I	
Winter (Heating OFF)	Outdoor	450			974.7
	Kitchen/Living room	589	139	I	
	Bedroom/balcony	915	465	I	
	Bedroom	596	146	I	
	Bathroom	641	191	I	
(Heating ON)	Kitchen/Living room	725	275	I	
	Bedroom/balcony	642	192	I	
	Bedroom	730	280	I	
	Bathroom	720	270	I	
Spring	Outdoor	483			982.8
	Kitchen/Living room	620	137	I	
	Bedroom/balcony	492	9	I	
	Bedroom	555	72	I	
	Bathroom	560	77	I	
Summer	Outdoor	405			977.4
	Kitchen/Living room	680	275	I	
	Bedroom/balcony	610	205	I	
	Bedroom	520	115	I	
	Bathroom	480	75	I	

5.2.6.2 RADON GAS CONCENTRATION

The concentration of carbon dioxide is a good indicator of air quality in buildings where occupants are the primary source of pollution. However, since the building is located on a granitic area, it is also necessary to measure the radon gas concentration [131]. The radon, without colour, odour or taste, is originated from the decay of the radium and is found in rocks and soils, as in the granitic massif where the building is located. Its infiltration in buildings generally takes place through the foundations. The high concentration of radon in the environment has health risks since the element is lodged in the lungs by inhalation and its main effect is lung cancer (risk potential increases in about 16% for each 100 Bq/m^3 in long-term average radon concentration) [172]. According to the World Health Organization (WHO), radon is the second leading cause of lung cancer, after smoking in smokers, and the first among those who have never smoked [172]. Directive 2013/59/EURATOM [173] states that the reference level for the annual average concentration of activity in the air should not exceed 300 Bq/m^3 per year in new construction homes and workplaces, whose approximate equivalence is 10 mSv annual, according to recent calculations by the International Radiological Protection Community [173]. In the Portuguese context, and according to national legislation [131], it is mandatory to study and measure the concentrations of radon in granitic sites, like the one where the case study is located.

In the case study, the concentration of radon was measured during the heating season, when the ventilation rate was lower. The living room/kitchen was the room chosen for the measurements since it has the lowest ventilation rates, has granite walls, is located on the ground floor, and it sits on a granitic massif. The measurements took place for 28 days, with integration periods of 10 minutes, started after a period of stabilisation of the radon sensor (about 60 days). Figure 5.43 shows the results of the measurements. It is possible to see an irregular distribution of values with several peaks. The peaks in the radon concentration are considerably above the maximum defined by the Portuguese law (400 Bq/m^3) [131], with a maximum of 2660 Bq/m^3, and an average concentration of 1432 Bq/m^3. Although the concentration of radon was high, it has to be taken into consideration that the building was unoccupied most of the time and thus had low ventilation rates.

During a short period of occupation, 7^{th} and 8^{th} of December, even with low ventilation rates (windows and doors were only open sporadically), as it was winter, the concentration of radon sharply fell to values below 300 Bq/m^3, as recommend by the Directive 2013/59/EURATOM [173]. Although the air change rate of the case study building was not measured, the results show that the way the occupants use the building is sufficient to maintain the radon concentrations within the mandatory values. Therefore, ventilation must not be neglected in this type of buildings, particularly after renovations when the airtightness of the envelope increases due to the replacement of windows and doors, and no other measures are implemented to mitigate the ingress of radon into the building. In buildings located in granitic areas, it is necessary to maintain a minimum hourly air change rate to remove radon or to renovate the ground floor, by introducing, for example, a waterproofing membrane that does not allow the flux of radon gas from the ground to the indoor environment. In the renovation of this case study, measures to prevent the ingress of radon gas into the building were not introduced, and therefore, the ventilation is the only way to control the radon gas concentration.

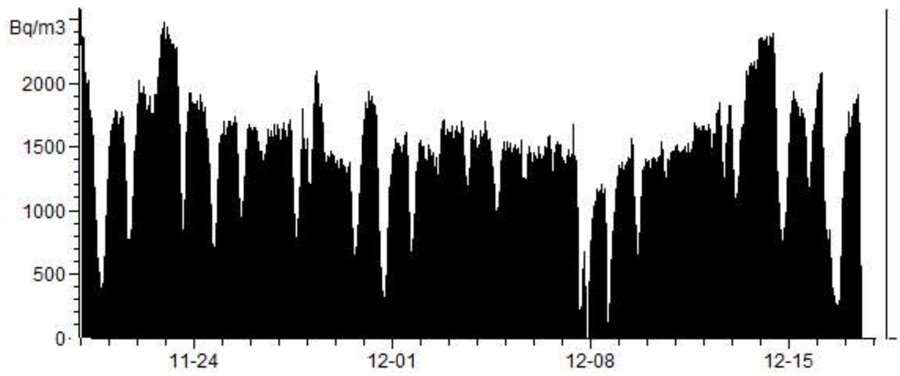


FIGURE 5.43. Concentrations of radon in the kitchen/living room during the Winter period.

5.2.7 CONDITIONS AND LIMITATIONS OF THE STUDY

The outcomes of this study are based on the analysis of the annual thermal behaviour of just one case study since in this region of Portugal it was not possible to identify other case studies in good state of conservation or that are still occupied. Nevertheless, this building is representative of the typical glazed balcony vernacular buildings of Northern Portugal, and has the typical functional organisation of this type of house, with the ground floor used to store goods and/or livestock (the coldest part of the building) and the occupied area on the first floor (part of the house with higher solar gains and comfort levels). In the case study building, the glazed balcony is the focus of the study, and it is representative of this type of architecture, due to its size and orientation. Additionally, the case study was refurbished and therefore presented good conditions to carry out the research.

The results presented are specific to this zone due to the particular type of climate. Nonetheless, the benefits of the glazed balconies can be extrapolated to other areas with similar climates and not only to buildings with similar characteristics.

Another limitation of this study is the fact that the building is a vacation house that is only used during weekends and holidays. Since this building is mainly used for short periods, especially during the winter, it is possible that some of the inhabitants' potential actions to improve the indoor environmental quality were not fully addressed.

5.2.8 CONCLUDING REMARKS

The results of this case study showed the viability of using glazed balconies as a passive heating strategy in a climate with cold winters. This type of building is common in the North of Portugal, in the North of Spain and in other regions where passive principles (as the glazed balcony) are implemented in buildings to increase solar gains during the heating season.

The glazed balconies act as a sunspace, increasing the contribution of solar gains in the maintenance of the thermal comfort conditions during the heating season. In the Portuguese vernacular architecture, these elements are usually well oriented, and there is a proportional relationship between their dimensions and the ones of the adjacent rooms. Glazed balconies are always on the upper floors, for better sun exposure, and are adjacent to living spaces (usually living rooms and bedrooms).

During the occupation period of the mid-seasons, the rooms in the balcony had adequate comfort conditions, since the occupants can easily control the solar gains using the shading system (opaque curtains). Not controlling the solar radiation increases the risk of overheating periods, as seen during autumn (when the building was not occupied).

In winter, the results showed that it is difficult to achieve adequate thermal comfort conditions without an active heating system. Nevertheless, during the thermal comfort assessment, performed on a cloudy day, the operative temperature was close to the lower limit of the thermal comfort range. Even when the building was in free-running mode, that was the case for most of the monitoring period, during sunny days with the solar shading active, it was possible to verify that the indoor air temperature increases considerably.

During the summer, the results showed that the thermal comfort conditions are within the comfort limits, but with some risk of overheating. The use of an external solar shading device will be more effective to reduce the risk of excessive solar gains and overheating during summer than the existing curtains.

From the results presented, it was possible to compare periods with and without occupation, which highlights the importance of occupants' actions in optimising the solar gains through the glazed balcony. Therefore, the occupants can regulate their comfort conditions by activating/deactivating solar shading and promoting natural ventilation (useful to remove air pollutants and heat loads — particularly during night-time).

Since the glazed balcony is the main passive strategy in this building, it is important to note that, by removing the partition wall between the glazed balcony and the other rooms, the original buffer zone was eliminated. The removed tabique wall thermal inertia was also useful, both in winter and summer, to maintain the indoor temperature more stable. The balcony would also act as a sunspace in winter, increasing the solar heat gains, and as a buffer space, reducing heat losses. In the summer, with the windows open, the glazed balcony will work as a shading device for the building walls.

The floor area of this kind of buildings is small for the current living standards and therefore, during refurbishment operations, the partition walls, between the rooms and the glazed balcony, were removed to increase the net floor area. Additionally, the traditional materials used in this type of buildings are being replaced by modern industrial materials (e.g. aluminium, steel and plasterboard). The lack of knowledge on the advantages of using this passive strategy is destroying this vernacular technique that is one of the architectonic identities of Northern Portugal vernacular architecture. Hence, during the renovation of this type of buildings, it is necessary to take into account the balance between the functional needs of the spaces and the effectiveness of existing passive strategies to harmonise them.

Additionally, further studies are needed to complement and corroborate the results presented, to understand better the effectiveness of this strategy, and to disseminate its advantages on improving thermal comfort conditions and reducing the energy needs for heating. Moreover, it is necessary to promote its use in new buildings, since the benefits have also already been discussed in other studies.

Regarding the indoor air quality, even after a renovation where the airtightness of the envelope was improved, the concentrations of carbon dioxide in the building did not exceed the most demanding design values for new buildings, according to EN 15251, even when the closed wood-burning fireplace was in operation. The measurements of the radon gas concentrations conducted during a long period without occupation showed average values above the maximum defined by national legislation. During the occupation period and even with low ventilation rates, the radon gas concentration rapidly decreased to acceptable values, thus, not harming the occupants' health. Nevertheless, the need to maintain a minimum hourly air change rate to remove air pollutants and assure a healthy indoor environment must be emphasised.

5.3 CASE STUDY 3 – SAFARA

In inland Southern Portugal, the vernacular architecture developed specific mitigation strategies, that in general are more focused on passive cooling during summer, as mentioned in previous publications [15, 16, 29]. From these strategies, the massive earthen walls stand out for keeping indoor temperature and relative humidity stable, as observed in other studies [15, 31, 174], particularly during summer, and are an element that characterises vernacular architecture from this region [40, 113]. The use of rammed earth in the region is ancient, and the flat terrain, dry climate and the abundance of clayey material were favourable factors to the use of earthen materials in a large scale [113].

5.3.1 SITE AND CLIMATE CONTEXTS

The case study is located in Safara, a small village in Moura's municipality, district of Beja, inland Southern Portugal (Fig. 5.44). The Safara territory has an ancient occupation, with some archaeological remains dating back to the 2nd Iron Age [175]. The Romans (3rd century BC to 5th century AD) and the Arabs (8th to 13th century AD) had a long dominance of this territory. This territory was integrated into the kingdom of Portugal in the 13th century [176, 177]. The origin of the village name has been attributed to the Arabs [176, 177] and means extensive flat land without trees, but also adjectives as desert, arid and harsh [178–180].

Strategically implanted, the village is next to the confluence between a river and two streams. It is located in a plain area of fertile agricultural land (abundant in cereals and olive trees [176, 177]). However, it is implanted in the transition area to the rugged terrain of streams' valleys and on the less fertile soil (lithosols), in border limit of the fertile land (Fig. 5.45a). Additionally, the characteristics of the surrounding soil show that they are

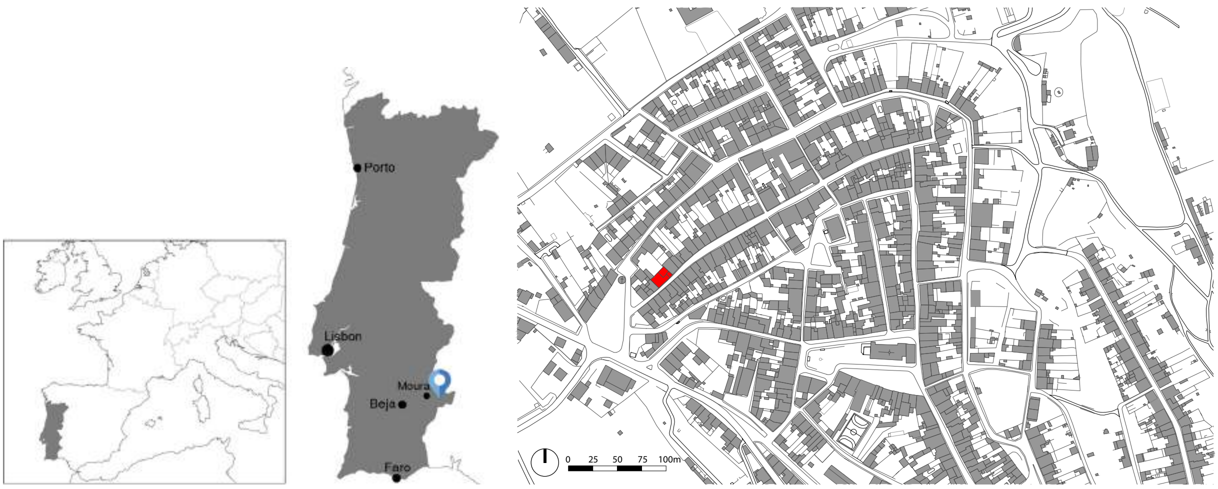


FIGURE 5.44. Case study's location. (left) country context; (right) Case study position in Safara's current urban layout.

rich in clay (luvisols and vertisols) (Fig. 5.45b) and at a lithological level the presence of limestone and calcareous formations (Fig. 5.45c). These features were favourable factors in this site for using earth as a building material - the clayey soils for rammed earth, tiles and bricks; and the limestone to produce lime for plasters, whitewash, etc. For example, the ancient military walls of Safara were built in rammed earth [181].

The village's urban layout is compact with a mix of narrow and wide streets, composed mostly of single-storey buildings (Fig. 5.44). Most of the buildings have a private courtyard, with vegetation, that acts as a thermal regulator, as explained in previous sections. The irregular and compact urban layout of narrow streets, with almost no streets and facades facing south, allows reducing heat gains by the envelope.

This region has a Mediterranean climate, sub-type Csa, with hot and dry summer, being one of the hottest Portuguese regions during summer (Fig. 5.46a) [110]. The annual average mean temperature is 17.5 °C, 12.5 °C in the winter (Fig. 5.46b), while in the summer it is between 22.5/25.0 °C (Fig. 5.46c) [110]. Summer is the most demanding season in this area. The average maximum air temperature in summer varies between 30 °C and 35 °C [110], reaching maximum temperatures of 40 °C or 45 °C in some days, and the number of days with a maximum temperature above or equal to 25 °C is around 110 [110] (Fig. 5.46d). The annual average rainfall is below 500 mm, and July is the driest month (below 5 mm) [110].

5.3.2 CASE STUDY BUILDING

The building chosen is representative of inland southern vernacular architecture, presenting a range of strategies to minimise heat gains and to promote passive cooling. All the original building elements and techniques were preserved and maintained. It was not possible to identify the date of construction, but, according to the owners, it is probably from the 19th century. It was renovated in 1983 and this intervention, beyond the maintenance of some building elements, introduced some improvements such as bathroom facilities, insertion of glass in windows (original windows had only wooden shutters), and the old kitchen was transformed into a small living room.

The case study is integrated into an urban mesh, in a row of buildings forming a street-front (Fig. 5.44). It has main and rear facades facing southeast (street) and northwest (patio), respectively (Fig. 5.47). The gross floor area is approximately 200 m^2 divided into two storeys.

The upper storey is just a small attic area (originally a granary). On the ground floor, facing southeast, are the living areas and the bedrooms, and in the northern part the kitchen and the bathroom (Fig. 5.48). A vaulted corridor connects these two parts, and is also the connection between the street and the courtyard (Fig. 5.49b). Most of the construction elements used in the building are made of earthen materials. The

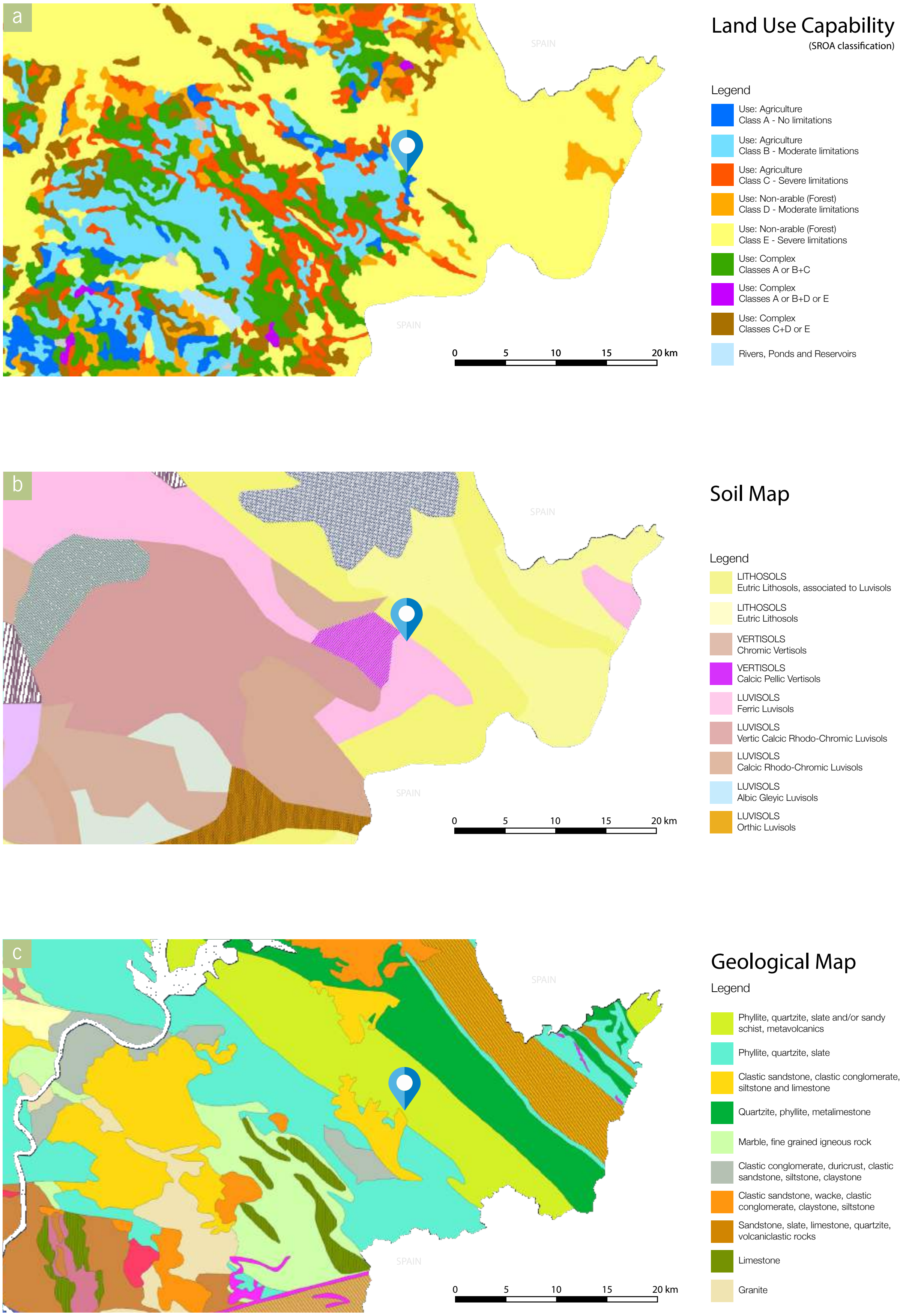


FIGURE 5.45. (a) Land Use Capability Map of Safara area (adapted from [150]); (b) Soil Map of Safara area (adapted from [151]); (c) Geological Map of Safara area (adapted from [152]).

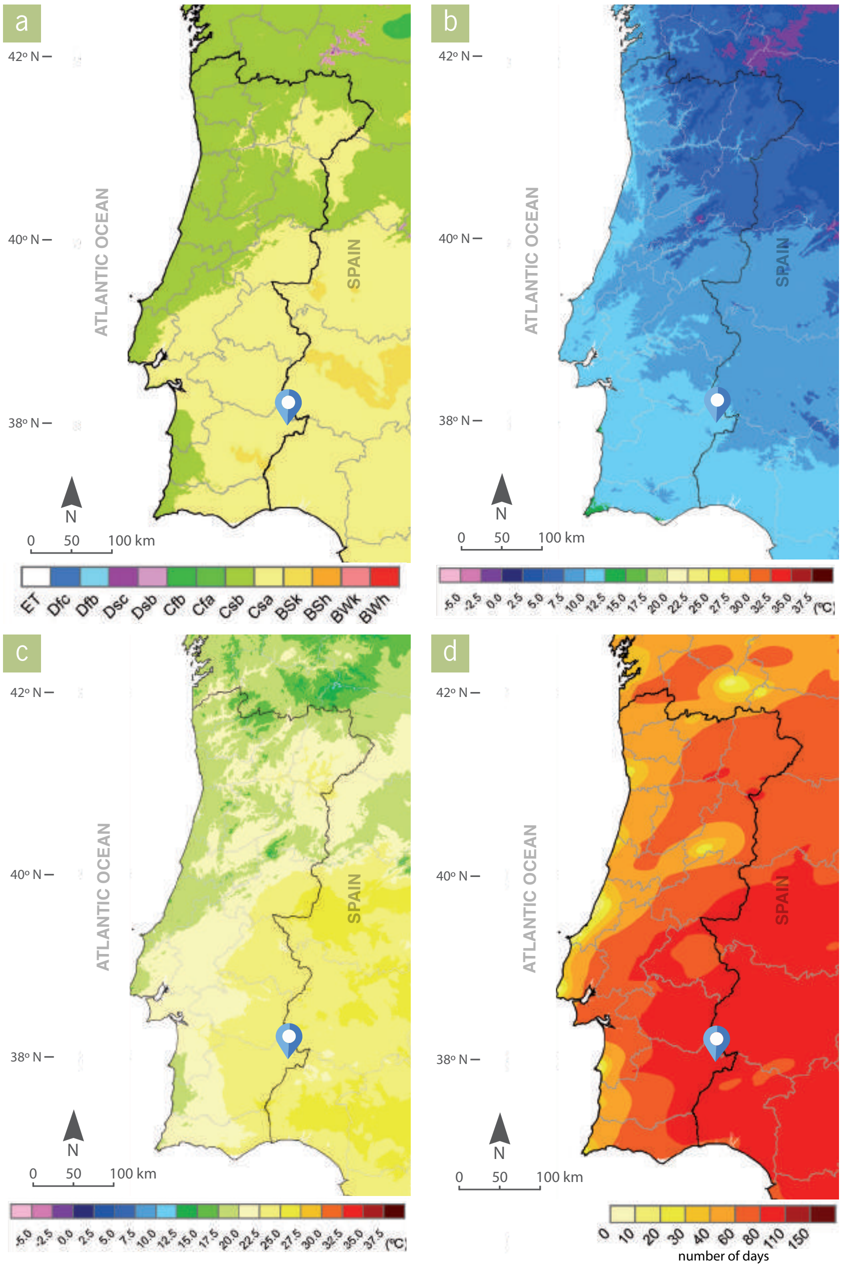


FIGURE 5.46. a) Köppen-Geiger Climate Classification for Portugal; b-c) Average mean temperature in winter and summer; d) Average number of days with maximum temperature ≥ 25 °C in summer (adapted from [110]).

building envelope consists of whitewashed rammed earth walls (average thickness of 60 cm) with a pitched roof, wooden doors and wooden framed single glazed windows (Fig. 5.49a). Indoors, the partitions walls are in rammed earth, and several of the indoor spaces are vaulted, and the floor is paved with *baldosa* - a sun-dried clay tile (Fig. 5.49c,e). It is relevant to highlight the existence of small ventilation shutters above the glazed windows to promote controlled natural ventilation, which are particularly useful for night cooling, without compromising the safety of the occupants (Fig. 5.49d). The building has no air-conditioning system. It has a wood-burning stove (Fig. 5.49f), and occupants sporadically use electric fan heaters to heat some rooms. Table 17 lists the calculated thermal transmittance coefficient (U-value) of the building envelope.

FIGURE 5.47. External views. (left) southeast façade; (right) northwest façade.

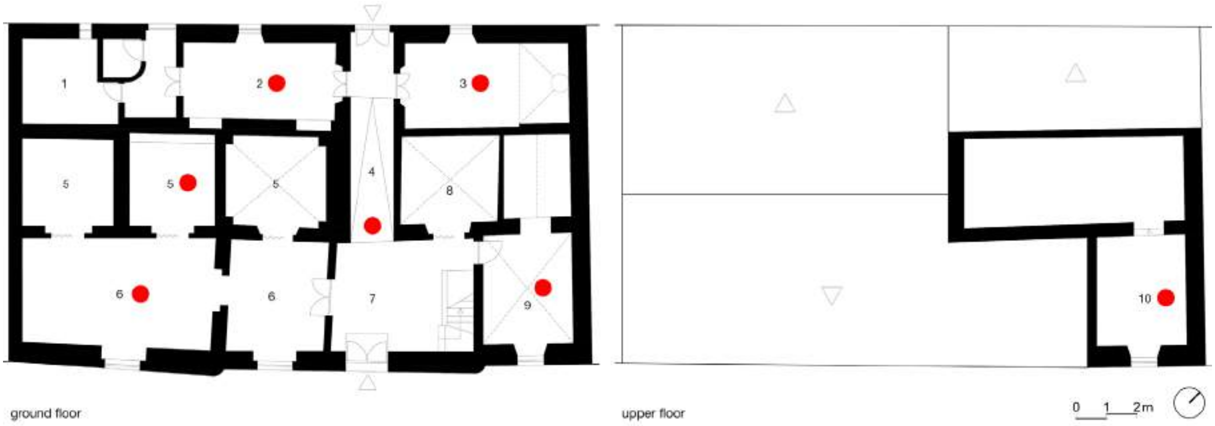


FIGURE 5.48. Floor plans showing the location of measuring instruments (1 – bathroom; 2 – kitchen; 3 – old kitchen (small living room); 4 – corridor; 5 – alcove; 6 – living room; 7 – entrance; 8 – library; 9 – bedroom; 10 - attic).

FIGURE 5.49. (a) Wooden-window; (b) Indoor corridor; (c) vaulted room; (d) ventilation shutter; (e) kitchen view; (f) Wood-burning stove.

TABLE 17. Characteristics of the building envelope

Envelope element	Materials	U-value (W/(m^2.°C))
External Walls	Rammed earth (60 cm)	2.87 [137]
Roof	Clay tiles, an insulation layer of sprayed polyurethane foam (SPF) (5 cm) and reeds on timber structure	0.49 [136]
Doors	Solid timber	2.15 [136]
Windows	Single glazed timber frame windows, indoor wooden shutters	3.40* [136]

*U_{wdn} - day/night heat transfer coefficient, including the contribution of shading systems.

5.3.3 PASSIVE STRATEGIES

To suit the climatic conditions mentioned, specific mitigation strategies were developed, focusing on passive cooling during summer [16, 29]. With this purpose, several vernacular architecture techniques were developed, like the ones found in the case study, such as [16, 29, 40, 112]:

- The size and number of windows and doors facing the outdoor environment are minimised to reduce solar gains. The use of small windows, recessed in the façade, allows the head and side jambs of the window to work as a shading element (Fig. 5.47);
- The use of high thermal inertia building elements, namely rammed earth walls and vaulted ceilings allow a first dampening of the external thermal wave and keeps the indoor temperature and relative humidity more stable. The vaulted ceilings also allow increasing the height of the indoor spaces and therefore the thermal stratification (Fig. 5.49c);
- The use of light colours for the building envelope, mainly whitewashed surfaces, to reflect the incident solar radiation (Fig. 5.47);
- Ventilation openings that are integrated into windows and doors, to promote air circulation and night cooling to remove diurnal thermal loads. This technique allows ventilation without compromising privacy and security (Fig. 5.49b, e);
- The patio (courtyard) allows not only creating a private outdoor space but also generating a microclimate close to the building. In this case, the patio has trees and several flower beds, useful to shade the ground and the building and also to generate a cooling effect through the evapotranspiration of plants;
- The urban layout, namely the use of narrow streets, is also a strategy used to reduce heat gains by the building envelope (Fig. 5.44).

The combination of all these strategies allows achieving indoor thermal comfort conditions during the summer season by passive means alone. This aspect highlights the advantages of a holistic understanding of the available resources.

The long tradition in applying the abovementioned strategies in the region, beyond a cultural influence, is a consequence of their effectiveness in mitigating the effects of the climate, as shown in previous studies [15, 16]. The quantitative study of these passive strategies, and their impact on the thermal performance, is described and discussed in the following sections.

5.3.4 OCCUPANCY AND USE PROFILE

Occupant's daily habits influence the thermal performance of a building, and the occupancy profile is synthesised in Table 18. During the monitoring, the building was kept in a free-running mode most of the time.

TABLE 18. Building occupancy and use profile

Season		Use and description
Spring	heating/cooling	Sporadic heating is used in cool days (March and April). The pattern is: wood-burning stove (6 pm-11:30 pm); fan heater in the kitchen (1 h, three times per day during meals) and in the main bedroom (10 pm-10:30 pm).
	ventilation	Daily opening of the ventilation shutters in the living room and bedroom (9 am-1 pm, until the middle of May; 7:30 am-9:30 am, from the middle of May till June).
	shading	From the middle of May, the main façade (SE) windows and shutters are closed until 2 pm; rear façade (NW) windows and shutters are closed between 2 pm-8 pm.
Summer	heating/cooling	No cooling or heating systems are used.
	ventilation	Daily opening of the ventilation shutters all around the house (6 am-9 am).
	shading	Main façade (SE) windows and shutters are closed from 9 am to evening; rear façade (NW) windows and shutters are closed between 2 pm-8 pm.
Autumn	heating/cooling	Heating (from middle November forward). The pattern is: wood-burning stove (working days, between 6 pm-11:30 pm; weekends and holidays, from 11 am-11:30 pm); Fan heater in the kitchen (1 h, three times per day during meals) and the main bedroom (between 10 pm-10:30 pm).
	ventilation	Sporadic opening of the ventilation shutters (between 9 am-11 am) is used.
	shading	No shading is used.
Winter	heating/cooling	Heating (for all season). The pattern is: wood-burning stove (working days, between 6 pm-11 pm; weekends and holidays, between 11 am-11:30 pm); fan heater in the kitchen (1 h, two to three times per day during meals) and in the main bedroom (between 10 pm-10:30 pm).
	ventilation	Sporadic opening of the ventilation shutters (between 9 am-11 am).
	shading	No shading is used.

5.3.5 THERMAL MONITORING AND INDOOR COMFORT EVALUATION

The thermal performance monitoring and indoor comfort evaluation were carried out for all seasons. The data obtained in thermal monitoring is presented for approximately 30 representative days of each season. In this chapter, the results are addressed and discussed.

5.3.5.1 AUTUMN

During Autumn monitoring (10th November to 19th December 2014), the outdoor mean air temperature was about 12.5 °C (Table 19). The daily maximum and minimum air temperatures have significant variations almost during all the monitoring period, with a clear difference between the first and second half of the monitoring period (Fig. 5.50a). Although the daily outdoor temperature varies between 5 °C and 10 °C, it is found that indoor temperature remained very stable over the monitoring period with a slight decrease in the second half (around 4 °C) (Fig. 5.50a). The rooms that are occupied during most of the time (living room, alcove, bedroom, and kitchen) have average temperatures between 17.4 °C and 18.5 °C, as shown in Table 19. These average values show that rooms are near the bottom comfort threshold defined by the standards (18 °C). The occupants used heating devices only in the coldest days and during short periods (Table 18). The use of these systems is easily visible by the temperature peaks in some hours of the day (Fig. 5.50a). Therefore, for a free-running building without thermal insulation in the majority of its envelope and without a heating system permanently operating to maintain a constant temperature, the building has an interesting temperature profile for this season, with stable temperatures (even if in some cases below the 18 °C comfort threshold) and considerably above the ones recorded outdoors. The rooms with sporadic occupation (attic, corridor, and old kitchen), showed similar stable profiles but with values slightly below the ones of the other rooms. This behaviour is due to their position, orientation, and use. The high thermal inertia of the building envelope justifies this behaviour, delaying the effect of outdoor temperature variation and stabilising indoor temperature.

The value of the average outdoor relative humidity was high (84%). In contrast, indoor spaces have stable relative humidity profiles with small day/night fluctuations and considerably lower average values (Fig. 5.50b; Table 19). The main rooms have relative humidity values above 60% most of the time — the maximum recommended for human health and comfort in new buildings [130, 182]. Nevertheless, the small difference to the recommended humidity range values and the difference between indoor and outdoor values should be highlighted. The hygroscopic inertia and the capacity of rammed earth walls and lime renders to absorb moisture are responsible for this good behaviour.

TABLE 19. Comparison between outdoor and indoor air temperatures and relative humidity values during the Autumn

AUTUMN								
	Outdoor	Living room	Alcove	Bedroom	Attic	Corridor	Old kitchen	Kitchen
Temperature (ºC)								
Mean	12.5	18.4	18.5	17.5	15.8	17.3	16.1	17.4
Maximum	21.0	25.0	20.0	19.4	20.4	19.4	18.1	21.7
Minimum	3.0	15.4	16.5	14.8	11.5	14.4	12.6	13.8
Relative Humidity (%)								
Mean	83.8	61.5	64.8	66.8	74.0	71.6	74.0	70.9
Maximum	96.1	71.0	73.0	74.0	80.0	83.1	80.8	88.6
Minimum	58.2	38.0	52.0	53.0	68.0	59.5	67.5	53.6

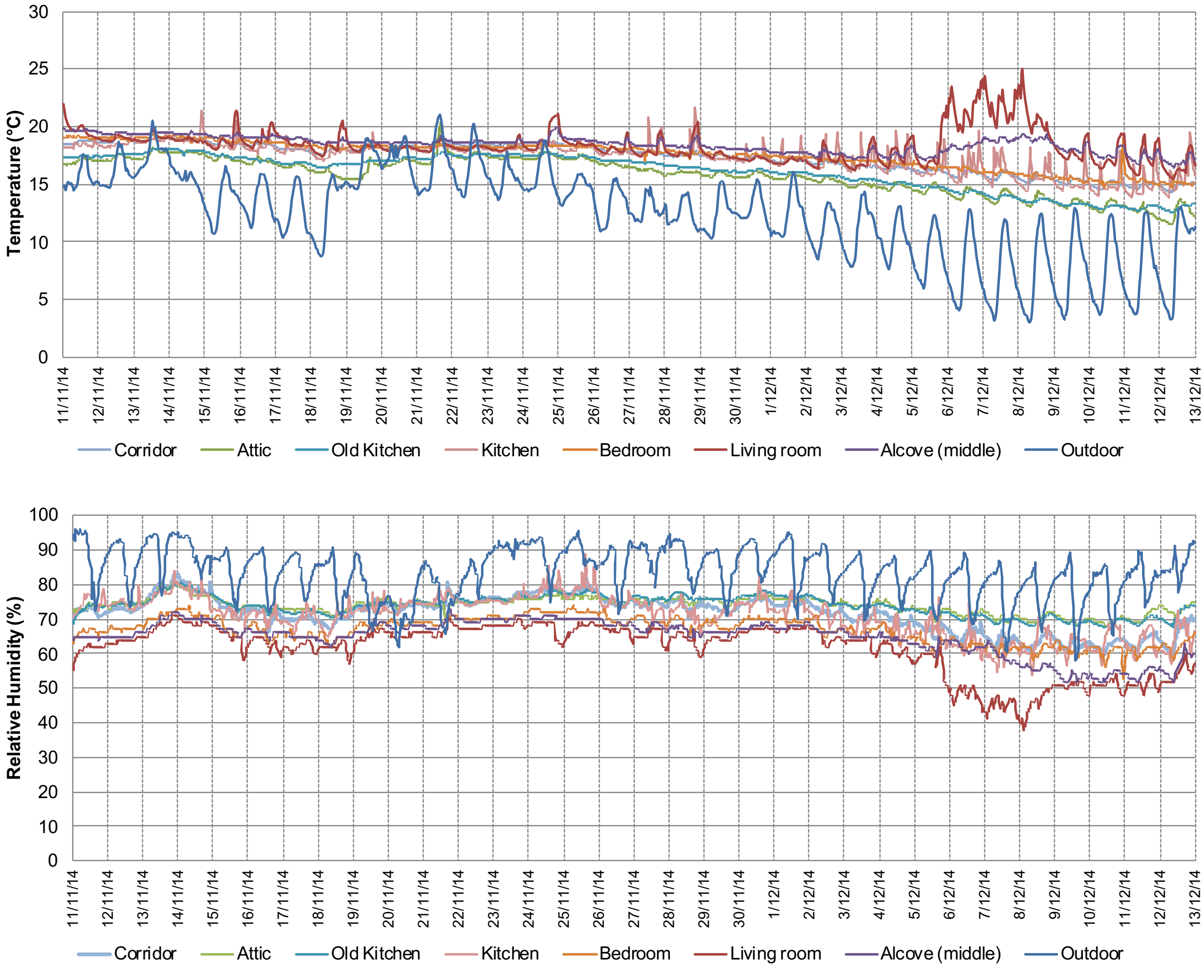


FIGURE 5.50. Autumn: (a) Indoor and outdoor air temperature profiles; (b) Indoor and outdoor air relative humidity profiles.

Regarding the assessment of thermal comfort (Fig. 5.51), the measurement of the thermal environment conditions was conducted during a day, with and without the heating system active. During autumn and without the heating system active (Fig. 5.51 left), the results show that the thermal comfort conditions in the living room (where the occupants remain longer during the day) are slightly higher than the lower comfort limit. With the use of the wood-burning stove, it was possible to reach thermal comfort conditions in the living room close to the upper level of the comfort temperature range (Fig. 5.51 right). From the temperature profile (Fig. 5.50a), it can be seen that it is possible to reach comfort temperatures with a simple heating system rapidly. Nevertheless, in other rooms, it was verified that the thermal sensation was below the thermal comfort limits and a heating system is necessary to achieve thermal comfort conditions.

In the "thermal environment survey", occupants expressed their thermal sensation in the following way: 1) when the wood-burning stove was "OFF", all occupants answered they were "slightly cool" (1.0 met; 0.88-0.98 clo); 2) when the wood-burning stove was "ON" – the occupants answered they were "neutral" (comfortable) (1.0 met; 0.75-1.25 clo). The differences in clothing insulation are related to the thermal sensation of each occupant that depend on different factors, such as age, gender, and psychological condition. The results from subjective evaluation validated the objective measurements.

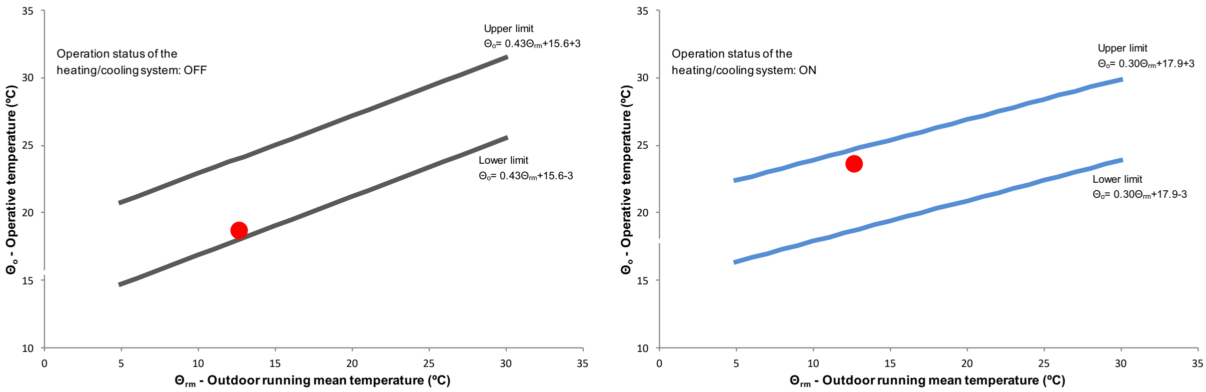


FIGURE 5.51. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the living room during one representative Autumn day – (left) Heating OFF; (right) Heating ON.

5.3.5.2 WINTER

In the winter monitoring, carried out between 22nd December 2014 and 8th February 2015, the outdoor mean air temperature was 7.3 °C, with the maximum often above 12 °C and the minimum usually below 5 °C, reaching some days nearly 0 °C (Table 20; Fig. 5.52a). In this season, the graph of indoor temperatures shows several peaks due to the use of heating devices, like the wood-burning stove and electric fan heaters, in the living room, and the kitchen and bedroom, respectively (Fig. 5.52a).

In a period when the occupants were out (between 5th to 8th January), it is possible to see the passive behaviour of the building and a gradual stabilisation of the indoor temperatures. In the living room, after the turn-off of the wood-burning stove, temperature values took about 24 hours to decrease from 24 °C to 18 °C, and more than 50 hours to reach 15 °C. At the same time, the temperature in the alcove next to the living room took more than 80 hours to decrease from 19 °C to 15 °C. This slow temperature decrease is explained by the thermal inertia and high heat storage capacity of the building elements, particularly the massive external and internal walls. If with short heating periods the temperature decrease is slow, it could be expected that with longer heating periods the temperature stabilisation would reduce the energy use for heating. Further studies are needed to confirm this since long heating periods are not frequent in Portuguese living habits.

Although the bedroom is a space where higher temperature values are expected, compared with the other occupied spaces it is the one with the lowest temperatures (slightly below 15 °C). The occupants heat the room only until they feel comfortable to undress/dress in the morning and at night and this is visible in the temperature peaks of about 18 °C in those periods of the day (Fig. 5.52a). The attic and the old kitchen are not heated areas and presented a stable temperature value around 12 °C.

In what relative humidity is concerned, maximum outdoor values were frequently around 90% (Fig. 5.52b) and indoor rooms with longer occupation periods had lower daily variations and average values between 50% and 65% (Table 20). The living room and the alcove showed values between 40-60% most of the time and this result is influenced by the stove. The bedroom also had a stable profile but with slightly higher values than previously referred rooms. Although the indoor relative humidity values reached in some rooms values above the one recommended for human health (≤60%), they were considerably lower than the outdoor values and were within the range of 20-70% for Category III buildings [130]. The lower values and the stability of the indoor relative humidity profiles are due to the hygroscopic inertia of the building elements, namely rammed earth walls, unfired clay tiles (baldosa), lime plaster, which have the capacity to regulate air humidity [1].

TABLE 20. Comparison between outdoor and indoor air temperatures and relative humidity values during the Winter

WINTER								
	Outdoor	Living room	Alcove	Bedroom	Attic	Corridor	Old kitchen	Kitchen
Temperature (ºC)								
Mean	7.3	18.0	17.1	13.8	12.0	14.1	12.1	15.4
Maximum	14.7	25.8	20.7	19.3	14.4	16.6	15.4	22.2
Minimum	0.2	13.6	14.9	12.3	10.4	12.6	10.7	12.2
Relative Humidity (%)								
Mean	81.1	49.5	56.2	65.1	73.9	68.2	73.4	61.3
Maximum	97.8	63.0	67.0	75.0	84.0	86.8	84.4	81.6
Minimum	24.7	33.0	39.0	52.0	63.0	55.2	64.9	45.8

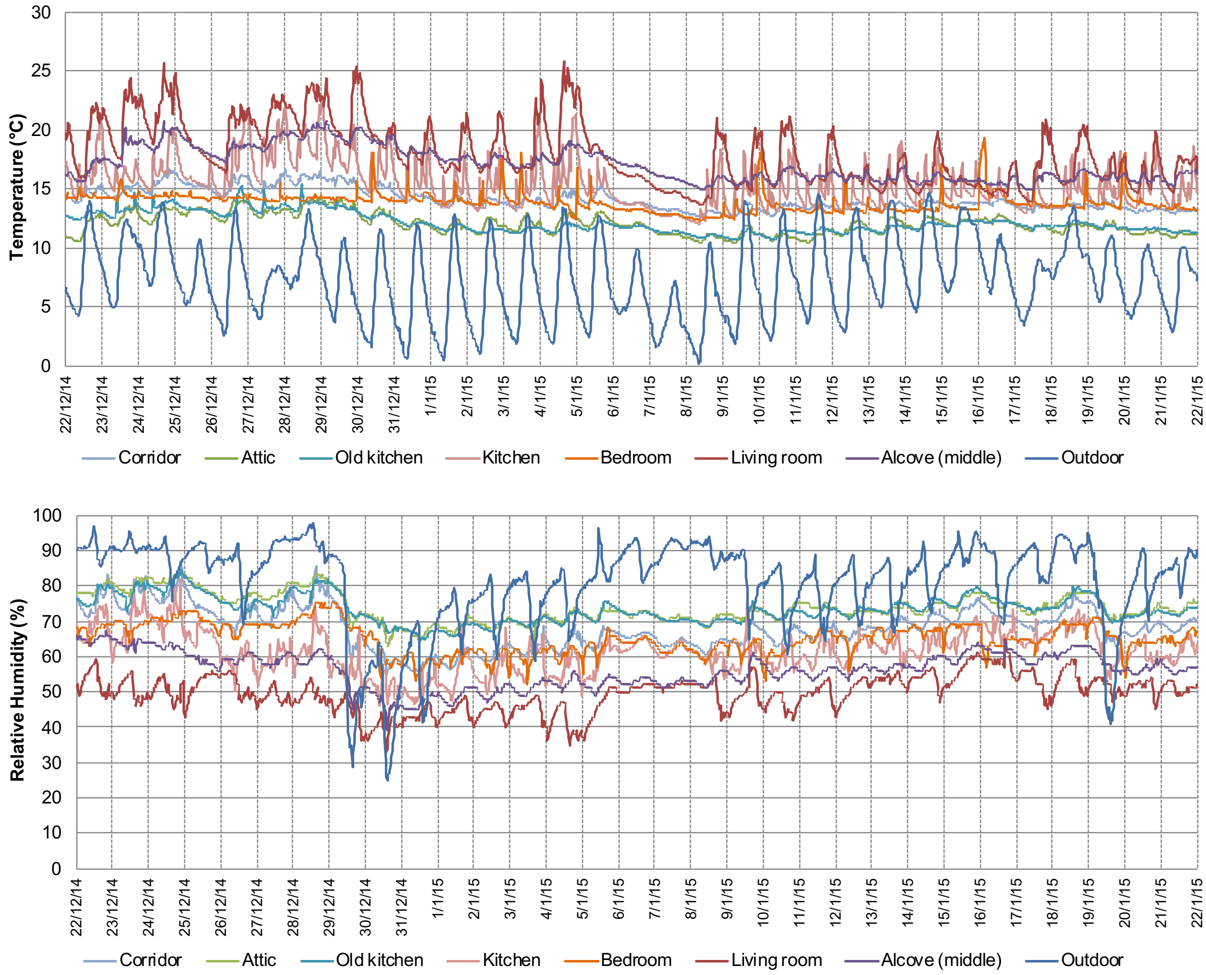


FIGURE 5.52. Winter: (a) Indoor and outdoor air temperature profiles; (b) Indoor and outdoor air relative humidity profiles.

Concerning thermal comfort, in this measurement, the wood-burning stove was in operation all the time. The results showed that the living room had good thermal comfort conditions, slightly above the middle of the comfort range (Fig. 5.53). In the context of a cold week (Θ_{rm} of 5.9 °C), it was only possible to reach adequate thermal comfort conditions when the wood-burning stove was in operation. From the measurements, it is possible to conclude that the conditions [126, 127, 130] that allow the use of the air temperature as a proxy for the operative temperature were satisfied. It was also possible to conclude that the alcove had acceptable comfort conditions and that the other rooms were below the thermal comfort limits.

In the survey, three occupants answered as being “neutral” (comfortable) (1.0 met; 1.08-1.31 clo) and one as being “slightly cool” (1.0 met; 1.04 clo). Although there was one occupant that was slightly uncomfortable, it is possible to conclude that most occupants feel comfortable with the thermal environment and therefore the results from the subjective evaluation corroborated the objective measurements. Compared to the other occupants, the occupant that felt slightly uncomfortable had lower clothing thermal insulation, and this can be an explanation for the different perceived comfort level.

From the results presented above, it was possible to conclude that a heating system is required to achieve thermal comfort conditions during the winter season. The calorific power of the wood-burning stove allowed rapidly increasing the air temperature to thermal comfort levels in the living room. Its use in the living room is adequate since it is the bigger room and where occupants stay for more extensive periods. Since the case study is an old building, without a central heating system, the effect of using the electric fan heaters cannot be neglected, even if for short periods. Though not a piece of energy-efficient equipment, the occupants had to use them to quickly increase the temperature by convection in the kitchen and the bedroom and to reduce thermal discomfort sensation during meals and dress/undress periods. The sporadic use of this type of equipment is also in line with Portuguese cultural habits of intermittent heating.

The results are in line with other studies devoted to high thermal inertia buildings [23, 31], where stable temperatures in the indoor environment were also observed, and that also highlighted the importance of using heating equipment to reach the comfort thresholds.

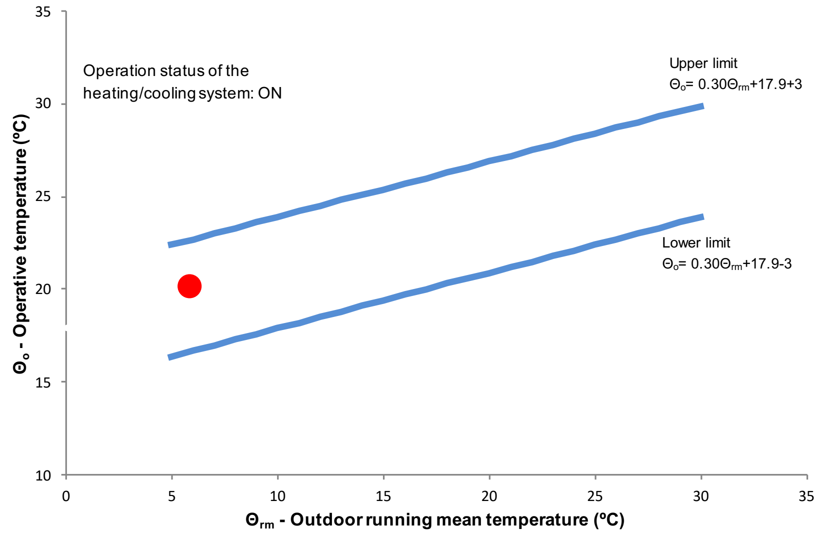


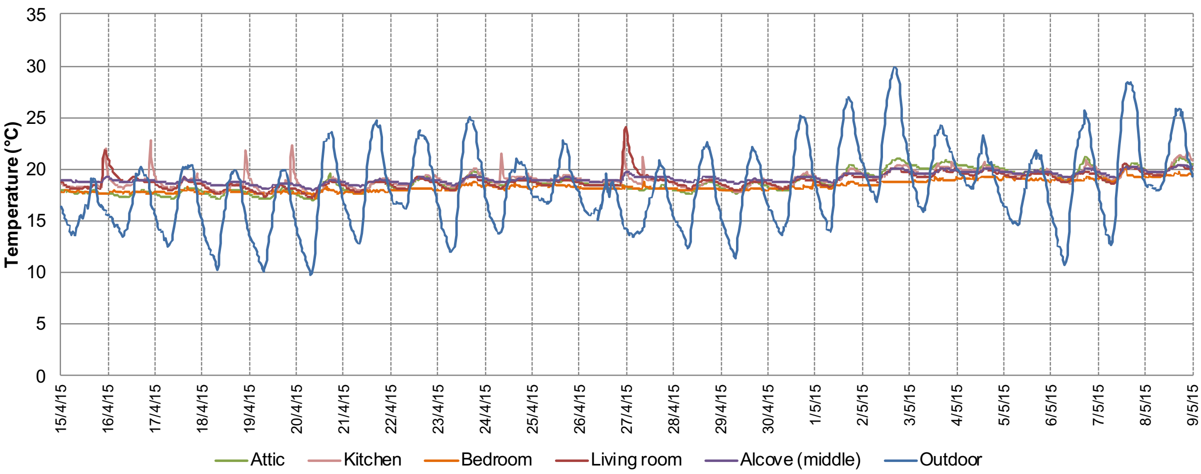
FIGURE 5.53. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the living room during one representative Winter day.

5.3.5.3 SPRING

During spring monitoring (14th April to 9th May 2015), the outdoor mean air temperature was about 18.2 °C, with maximum values often above 20 °C and minimum values frequently above 10 °C (Table 21; Fig. 5.54a). In this monitoring campaign, data for two compartments (corridor and old kitchen) was lost due to equipment errors. Indoor air temperature variations were practically imperceptible, with mean temperature values for the main rooms between 18.3 and 19.1 °C (Table 21), above the minimum comfort threshold (18 °C) for the heating season.

TABLE 21. Comparison between outdoor and indoor air temperatures and relative humidity values during the Spring

SPRING						
	Outdoor	Living room	Alcove	Bedroom	Attic	Kitchen
Temperature (ºC)						
Mean	18.2	18.9	19.1	18.3	18.8	19.1
Maximum	29.9	24.0	20.4	20.1	21.2	22.8
Minimum	9.8	17.2	18.0	17.2	17.0	17.5
Relative Humidity (%)						
Mean	64.2	61.6	64.9	68.8	67.9	68.7
Maximum	92.7	66.0	69.0	75.0	74.0	82.1
Minimum	25.1	49.0	54.0	52.0	46.0	45.7



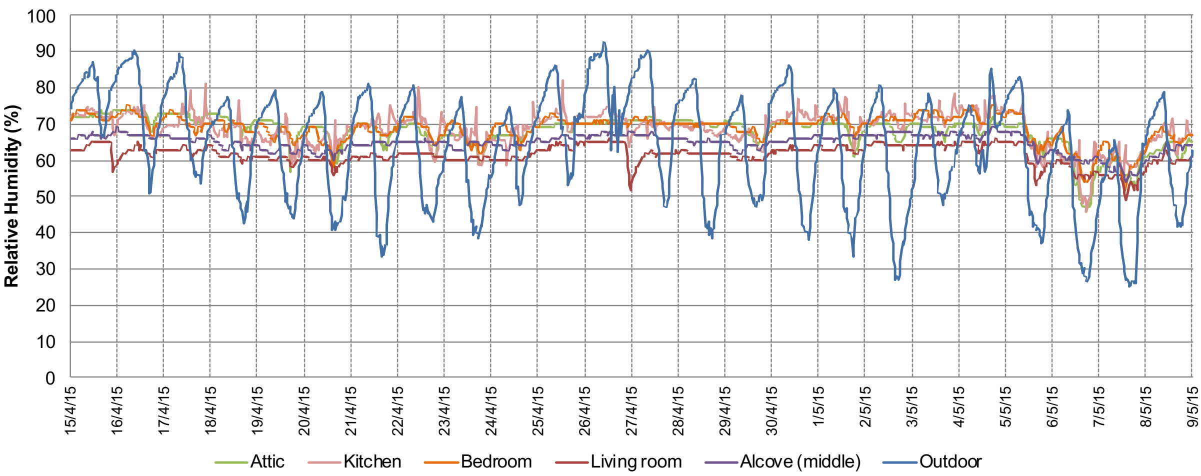


FIGURE 5.54. Spring: (a) Indoor and outdoor air temperature profiles; (b) Indoor and outdoor air relative humidity profiles.

The variation of the outdoor day/night relative humidity was high, frequently with maximum values around 80% and minimum between 40-50% (Fig. 5.54b; Table 21). Indoor mean values were similar (62-69%) to the outdoor mean value, however significantly more stable and, in some rooms, with almost no variation. All rooms had relative humidity values above the recommended for human health (≤ 60%), but they were very stable, and some were only slightly above this limit.

The thermal comfort assessment was conducted on two different days, one in mid-April and the other in mid-May. The results show that the living room had thermal comfort conditions on the lower limit of the comfort range for both days (Fig. 5.55).

In the survey carried out in mid-April, the occupants answered they were "neutral" (comfortable) (1.0 met; 0.68-1.25 clo). In this measurement, one of the occupants had a "clo" value significantly higher (almost the double) than the others. A possible explanation is that there was a physiological factor influencing the perceived thermal comfort of this occupant. In the other survey (mid-May), the occupants answered they were "neutral" (comfortable) (1.0 met; 0.43-0.51 clo). Although the adaptive comfort graphs (Fig. 5.55) show a thermal comfort condition in the lower limit, the results from subjective evaluation show occupants' "neutrality", which confirm the results from the objective measurements. In this case, the influence of outdoor conditions in occupants' adaptation is well expressed. The charts in Figure 5.55 show almost the same thermal sensation for a higher outdoor and indoor temperature, being the clothing thermal insulation considerably different in the two days.

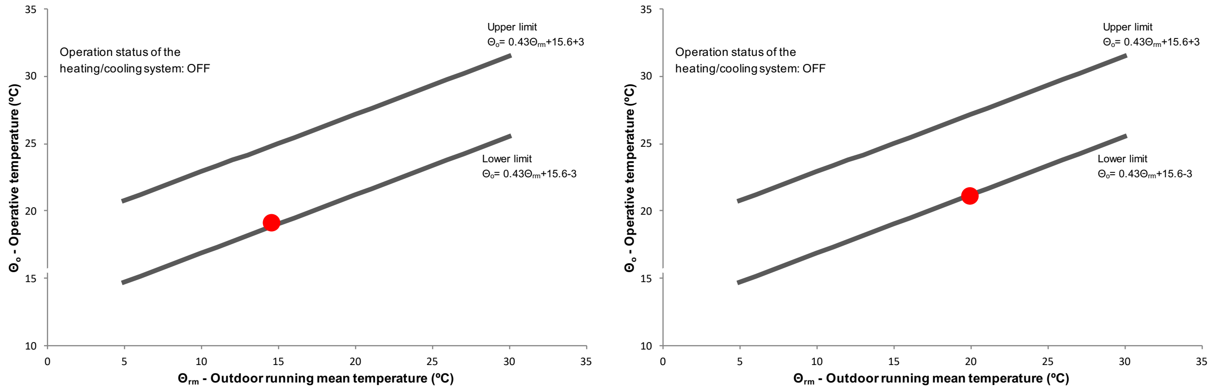


FIGURE 5.55. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the living room during two representative Spring days – mid-April (left) and mid-May (right).

5.3.5.4 SUMMER

In this monitoring (22nd June to 22nd September 2015), the outdoor mean air temperature was 28.4 °C, the maximum was often above 35 °C, reaching 40 °C in some days (Table 22; Fig. 5.56a), and the minimum was usually above 20 °C. In this monitoring period, data were lost for the kitchen due to equipment errors. Although there was a significant daily outdoor temperature variation, with high maximum temperatures, it is verified that indoor temperatures remained very stable over the period, with mean temperature values between 26.7 °C and 27.1 °C in the main rooms (Table 22; Fig. 5.56a). The maximum temperature values recorded were slightly higher than the value of the mean temperatures but only express sporadic conditions (less than 2 hours) (e.g. windows openings, etc.). The attic, due to its location near the roof, had the highest mean air temperature. Nevertheless, it acts as a buffering space, protecting the bedroom below from the outdoor heat.

The indoor temperature profiles showed that the heavy thermal inertia of the building envelope has an important role in delaying the heat transfer process and in stabilising the indoor temperatures. Additionally, the materials/building elements used indoors namely rammed earth partition walls, vaulted ceilings and unfired clay tiles provide additional heat storage capacity, particularly useful to stabilise indoor temperature during the summer.

For the relative humidity, there was a high outdoor day/night variation (in some cases of about 60%) (Table 22; Fig. 5.56b). In contrast, indoor rooms had more stable relative humidity profiles, with fluctuations between 40% and 60%, within the most appropriate range for human health and comfort [182]. As mentioned before, the differences between indoor and outdoor relative humidity values are justified by the hygroscopic inertia of the building elements.

Regarding the thermal comfort assessment, the results for this season showed that the living room had thermal comfort conditions in the centre of the comfort range (Fig. 5.57). In the survey, the occupants answered they were “neutral” (comfortable) (1.0 met; 0.35-0.47 clo) and these results

TABLE 22. Comparison between outdoor and indoor air temperatures and relative humidity values during the Summer

SUMMER						
	Outdoor	Living room	Alcove	Bedroom	Attic	Kitchen
Temperature (ºC)						
Mean	28.4	26.8	27.1	26.7	28.6	26.8
Maximum	40.0	28.4	28.2	27.8	30.2	30.3
Minimum	16.9	24.2	25.1	24.9	25.2	22.2
Relative Humidity (%)						
Mean	43.1	47.9	50.6	52.2	47.8	49.2
Maximum	78.7	58.0	60.0	61.0	55.0	64.3
Minimum	11.9	34.0	37.0	37.0	34.0	31.5

confirmed the objective measurements.

To achieve these thermal conditions, the active behaviour of the occupants to improve their comfort conditions should be highlighted. For instance, they promoted passive cooling by natural ventilation during the night and early morning and shut the doors and windows during the rest of the day, as presented in Table 18.

From these results, it is possible to conclude that the building has a good thermo-hygrometric performance during the most demanding season of this climate zone, without having mechanical cooling systems, confirming the effectiveness of the passive cooling strategies used. The results of this study are in line with the results and conclusions observed in other studies focusing high thermal inertia buildings in Mediterranean countries [23, 31, 183], which also highlight, for this type of buildings, the possibility of achieving good comfort conditions during summer by passive means alone.

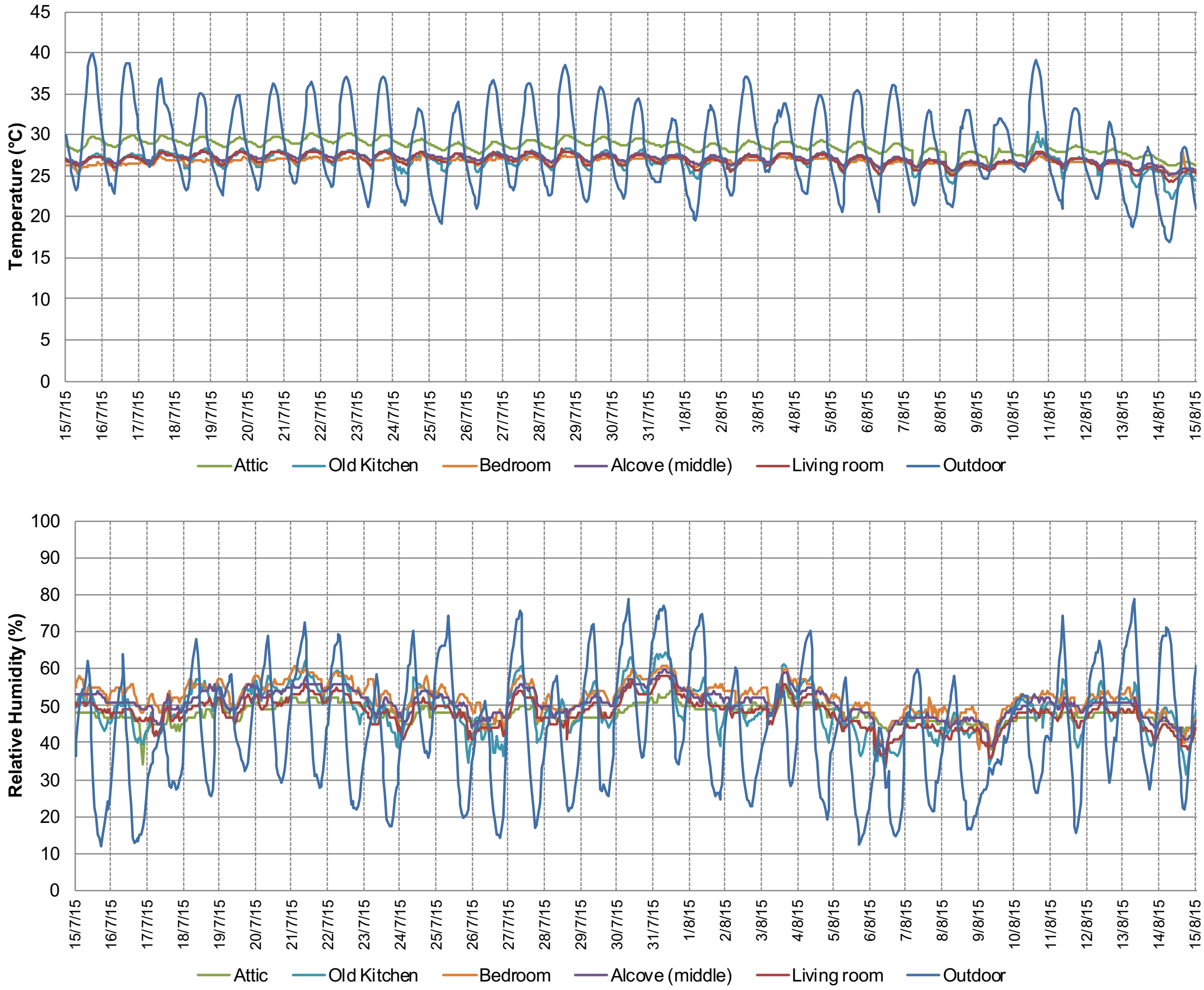


FIGURE 5.56. Summer: (a) Indoor and outdoor air temperature profiles; (b) Indoor and outdoor air relative humidity profiles.

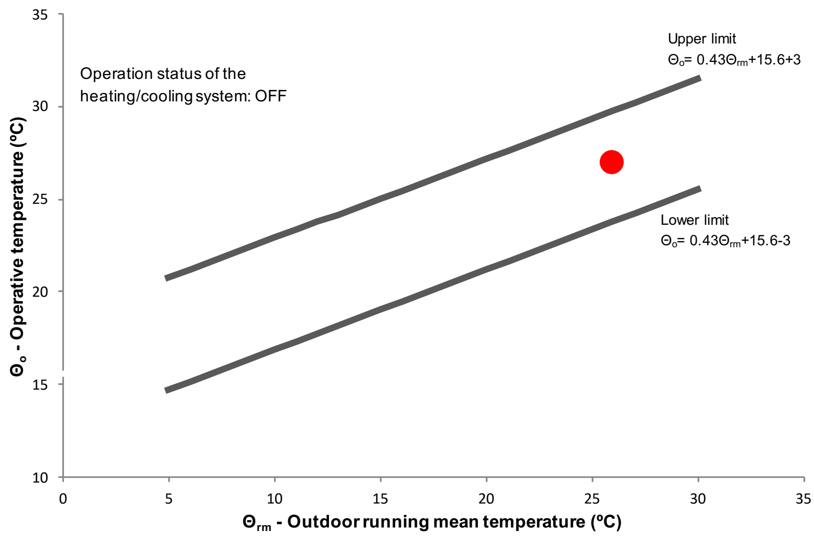


FIGURE 5.57. Adaptive comfort chart. Thermal comfort temperature (operative temperature) in the living room during one representative Summer day.

5.3.6 CLASSIFICATION OF THE INDOOR ENVIRONMENT ACCORDING TO THE STANDARD EN15251

In this section, the indoor environment of the case study is evaluated and classified, according to the categories defined by standard EN15251 [130]. The results are presented as the percentage of time that the selected indoor environment parameters were within the different categories (I, II, III, and IV). The explanation of each category is presented in Table 2.

5.3.6.1 THERMAL CRITERIA FOR WINTER AND SUMMER

The range of values used to analyse the two seasons are different, due to the occupancy profile and characteristics of the case study but also to the level of adaptation and expectation of occupants for both seasons. In winter, since active systems are used, the values to design heating systems were considered [130]. During summer, since the building is naturally ventilated and has no mechanical cooling system, the adaptive comfort model was applied. In this case the upper and lower temperature limits for each category are strongly related to the outdoor running mean temperature [130].

During most of the time of the heating season, the thermal conditions in the rooms were out of the limits defined for Category III (18 °C) (Fig. 5.58-5.59). In Figure 5.58, the points within the range represent heating periods. The living room, as the room with longer occupation periods, had more points within the thermal comfort range than the other rooms due to the use of the wood-burning stove. The bedroom showed the worst performance, but occupants heat it sporadically, only when dressing and undressing. Regarding the latter, the occupants can accept temperatures below the range mentioned in the standard (18 °C), as it is visible in the ranges of the adaptive model of comfort for Portugal. However, even considering this and that the building is not heated permanently, as it is common in Portugal, the results showed an inadequate thermal performance during winter. Additionally, if considering the widely stated health problems and mortality rates related to inadequately heated indoor environments [184, 185], the minimum indoor temperature of 18 °C, recommended by the standard, must be maintained in indoor living spaces.

Regarding the cooling season, the results confirmed the climate-responsiveness of the building during the most demanding season in this region, since it was most of the time into Category I (the highest level of expectation) (Fig. 5.59-5.60). In the remaining time, the building was classified as belonging to Category II. This result shows that this kind of buildings was built to mitigate the intense summer heat by using only passive cooling strategies to address the thermal comfort of its occupants.

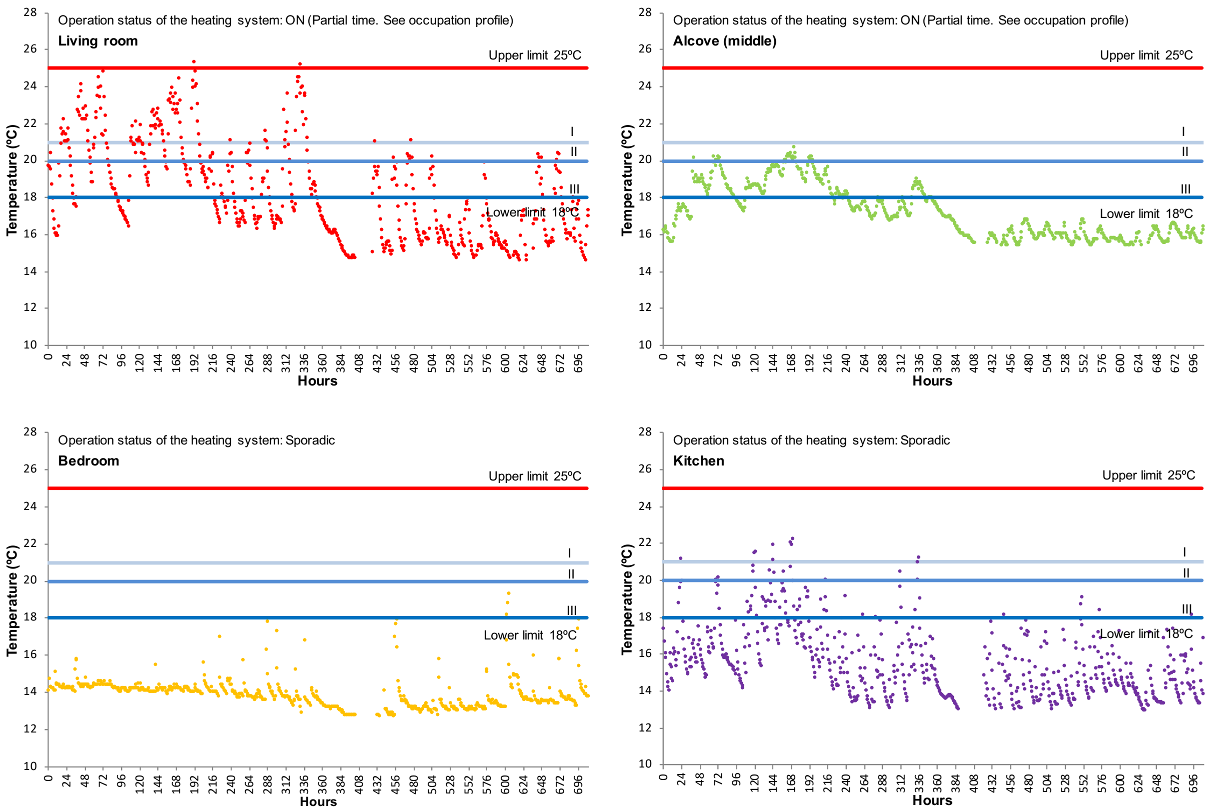


FIGURE 5.58. Thermal conditions in representative indoor rooms during the heating season, according to the limits of each category defined by EN15251.

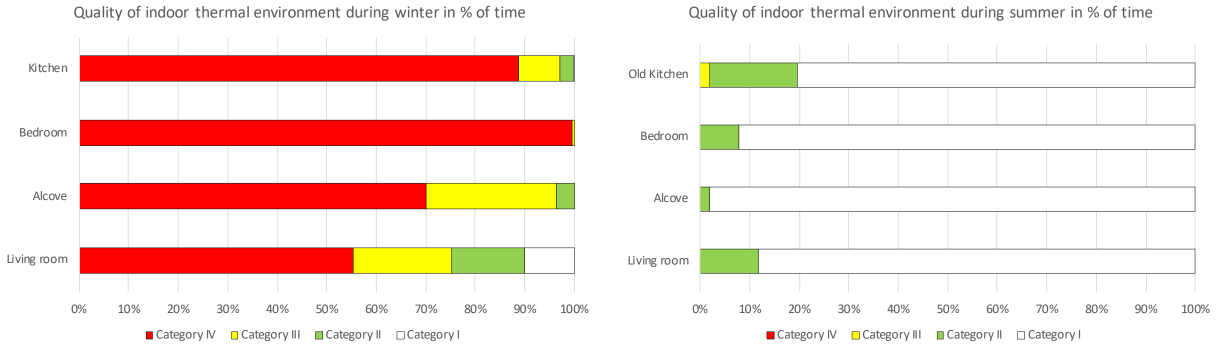


FIGURE 5.59. Classification of indoor thermal environment for representative rooms of the building. (left) Winter; (right) Summer.

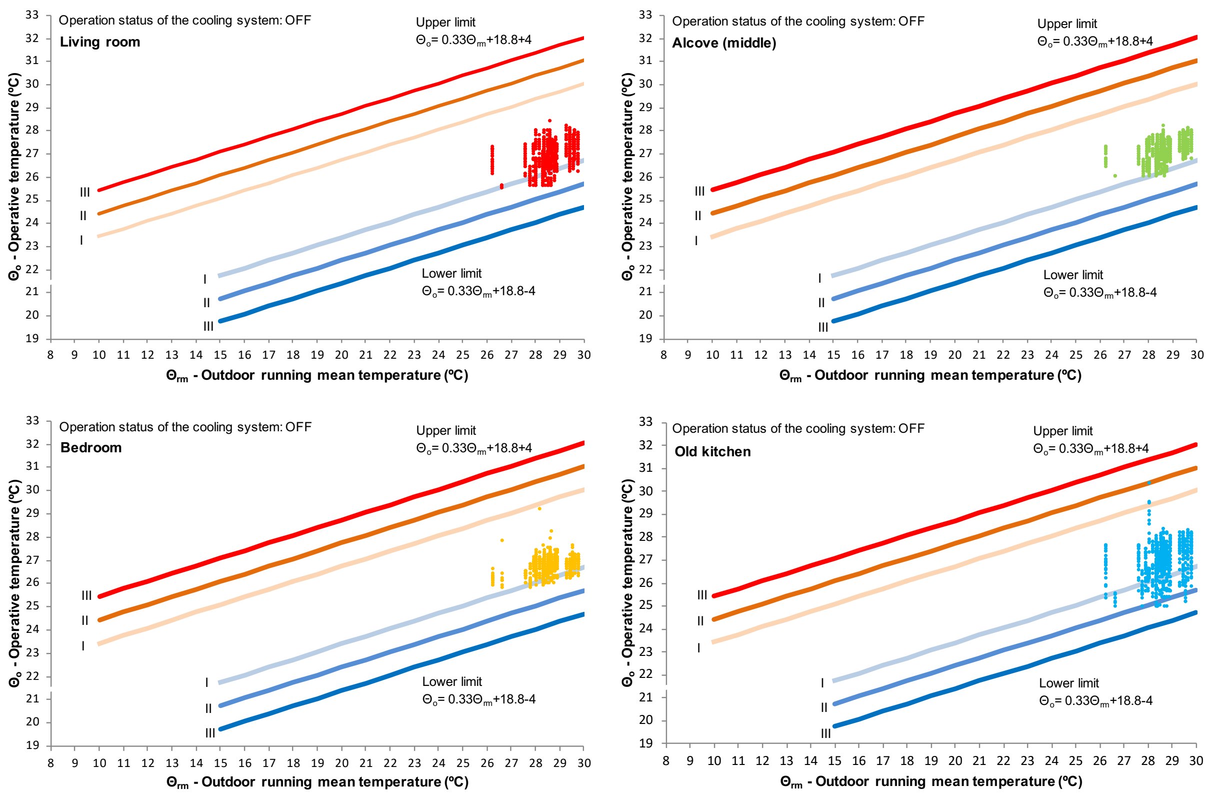


FIGURE 5.60. Thermal conditions in representative indoor rooms during the cooling season, according to the limits of each category defined by EN15251.

5.3.6.2 HUMIDITY CRITERIA

The standard EN15251 underlines that long-term high or low humidity values have an adverse effect by causing microbial growth or irritation of the eyes and respiratory tract, respectively. Since earthen materials are considered as having good moisture regulation properties, this analysis is relevant to evaluate the performance of the case study.

As presented in Figure 5.61, in winter, the monitored rooms were categorised differently. The rooms with the best performance were the living room and the alcove, due to the use of the stove that allowed reducing the relative humidity. The old kitchen had the worst performance, and this might be caused by the infiltration of the exterior air (with high relative humidity) through the open chimney.

During the summer, all rooms showed a high-performance level (Categories I and II). Although outdoor relative humidity was frequently low in summer, indoor values were stable and at comfort levels.

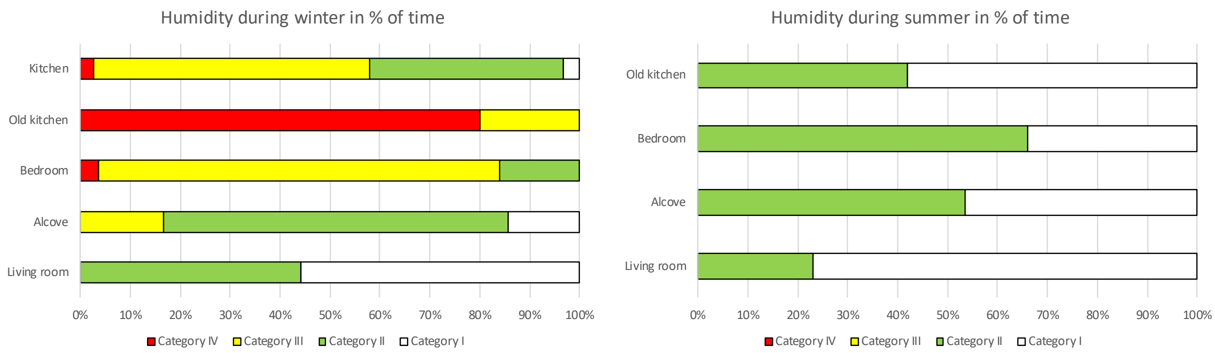


FIGURE 5.61. Classification of indoor humidity for representative rooms of the building: (left) Winter; (right) Summer.

5.3.6.3 INDOOR AIR QUALITY CRITERIA

In buildings where occupants are the main source of pollution, air quality can be analysed by measuring the carbon dioxide concentration. The carbon dioxide concentrations were measured in different occupied rooms during a representative day of each season. During the winter season, the measurement was carried out in a day with the wood-burning stove in operation (marked in yellow in Table 23) to verify the influence of the stove on the CO_2 levels.

From the measurements, it was verified that the use of the wood-burning stove does not increase the CO_2 concentrations when compared with the summer season (Table 23). The small differences between outdoor and indoor carbon dioxide concentrations can be due to the low occupation density of the building, to the natural ventilation and infiltration rate, to the effectiveness of the wooden-stove exhaust system and the earthen materials pollutants-absorbing properties [80]. The results show that, although this is an ancient building, the CO_2 concentration levels are within the requisites of the most demanding category.

TABLE 16. Classification of the indoor air quality in representative rooms for all seasons (asterisk = wood-burning stove ON)

CARBON DIOXIDE (CO_2) CONCENTRATION					
Season	Place/room	Concentration (ppm)	Difference above outdoor	Category	Pressure (hPa)
Autumn	Outdoor	430			995
	Living room	515	85	I	
	Alcove	515	85	I	
	Bedroom	493	63	I	
	Kitchen	545	115	I	
	Old kitchen	515	85	I	
	Corridor	495	65	I	
Winter	Outdoor	450			999
	Living room	620*	148	I	
	Alcove	600	128	I	
	Bedroom	602	130	I	
	Kitchen	552	80	I	
	Old kitchen	557	85	I	
	Corridor	549	77	I	
Spring	Outdoor	394			996
	Living room	458	64	I	
	Alcove	458	64	I	
	Bedroom	480	86	I	
	Kitchen	471	77	I	
	Old kitchen	494	100	I	
	Corridor	457	63	I	
Summer	Outdoor	323			998
	Living room	465	142	I	
	Alcove	495	172	I	
	Bedroom	462	139	I	
	Kitchen	354	31	I	
	Old kitchen	362	39	I	
	Corridor	408	85	I	

5.3.7 CONCLUDING REMARKS

The results presented in this study show that there is a strong relation of cause and consequence between local conditions and vernacular architecture in inland southern Portugal.

The results of the thermal environment monitoring show that the case-study building presented good or satisfactory indoor thermal comfort conditions during almost all year. As expected, the worst performance was during the winter season, when an active heating system was necessary to overcome the periods of thermal discomfort. However, taking as an example the living room, using simple heating systems, such as a wood-burning stove, it was possible to reach thermal comfort conditions rapidly. The other rooms had temperature profiles out of the comfort zone because occupants heat them sporadically or do not heat them at all. Since there is no central heating system, the occupants used the portable electric fan heaters to heat these rooms, even if only for short periods. Although not an energy-efficient equipment, using fan heaters is a practical and straightforward way to increase air temperature by convection and assure a thermal comfort sensation when needed. It should be highlighted that these good results were achieved in a building that was in a free-running mode for most of the time in most of the rooms. For a vernacular building, with single glazed windows and original wooden frames (i.e. with poor airtightness) and without thermal insulation (except in the roof), it has stable temperature profiles. With more efficient heating systems, and improving the thermal insulation of some building elements (e.g. the windows), it would be possible to assure thermal comfort conditions in all rooms during longer periods. However, this topic needs more in-depth research to verify its effectiveness.

The results on the subjective assessment of the occupants' thermal comfort, using a Thermal Environment Survey, validated the objective assessments. These results show that the adaptive model of comfort adjusted to the Portuguese context is adequate to analyse the thermal comfort conditions in Portuguese vernacular buildings.

Regarding relative humidity, the building also had a good performance with values within the comfort range during almost all the year, except for the winter, when the values were slightly higher than for the other seasons. As in the case of the thermal performance, the relative humidity performance had its best results during the summer season. The high thermal and hygroscopic inertia of the envelope, partition walls, ceilings, and floors was responsible for the stabilisation and regulation of these two parameters. These good results were also confirmed by the use of the EN15251 methodology to categorise the quality of the indoor environment.

Therefore, it is possible to conclude that vernacular architecture from southern Portugal is a climate-responsive architecture, or in a holistic point of view, an environmentally responsive architecture that is focused on providing an adequate level of thermal comfort during the intense summer heat. As seen in the case study, the passive cooling strategies provided good thermal comfort conditions without the use of any mechanical cooling system. The contribution of these strategies to stabilise indoor temperature and reduce solar gains show that these buildings were conceived to perform better during summer. Nevertheless, these features do not guarantee an adequate thermal comfort environment during the winter, being necessary, among others, to reduce heat losses by the envelope and ventilation. From these strategies, rammed earth walls have to be highlighted, and it is correct to state that the use of this technique for centuries demonstrates its suitability and close relationship with the geological and climatic conditions of the region. Thus, the preservation of such strategies in existing buildings of this region (or regions with similar conditions) and their implementation in new buildings can contribute to reduce energy demand for cooling and therefore to reduce the life cycle energy use of the buildings and related potential environmental impacts. However, despite the presented advantages, these building elements do not comply with the current minimum requirements for the U-value defined by the national regulation on the Energy Performance of Buildings [135].

As an example, the U-value of a 40 cm and a 60 cm thickness rammed earth wall is 1.60 and 1.30 W/(m^2.°C), respectively [137]. According to the legal requirements for external opaque vertical elements, the U-values must be lower than 0.35 or 0.50 W/(m^2.°C), depending on the climatic zone [135]. Therefore, it is difficult for earthen building materials alone to satisfy this requirement. Thus, without thermal insulation, it is not possible to meet the minimum thermal insulation level defined by law. The problem seems easy to solve, but the aesthetic aspects, the physical properties of these earthen materials, like the need to “breathe”, are incompatible with most used insulation materials and solutions (e.g. External Thermal Insulation Composite Systems - ETICS).

Even with this limitation in what the U-value is concerned, and during winter (the season with lower thermal performance), it was found that it is possible to reach adequate comfort conditions when the building is heated with a simple wood-burning stove. Additionally, when the stove is turned off, the air temperature in the room took several hours, days on some occasions, to decrease, therefore maintaining the comfort conditions for long periods.

The main goal of the regulation on defining low U-values is to reduce the energy demand, while increasing thermal comfort conditions and preventing the occurrence of condensations, to achieve the medium-term nZEB targets. Although during the cooling season the low U-value envelopes also contribute to reducing the heat gains, it has the drawback of increasing the difficulty to dissipate internal heat and to cool the indoor environment. This issue is particularly relevant in the specific climate of Southern Portugal and other Mediterranean areas. Additionally, due to climate change and the related increase in average annual temperatures, it is expected that in these areas, the impact of the cooling season in the annual energy consumption of buildings will rise considerably. It is predicted that the global energy demand for cooling will triple by 2050 [186]. Although the building does not comply with the minimum thermal insulation requirements, it presents adequate thermal comfort conditions. As shown by Verbeke & Audernaert [187], a high thermal mass has a relevant contribution for improving thermal comfort and reducing the energy demand. In this type of buildings, the very high thermal inertia has a positive contribution in maintaining the indoor environment within the comfort zone, and this feature is not fully conveyed in the Portuguese regulation on the Energy Performance of Buildings [135].

It is possible to implement some solutions to overcome the weak performance during the winter, but they will be different, whether it is an existing building or a new one. In existing buildings, the optimisation of the windows and the building airtightness, and the insulation of the roof are feasible and will increase buildings performance without renovating the walls. In new buildings, besides the solutions mentioned before, it will be easier to implement other solutions as the insulation of the envelope and implementation of passive systems to reduce heat losses and increase gains (e.g. Trombe wall).

Rammed earth is being used for centuries in the southern part of Portugal and is one of the most widely vernacular techniques still used today. Therefore, it is important to analyse, through quantitative studies like the one presented in this research, the real benefits of using this technique nowadays.

The contents presented in this chapter are, entirely or partially, published in the following publications:

Thermal Performance and Comfort Conditions Analysis of a Vernacular Palafitic Timber Building in Portuguese Coastline Context
Sustainability (2020), 12, 10484. doi:10.3390/su122410484
Thermal Performance and Comfort Condition Analysis in a Vernacular Building with a Glazed Balcony
Energies (2020), 13, 624. doi:10.3390/en13030624
Analysis of the Thermal Performance and Comfort Conditions of Vernacular Rammed Earth Architecture From Southern Portugal
Encyclopedia of Renewable and Sustainable Materials (2020), 4, 1-10. Elsevier. doi:10.1016/B978-0-12-803581-8.11460-2
Passive strategies used in Southern Portugal vernacular rammed earth buildings and their influence in thermal performance
Renewable Energy (2019), 142, 345–363. doi:10.1016/j.renene.2019.04.098
Contribution of Portuguese Vernacular Building Strategies to Indoor Thermal Comfort and Occupants' Perception
Buildings (2015), 5, 1242–1264. doi:110.3390/buildings5041242
Portuguese vernacular architecture: the contribution of vernacular materials and design approaches for sustainable construction
Architectural Science Review (2015), 58, 324–336. doi:10.1080/00038628.2014.974019

CHAPTER 6

BUILDING ENERGY SIMULATION: COMPARISON OF THE INFLUENCE OF DIFFERENT STRATEGIES ON ENERGY PERFORMANCE

6. BUILDING ENERGY SIMULATION: COMPARISON OF THE INFLUENCE OF DIFFERENT STRATEGIES ON ENERGY PERFORMANCE

This section presents the results of the energy simulation under dynamic conditions of building models based on the case studies. The purpose of the simulations was to compare under the same conditions the impact of different vernacular and conventional strategies/building solutions on the energy performance for heating and cooling.

A set of conditions were defined to simplify simulation and analysis procedures. These conditions were kept stable or unchanged between the several simulated scenarios for each case study. Since the EnergyPlus weather (EPW) files for simulations are only available for few Portuguese locations [134, for each case study the weather data from the closest location and/or that has similar climate conditions were considered. Table 24 describes the conditions and input information considered for each case study.

Although simplified, the building models simulate the characteristics of the original buildings (construction systems; operation; etc.). Nonetheless, to simplify and carry out the comparative analysis, for some parameters were considered values based on standards and/or national legislation, namely:

i. The characteristics of the envelope (U-value, density, etc.) are the same as calculated for the original buildings, considering properties values from technical publications [136, 137]. For other thermo-physical properties such as specific heat, thermal diffusivity, etc., the values available in DesignBuilder materials library were considered.
ii. The minimum air change rate defined for all buildings had into consideration the recommendations of EN16798 standard [138] for new residential buildings (Category II) [138]. Although Case Study 1 is a Museum and Tourist Office, the building has a low occupancy density, and the considered value of 0,6 ach is adequate and higher than the minimum required for a low polluting building. To simplify the models and to assure a minimum constant air change per hour in the buildings, a mechanical ventilation system was considered.
iii. The values or conditions for internal gains, heating and cooling temperature setpoints, and maximum U-values for external walls (for each climate zone) follow the preconized in national legislation on the Energy Performance of Buildings [135].

The comparative analysis of the different scenarios is based on the annual energy demand for heating/cooling (kWh/m^2) to maintain a temperature range between 18 °C and 25 °C. The simulation results for energy needs are not affected by the efficiency of the HVAC system.

The comparison scenarios defined for each case study are described in the following sub-sections.

TABLE 24. Building energy simulation conditions, input information and comparison purpose.

	C1 – PRAIA DE MIRA	C2 – GRANJA DO TEDO	C3 – SAFARA
Weather data (EPW) [134]	Porto	Bragança	Évora
Climate zone [135] Winter: I1-I3 Summer: V1-V3 1 - Mild 2 - Medium 3 - Harsh	I2-V2 Heating Degree Day: 1304 °C Summer mean outdoor temperature: 20,9 °C	I2-V3 Heating Degree Day: 1764 °C Summer mean outdoor temperature: 22,7 °C	I1-V3 Heating Degree Day: 1068 °C Summer mean outdoor temperature: 24,7
Internal heat gains [135]	7 W/m^2	4 W/m^2	4 W/m^2
Maximum U-value for external walls [135]	0.40 W/(m^2.°C)	0.40 W/(m^2.°C) (not considered in simulations)	0.50 W/(m^2.°C)
Air change rate	Minimum 0.6 ach	Minimum 0.6 ach	Minimum 0.6 ach
Heating/Cooling temperature setpoint	18-25°C	18-25°C	18-25°C
Operation Schedules			
Internal gains	On 9 a.m. to 5 p.m.	On 24/7	On 24/7
Windows opening	Off 24/7	Balcony: Summer - Open 7 a.m. to 7 p.m. All other days: Closed. Other windows: Summer - Open 7 to 9 a.m. All other days: Closed.	Summer - Open 7 to 9 a.m. All other days: Closed
Window shading	Ground floor: On 24/7 Upper floor: No shading	Balcony: Summer - On 9 a.m. to 7 p.m.; Off 7 p.m. to 10 p.m. All other days: Off 9 a.m. to 7 p.m; On 7 p.m to 7 a.m. Other windows: All days Off 7 a.m. to 7 p.m.;	Summer - On 9 a.m. to 7 p.m.; Off 7 p.m. to 10 p.m. All other days: Off 9 a.m. to 7 p.m; On 7 p.m to 7 a.m.
Doors opening	Main entrance and first floor east façade balcony Summer: Open 9 a.m. to 5 p.m. All other days: Closed.	Entrance door Summer: Open 7 to 9 a.m.; All other days: Closed.	Courtyard door Open 7 to 9 a.m.; All other days: Closed.
HVAC (18-25 °C)	On 7:30 a.m. to 5 p.m.	On 24/7	On 24/7
Mechanical ventilation (to assure the minimum 0.6 ach)	On 24/7	On 24/7	On 24/7
Comparison purpose	To compare the influence of thermal transmittance and low thermal inertia on energy performance of a building located in a mild climate.	To compare the effectiveness of glazed balconies on energy performance of a building located in a cold winter climate.	To compare the influence of thermal transmittance and high thermal inertia on energy performance of a building located in a hot summer climate.

6.1 CASE STUDY 1 – PRAIA DE MIRA

In the case of traditional timber buildings, the purpose is to compare the thermal performance of this type of structures with the conventional construction systems that have been replacing them. Thus, the intention is to study the suitability of low thermal inertia buildings for locations with a mild climate, in comparison with conventional systems with higher thermal inertia. The base model for comparison is the case study building, as monitored (Fig. 6.1). In all the scenarios defined only the external walls were changed, and all the remaining parameters and building characteristics were kept constant. The scenarios defined for comparison are the following:

i. Original building wall (wooden planks (1.5 cm) + air gap (7 cm) + XPS (3cm) + indoor timber plank (1.2 cm); U=0.81 W/(m^2.°C));
ii. Double hollow clay brick cavity wall (Render (2cm) + Clay brick (15 cm) + air gap (3 cm) + XPS (2 cm) + Clay brick (11 cm) + Render (2 cm); U=0.82 W/(m^2.°C) (considering thermal bridges));
iii. Hollow clay brick + ETICS wall (Render (2cm) + Clay brick (22 cm) + Render (1 cm) + EPS (6 cm) + Render (0.5 cm); U=0.40W/(m^2.°C));
iv. Timber cavity wall, with insulation (wooden planks (1.5 cm) + air gap (2 cm) + ICB (8 cm) + indoor timber plank (1.2 cm); U=0.40 W/(m^2.°C));
v. Timber cavity wall, without insulation (wooden planks (1.5 cm) + air gap (10 cm) + indoor timber plank (1.2 cm); U=2.39 W/(m^2.°C)).

Scenario ii) represents a conventional façade solution at the time the building was built. In scenarios iii), and iv), the thermal insulation material thickness was set to comply with the maximum U-value defined in the Portuguese thermal regulation for the region.

The analysis of the simulation results shows that regarding the annual energy demand for heating and cooling (Fig. 6.2), the solution with the best overall performance is the "Hollow clay brick+ETICS wall (U=0.40W/(m^2.°C))", requiring 27.7% less energy than the worst solution, the "Timber cavity wall, no insulation (U=2.39 W/(m^2.°C))". The significant performance differences between the five solutions were for heating, with the same walls in the best and worst positions, i.e., Hollow clay brick+ETICS wall (U=0.40W/(m^2.°C))" and the "Timber cavity wall, without insulation (U=2.39 W/(m^2.°C))", respectively (Fig. 6.2 and 6.3). The best solution required 52.6% less energy for heating than the worst. Nevertheless, and although the comparison between solutions with and without insulation, it has to be highlighted that these two solutions have the same energy demand for cooling (20.9 kWh/m^2) (Fig. 6.2).

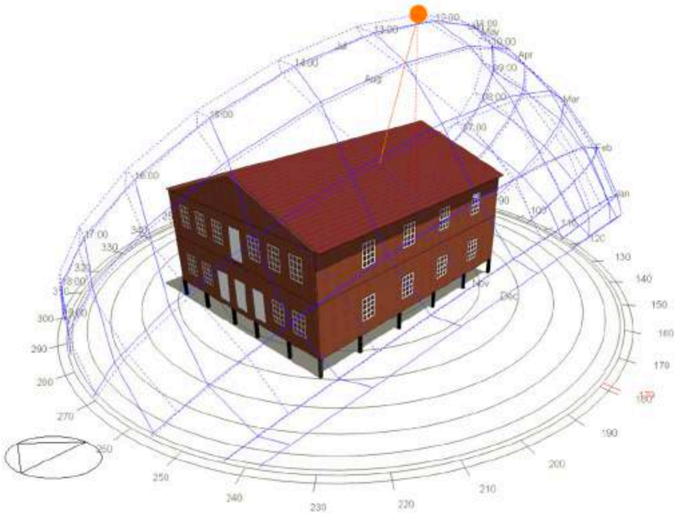


FIGURE 6.1. DesignBuilder model of Case Study 1 – Praia de Mira.

Regarding the energy for cooling, the performance of all solutions is very similar, with differences between 0.4 and 1.4 kWh/m^2. Comparing the two scenarios that represent the solutions for the façade at the time the building was built, namely the "Original building wall (U=0.81 W/(m^2.°C))" and the "Double hollow clay brick cavity wall (U=0.82 W/(m^2.°C)), the energy performance is very similar, being the first slightly better for heating (1.4 kWh/m^2) and the latter slightly better for cooling (0.4 kWh/m^2).

Comparing the two scenarios that satisfy the minimum requirements for the U-value in force in this climate zone (0.40W/(m^2.°C)), the "Hollow clay brick+ETICS wall" has a slightly better heating (less 1.1 kWh/m^2) and cooling performance (1.4 kWh/m^2) than the "Timber cavity wall, with insulation". The mass and slightly higher thermal inertia of the brick layer are probably the factors favouring the thermal performance of this solution. However, the difference between the two solutions is not significant in the annual energy demand (2.5 kWh/m^2, or 7.2%). Moreover, by adding the original solution to the comparison (in which the U-value is the double, 0.81W/(m^2.°C)), it is possible to verify that the improvement in the annual performance by using lower U-values is not exponential, being of 12.1% (4.4 kWh/m^2) for the "Hollow clay brick+ETICS wall" and 5.2% (1.9 kWh/m^2) for the "Timber cavity wall, with insulation".

Since the changes between scenarios are only at the level of the external walls, the overall thermal inertia of the scenarios is not substantially different and thus, the small difference in annual energy demand.

The results indicate that timber structures are suitable in this area, beyond the advantages mentioned in previous sections. However, a more in-depth study, considering the overall optimised building systems for the envelope and the specific weather data for this area, would be useful to understand more accurately the thermal performance and suitability of timber construction in the coastline.

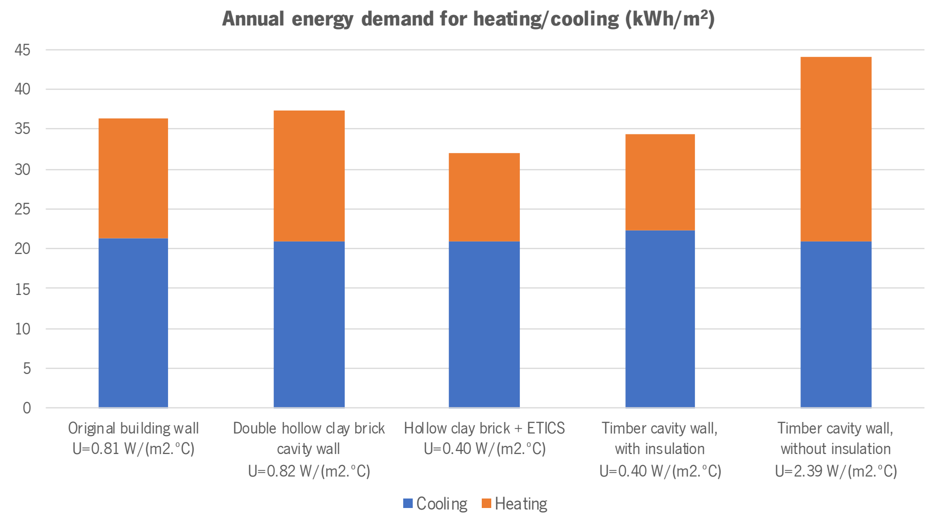


FIGURE 6.2. Case study 1 – Annual energy demand for heating and cooling.

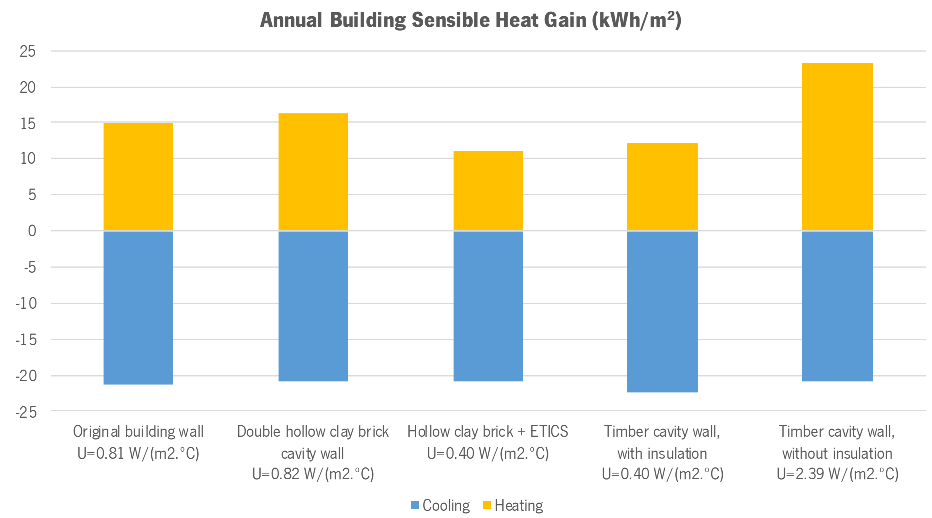


FIGURE 6.3. Case study 1 - Annual building sensible heat gain.

6.2 CASE STUDY 2 – GRANJA DO TEDO

In case study 2, the purpose is to compare the effectiveness of glazed balconies on the energy performance of buildings located in a cold winter climate. Thus, the aim is to compare the annual energy demand for different design scenarios. The base model for comparison is the case study building, but in the simulation a semi-exposed wall (tabique) between the balcony and the indoor rooms (as existed in the original building, before the refurbishment), connected by two windows (Fig. 6.4) was introduced. In the scenarios defined, only the southwest façade was modified, and being all the other conditions are kept unchanged. In all the scenarios, the same calculated thermal transmittance values of the existing building were considered, except for the tabique wall (U=1.59 W/(m^2.°C)[188]). The design scenarios defined for simulation and comparison of the energy performance of this case study are the following (Fig. 6.5):

i. Case study building with glazed balcony (semi-exposed wall in tabique dividing the sunspace from bedroom and bathroom, and connected by two windows);
ii. Building with balcony, the external wall in tabique, facing SW in the first floor with two windows.
iii. Building with all external walls in granite and two small windows in the SW façade.

The results of the simulations reveal that the "building with the glazed balcony" has the lowest annual energy demand, being 5.3% and 7.4% better than the scenarios "Balcony" and "No Balcony", respectively (Fig. 6.6). The building with the glazed balcony is also the scenario with the best performance, both for

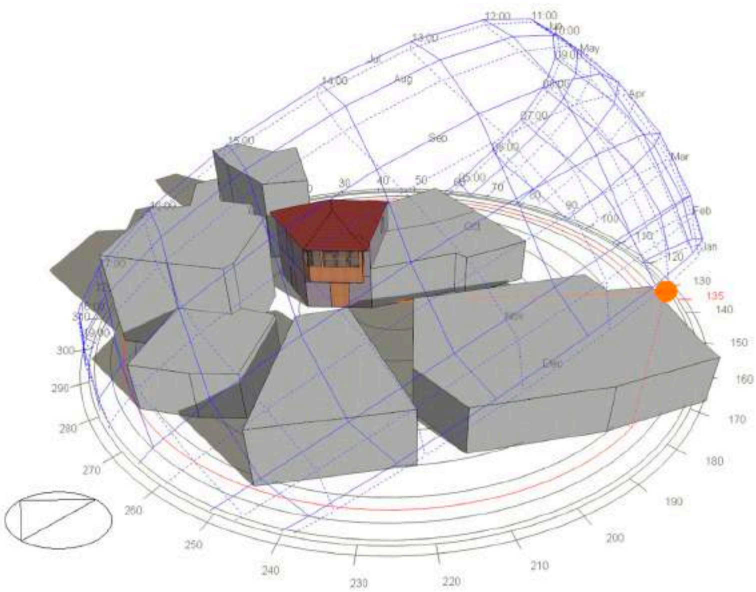


FIGURE 6.4. DesignBuilder model of Case Study 2 – Granja do Tedo.

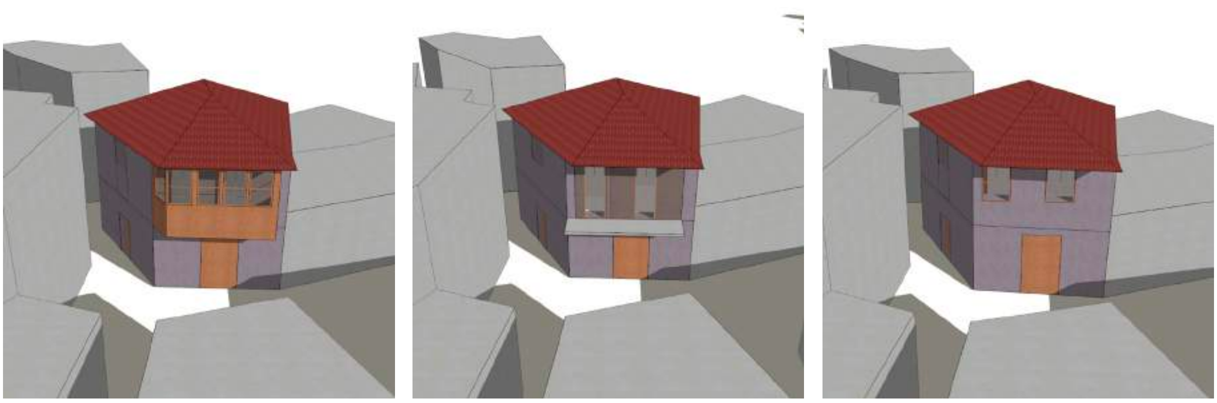


FIGURE 6.5. Case Study 2 – models of the three scenarios considered in simulations. (left) glazed balcony; (center) balcony; (right) no balcony, small windows.

heating and cooling (Fig. 6.6 and 6.7). The other two scenarios have higher energy demand and are very similar, in which the scenario with small windows is slightly worst for heating (more 4.7 kWh/m^2, 3.1%) since it has fewer direct solar gains. It is also possible to see that heating needs represent a considerable share of annual energy demand, 92,4% in the case of the "building with the glazed balcony", confirming that the heating season is the most demanding.

From the comparison between the three scenarios, it is clear that the sunspace effect of the glazed balcony has a positive impact. However, the sum of the energy demand for all zones does not clearly express the influence of the glazed balcony in the contiguous rooms, namely in the bedroom. Focusing the analysis only on the energy demand for the bedroom adjacent to the glazed balcony, the scenario with the glazed balcony has the best performance both for heating and cooling (Fig. 6.8 and 6.9). Re-

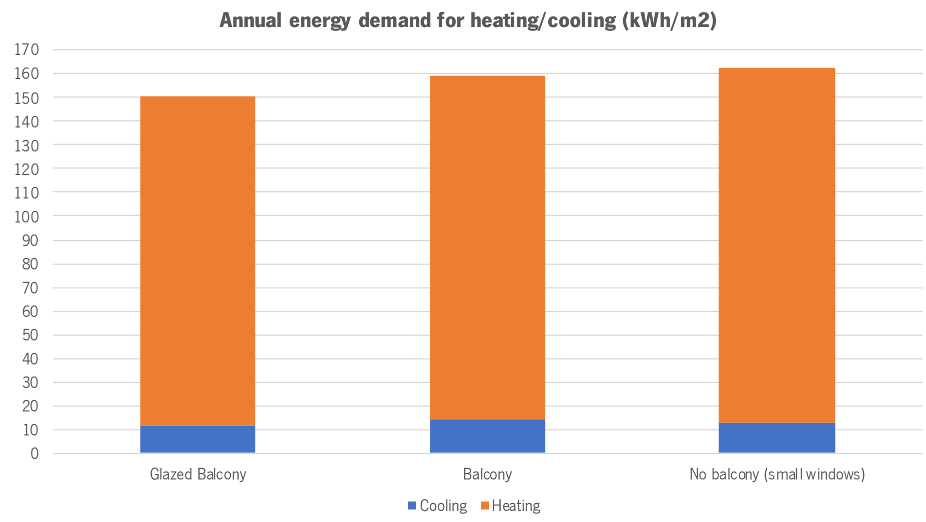


FIGURE 6.6. Case study 2 – Annual energy demand for heating and cooling (all zones).

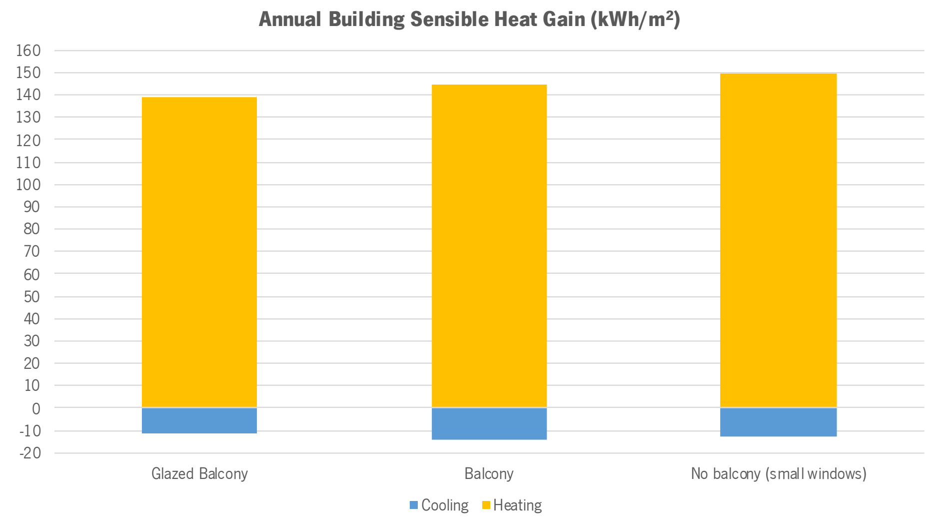


FIGURE 6.7. Case study 2 - Annual building sensible heat gain (all zones).

garding heating, the bedroom in the scenario with the glazed balcony needs less ≈34 kWh/m^2 (24.7%) than the scenario with balcony, and less ≈56 kWh/m^2 (35.1%) than the scenario with small windows (Fig. 6.9). In the best scenario, heating needs represent 83.1% of annual energy demand. Regarding cooling, it also has the best performance with lower energy needs, less 12.7 kWh/m^2 (37.5%) than the worst scenario (Balcony) and less 4.1 kWh/m^2 (16.2%) than the scenario “No Balcony”(Fig. 6.9).

Since it is a sunspace, on sunny winter days, the glazed balcony can reach considerably higher temperatures than the ones recorded outdoors (Fig. 6.10). In the two winter weeks with the lowest minimum temperatures, it is possible to verify that on sunny days the maximum temperature inside the glazed balcony is frequently ≈15°C higher than outdoors, with temperature peaks surpassing the 25°C in some days (Fig. 6.10). By comparing the days with the highest temperature peaks inside the

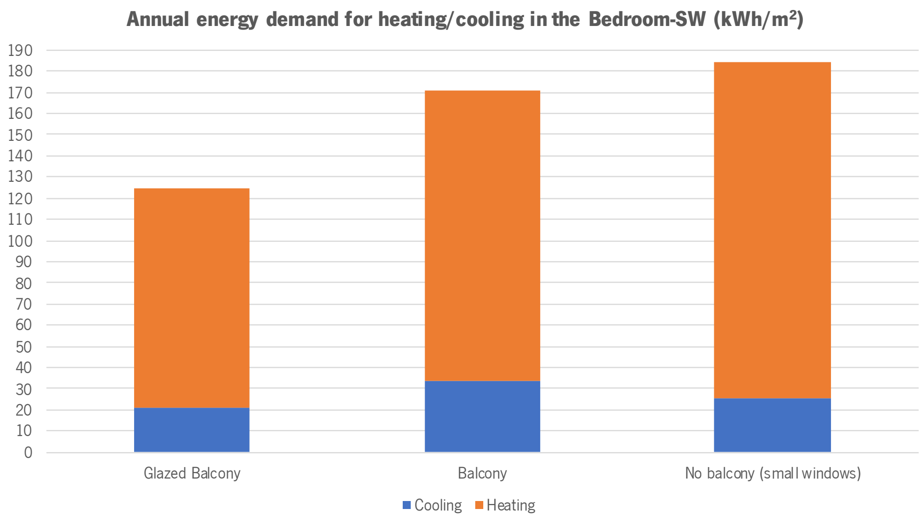


FIGURE 6.8. Case study 2 – Annual energy demand for heating and cooling in the Bedroom-SW.

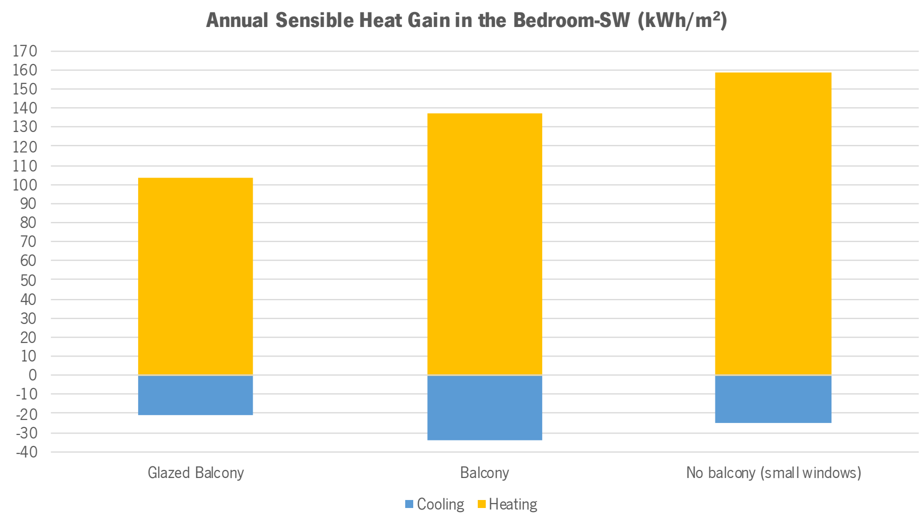


FIGURE 6.9. Case study 2 – Annual building sensible heat gain in the Bedroom-SW.

glazed balcony with the solar radiation on those days, it is possible to verify that there is a direct relation between the days with higher solar radiation and the days with higher temperature peaks (Fig. 6.10 and 6.11).

Although the glazed balcony has been conceived to work as a sunspace during winter, during summer by opening windows to promote ventilation and by also working as shading element, this strategy shows to be effective in both seasons.

As in case study 1, a more in-depth study considering optimised building systems for the envelope and specific weather data for this area would be useful to understand more accurately the effectiveness of this passive strategy.

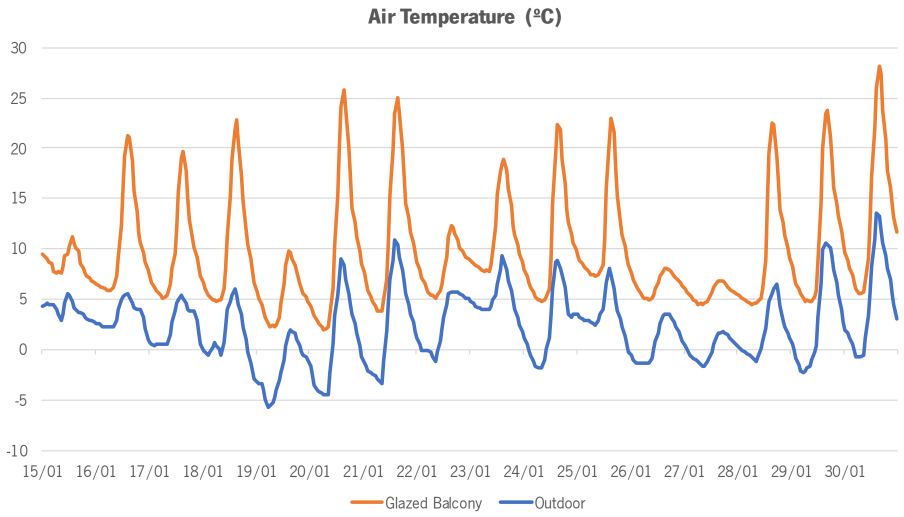


FIGURE 6.10. Case study 2 – Air temperature in the glazed balcony and bedroom in the coldest Winter weeks.

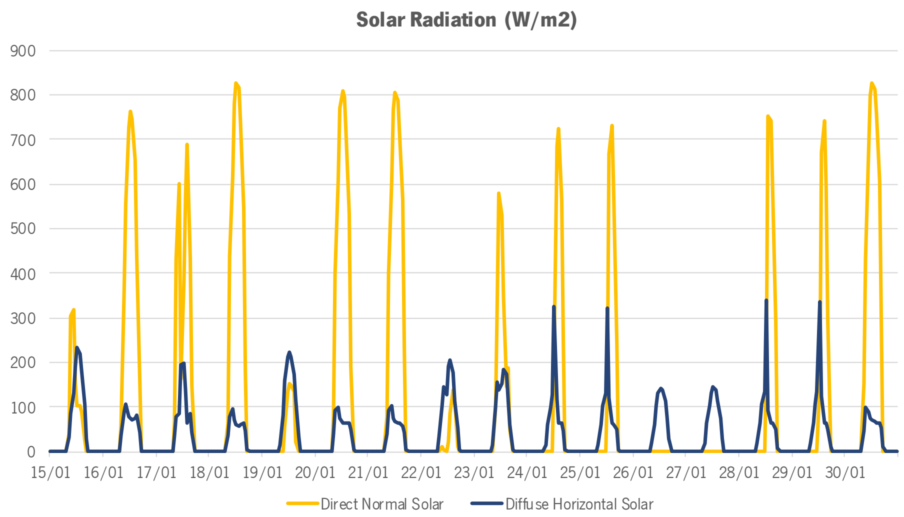


FIGURE 6.11. Case study 2 - Solar radiation during the coldest Winter weeks.

6.3 CASE STUDY 3 – SAFARA

In the case of the earthen buildings, the purpose is to evaluate the thermal performance of this type of structures in comparison with current conventional construction systems. Thus, the intentionis to study the suitability of high thermal inertia building elements for locations with a hot summer climate, in comparison with conventional systems with lower thermal inertia. The base model for comparison is the case study building, as monitored (Fig. 6.12). In all the scenarios defined only the external was changed, and all the other conditions are kept unchanged. The design scenarios set for comparison are the following:

i. Original building wall (Lime render (2 cm) + Rammed earth (56 cm) + Lime render (2 cm)). U=1.30 W/(m^2.°C);
ii. Double hollow clay brick cavity wall (Render (2 cm) + Clay brick (15 cm) + air gap (5 cm) + Clay brick (11 cm) + Render (2 cm). U=1.30 W/(m^2.°C) (considering thermal bridges);
iii. Hollow clay brick + ETICS wall (Render (1.5 cm) + Clay brick (22 cm) + Render (1 cm) + EPS (4.5 cm) + Render (0.5 cm)). U=0.50W/(m^2.°C);
iv. Rammed earth + ETICS wall (Rammed earth (60 cm) + ICB (5 cm)). U=0.50 W/(m^2.°C).

Scenario ii) represents a conventional solution of façade with the same thermal transmittance of scenario i) and complying with the maximum U-value until 2013 [189]. In scenarios iii) and iv), the thermal

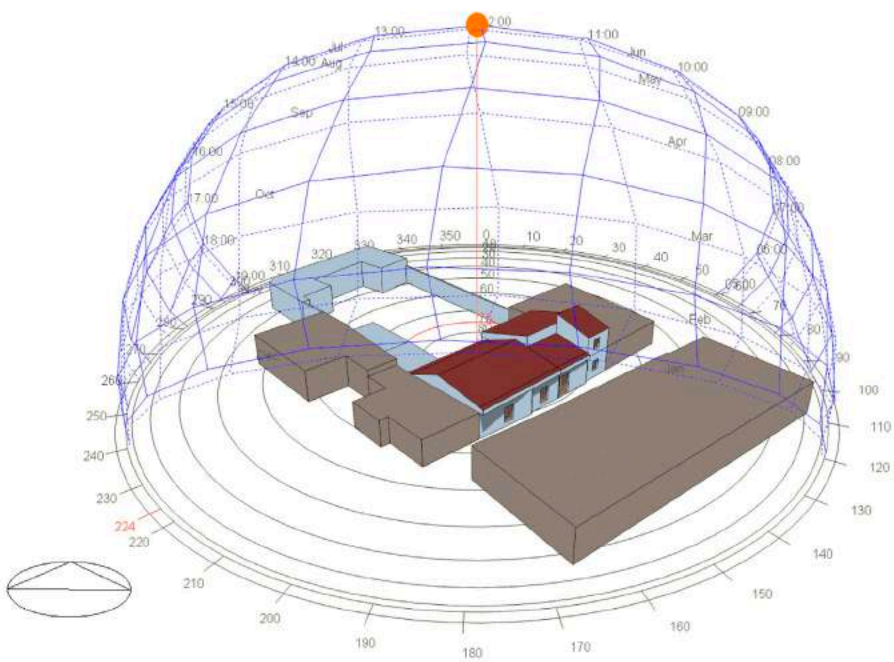


FIGURE 6.12. DesignBuilder model of Case Study 3 – Safara.

insulation material thickness was set to comply with the maximum U-value in force, defined in the Portuguese thermal regulation for the region [135].

The results from simulations showed that the scenario of the original building (rammed earth) has the worst performance on the annual energy demand, while the best is the scenario of "Hollow clay brick + ETICS (U=0.50 W/(m^2.°C))" (Fig. 6.12). The energy demand for heating of the original building scenario is more than three times higher than the best solution. However, in terms of the energy demand for cooling, the original building scenario is the best of all solutions by far, needing 37% less energy than the scenario "Hollow clay brick + ETICS" (Fig. 6.13 and 6.14).

Comparing the two first scenarios, i.e. the walls without thermal insulation but with the same U-value, the annual performance of the two is not very different (≈1,90 kWh/m^2). Still, the performance between heating and cooling parameters is considerably different. Approximately, the "original building" scenario has twice the energy needs for heating but a half the energy needs for cooling (Fig. 6.13 and 6.14). Since the two types of walls have the same U-value, the difference of weight/m^2 between the two and therefore the thermal inertia is the plausible reason to justify this behaviour.

Considering the two scenarios for thermally insulated walls, they also have almost the same performance, being the rammed earth slightly better for cooling (0,4 kWh/m^2) and slightly worst for heating (≈1,50 kWh/m^2). However, in this case, the higher mass of the Rammed earth+ETICS wall does not seem to have a considerable advantage over the Hollow clay brick+ETICS wall to reduce the energy needs for cooling, as in the scenarios without insulation. Moreover, it is interesting to observe that, although these thermally insulated solutions have a lower annual energy demand, mainly due to the significantly lower energy needs for heating, they have the worst performance for cooling. In the two thermal insulated scenarios, the energy demand for cooling is double or more than for heating. Therefore, it raises the question of wheter the level of insulation of these solutions is viable or adequate in a climate where hot summers are the major comfort issue.

Nevertheless, it has to be highlighted that the original solution (rammed earth) is the one with the lowest energy demand for cooling, confirming the suitability of this construction system in a climate with a hot summer. Moreover, it should be noted that it is more difficult to cool than to heat a room [45]. In the case and construction context of vernacular buildings, heating could be solved with a simple fireplace, but for cooling, occupants could not rely on anything beyond passive cooling strategies. Taking into consideration that due to climate change it is predicted that global energy demand for cooling will triple by 2050 [186], the annual balance between heating/cooling can also change the perspective on the performance of rammed earth.

In this sense, a more in-depth study on the performance of rammed earth, using optimised models and weather data that considers future scenarios of global warming, would be useful to test the performance and suitability of rammed earth walls in new buildings. Moreover, it would also allow optimising insulation thicknesses that do not hinder the performance for cooling. Additionally, for the future development of this study, it is necessary to have detailed data on the thermo-physical properties of rammed earth in the Portuguese context, and that will allow using more complex and accurate algorithms to calculate the behaviour of this type of walls.

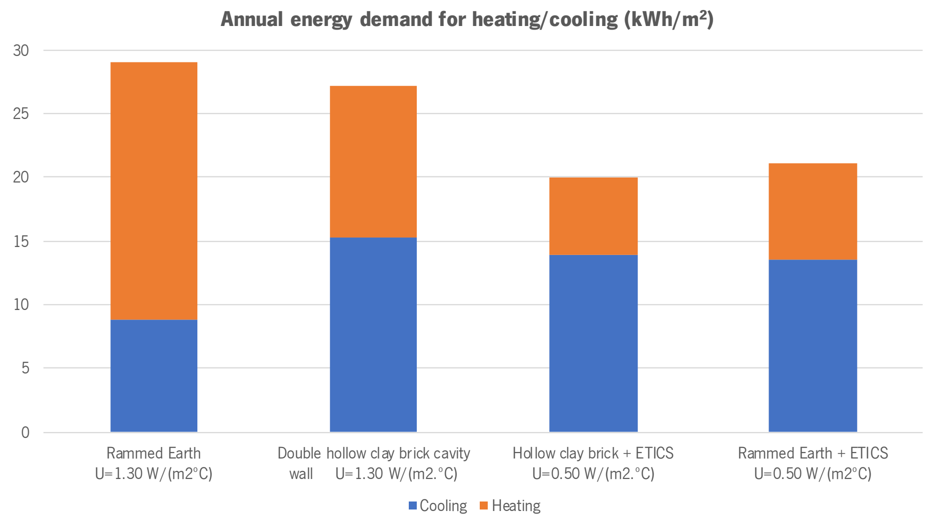


FIGURE 6.13. Case study 3 – Annual energy demand for heating and cooling.

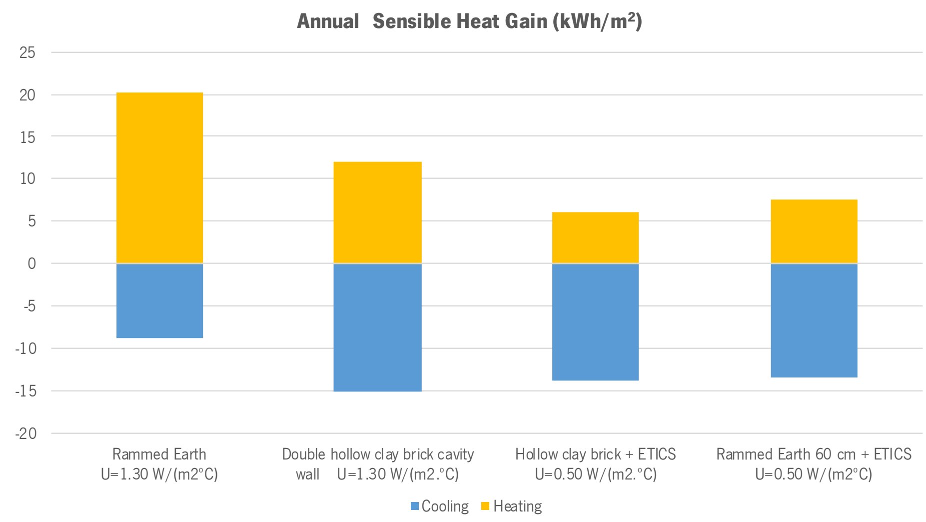


FIGURE 6.14. Case study 3 - Annual building sensible heat gain.

6.4 CONDITIONS AND LIMITATIONS OF THE STUDY

The outcomes of the study presented in this section are based on simulations and scenarios. Therefore, the extrapolation of results for other contexts has to be done carefully, taking into consideration the conditions and the limitations of the study.

The first step planned to develop this study consisted of calibrating the building models by comparing measured and simulated data. For this process, weather data for the same periods of monitoring of the case studies would be used, collected from closest weather stations. The task of adapting weather data to use in simulation models turned out to be extremely time consuming and required a lot of work to compile and create the EnergyPlus Weather (EPW) files, that in turn revealed not to be a very reliable process. Another limitation was the data on the properties of non-conventional materials since it was difficult to find specific and reliable data, and when existed, it was very different among the sources. Thus, due to these limitations that hindered a more rigorous analysis, the alternative method was to define clear simulations conditions that still could represent the case studies and allow carrying out the study without perfectly calibrated building models.

6.5 CONCLUDING REMARKS

The results from the energy simulation models show that vernacular strategies/construction systems, in comparison with conventional ones, have the potential to be used nowadays in their specific climates.

In the case of timber buildings, the results show that this type of buildings can have a thermal performance close to that of a conventional hollow clay brick wall+ETICS, if properly thermally insulated. An optimisation of the construction system would certainly increase the thermal and energy performances. To not hinder the environmental advantages of this type of construction, natural insulation materials as cork or reeds, as used in some *palheiros* in nearby coastal areas (Figueira da Foz region) should be used.

The glazed balconies of the North showed to work correctly in the heating season, allowing considerably reducing the energy demand for heating the rooms contiguous to the balcony. Moreover, it also reveals good performance during the cooling period by promoting ventilation and acting as a shading device. This simple strategy shows good potential nowadays to be applied in new buildings or during renovation operations.

Regarding earthen buildings and the rammed earth walls, the simulations confirmed their good thermal behaviour during the cooling season. However, the weaknesses in the heating season should be covered. However, the addition of an insulation layer to fulfil legislation requirements do not seem the most adequate, since the energy demand for heating was significantly reduced, but for cooling it had also increased.

This part of the study needs to be further developed with more accurate data on the properties of materials.

CHAPTER 7

LIFE CYCLE ANALYSIS OF ENVIRONMENTAL IMPACTS OF EARTHEN MATERIALS IN THE PORTUGUESE CONTEXT

7.1 FRAMEWORK

The assessment of the environmental impacts has a significant relevance on the promotion of environmentally friendly materials since it allows an equative and quantitative comparison. This assessment is complex, and it is difficult to describe all the impacts that result from all the life cycle stages [57, 61] and results cannot be directly extrapolated for specific local contexts [58], mainly when products come from a remote source. Moreover, it is difficult to compare products since the number of Environmental Product Declarations (EPDs) is scarce [102], and only cover the industrially based building products.

In the case of vernacular materials, although acknowledged as ecological, currently there is no quantitative data about the environmental performance of these materials, and no EPDs are available worldwide [104, 105].

As mentioned in previous sections, in Portugal, there are many different vernacular building materials. However, in this study, the focus is on the development of the LCA of two of the most used materials, and which have potential to grow and to be applied in the future, namely rammed earth and compressed earth blocks.

Rammed earth is a traditional monolithic wall construction technique, dating back to 5000 B.C., well-known worldwide [80], where moist earth is poured into a formwork in layers compacted by ramming. This technique seems to have been developed independently in China and around the Mediterranean basin [190]. In the Iberian Peninsula, and particularly in Portugal, this building technique has been used for over two thousand years, as described by Vitruvius and Pliny the Elder, i.e. centuries before the arrival of the Moors to the region [115, 190]. Nevertheless, the latter were probably responsible for spreading the technique in the south of Portugal [113].

In the 18th century, the use of rammed earth in Europe had a new impulse by the publications of Goiffon and Cointeraux [190, 191]. In the 20th century, rammed earth gained importance as a building solution for the housing shortages following each world war, and from the 1970s forward, different groups around the world began to investigate the properties of rammed earth scientifically [190]. Also, in the 20th century, the development of electric and pneumatic rams allowed significantly increasing productivity and reducing time and labour intensity [80].

In the case of the Compressed Earth Block (CEB), it is one of the most widespread earthen building techniques nowadays and represents a considerable improvement over traditional earth building techniques [192]. The production technology emerged in the 1950s in Columbia and can be considered a modern version of the moulded earth block, more commonly known as adobe [192]. The first mechanical presses are from the beginning of the 20th century, but the idea of compacting soil to improve the quality and performance of the blocks is older [192, 193]. The compaction allows higher density blocks and thus increases their compressive strength as well as their resistance to erosion and damage from water [192, 194, 195]. Over the last seventy years, the CEB technology has seen great progress due to scientific research, experimentation and architectural applications. The technology can offer a high-quality alternative building product, flexible enough to be suitable for small or large-scale production plants and an application range from social housing to luxury homes [192]. The CEB can be easily compared with other materials such as concrete blocks or fired bricks if guaranteed by quality control [192, 193].

In Portugal, the interest on these earthen materials is increasing, namely in the southern part of the country, with a small number of builders specialised in building with them. Some professionals argue that the cost of this type of construction is still not competitive in comparison to conventional solutions, even with the mechanisation of the construction process. However, the growing interest and importance given to sustainability issues can contribute to promoting the use of these techniques in new constructions, allowing reducing its cost.

In this section, the results of the life cycle assessment of rammed earth and CEBs, manufactured in Portugal, in compliance with standard EN15804, i.e. with Product Category Rules for Type III environmental product declaration of construction products [106] are presented.

7.2 MATERIALS AND METHODS

The LCA of Compressed Earth Blocks (CEB) and Rammed Earth (RE), produced by a Portuguese company located in the south of the country, municipality of Serpa, district of Beja, was carried out according to standard EN 15804 [106].

7.2.1 GOAL AND SCOPE DEFINITION

The LCA of materials based on specific life cycle inventory data is essential for an accurate comparison. The goal of the study is to assess the potential environmental impacts and the total embodied energy in the production of CEBs and Rammed Earth. The research is focused on the "cradle-to-gate" stage, but also presents some scenarios for the remaining life-cycle stages. In addition, the study aims to identify the processes that most contribute to the life cycle potential environmental impacts.

At the end of this chapter, a comparison between the two earthen products and conventional buildings materials is performed, based on a declared unit corresponding to 1 m^2 of a wall.

7.2.2 LIFE CYCLE ASSESSMENT

The life cycle inventory data was converted into environmental impacts using two life cycle impact assessment (LCIA) methods. The CML-IA baseline method (version 3.04) was used to assess the environmental indicators expressed in impact categories, and the Cumulative Energy Demand (CED) method (version 1.09) was used to assess the life cycle energy inputs. The improvement of energy efficiency and the reduction of operating energy in buildings has emphasised the importance of the embodied energy in building materials. Therefore, to complement this study, the total embodied energy of the products was also assessed, considering the energy inputs of the processes within the considered system's boundaries.

SimaPro v8.4 software [196] was used to model the life cycle of two construction products.

Table 25 lists the environmental indicators considered in this study and the corresponding LCIA method.

7.2.3 COMPRESSED EARTH BLOCK (CEB)

7.2.3.1 DECLARED UNIT

According to EN 15804 [106], in a "cradle to gate" analysis, a declared unit should be used instead of a functional unit. For the production of CEBs, the declared unit considered is 1 block, with dimensions 300x150x70 mm.

TABLE 25. Environmental indicators and life cycle impact assessment methods

Environmental indicators	Unit	LCIA method
Depletion of abiotic resources – mineral elements (ADP_elements)	kg Sb eq	CML-IA baseline v3.04
Depletion of abiotic resources – fossil fuels (ADP_ff)	MJ	CML-IA baseline v3.04
Global warming potential (GWP)	kg CO_2 eq	CML-IA baseline v3.04
Ozone depletion (ODP)	kg CFC-11 eq	CML-IA baseline v3.04
Photochemical ozone creation (POPC)	kg C_2H_4 eq	CML-IA baseline v3.04
Acidification (AP)	kg SO_2 eq	CML-IA baseline v3.04
Eutrophication (EP)	kg $(PO_4)^{3-}$ eq	CML-IA baseline v3.04
Embodied Energy (EE)	MJ	Cumulative energy demand v1.09

7.2.3.2 SYSTEM BOUNDARIES AND DESCRIPTION OF THE PRODUCTION SYSTEM

In the analysis of the Compressed Earth Blocks, the study covers the life cycle of the material, in a cradle to gate approach with options. Although the company has planned to implement processes to close the loop of the used materials (e.g. waste processing to recover/recycle the product), these have not been implemented yet. Therefore, since the company has no data to quantify the environmental impacts beyond the Product Stage, for the life cycle impact analysis of the CEBs production, only the mandatory stages of the production system were considered (Modules A1-A3) (Fig. 7.1). The information is presented according to the following information modules: A1 – Raw material supply, A2 – Transport and A3 – Manufacturing. In addition to these information modules, technical information was declared for modules B, C and D, according to the scenarios defined by the company (Fig. 7.1), but the respective environmental impacts were not calculated. This method is preconized in standard EN15804 to ensure a proper understanding of the function of a product. Figure 7.1 shows the diagram of processes of the CEBs, presenting all the inputs and outputs in each process, for all life cycle stages. This research is focused on presenting and analysing the impacts resulting from the production of the Compressed Earth Blocks (product stage, modules A1 to A3).

PRODUCT STAGE | Module A1 – Raw material supply

The compressed earth block under analysis is made mostly of soil (more than 80%) with the addition of hydraulic lime and water. The raw material supply process considers the extraction of soil and the supply of ancillary materials. The primary raw material is soil and is extracted in sites within a radius of 30 km from the CEB production plant. The soil extraction and loading of the lorry are carried out by a diesel-powered backhoe loader, with an average consumption of 14.55 l/h at medium-load operation service. During the extraction process, there is a first selection of the raw material – since the layer of soil that is suitable for construction (gravel, sand, silt, clay) is beneath the organic topsoil (agronomic soil). Additionally, before loading it into the lorry, the soil is roughly sieved to remove stones. The “waste” from the selection is returned to the extraction site. For secondary materials, i.e. materials used in the manufacturing process that are produced by other companies (e.g. hydraulic lime), or for which the company does not have direct influence or specific data (e.g. electricity mix), generic data from the Ecoinvent v3.3 life cycle inventory database was used.

PRODUCT STAGE | Module A2 – Transport

In the process of transportation of raw materials/products to the production site, the travelling distance from the suppliers to the production unit of CEBs was considered. The suppliers were the ones indicated by the manufacturer, i.e. where the manufacturer usually buys the needed raw materials/

FIGURE 7.1. Diagram of inputs and outputs of processes in the production of CEBs.

products. A map application (e.g. Google Maps) was used to calculate the transportation distances. In the case of the soil, according to the data presented by the company, the extraction sites are located at an average distance of 30 km. A diesel-powered 7-ton lorry is used in the transportation of soil, and this vehicle is usually rented to a company that provides this kind of service. For the transportation of the other ancillary materials and products, namely the wrapping plastic film, hydraulic lime and wooden pallets, 7 to 32-ton diesel-powered lorries, are used (Fig. 7.2). Figure 7.2 presents the load capacity of the lorries used in the transportation processes and the transportation distance of each material/product used in the manufacturing process.

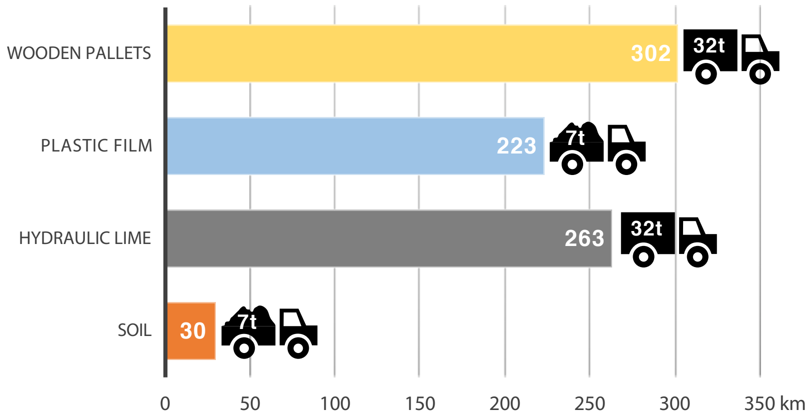


FIGURE 7.2. Travelling distances and type of transportation for each material/product of the CEB production process.

PRODUCT STAGE | Module A3 – Manufacturing

The manufacturing process of the CEB comprehends the following unitary processes:

a. Administrative services – This process includes the office activity necessary for the company operation. This process includes the water consumption and the energy used in the office. The public grids supply both resources.

b. Raw materials reception and drying – the ancillary materials as lime, pallets and plastic film are received and stored. The soil is unloaded and stored in a protected place to dry.

c. Soil crushing and sieving – to obtain an adequate gradation, the soil is crushed and afterwards sieved. The soil crusher (power 3.21 kWh; productivity 9 m^3/h) and the sieve (power 0.85 kWh; productivity 3 m^3/h) equipment are both electric and connected to the public grid. The soil that is "wasted" in the sieving process is recycled and used in other construction works of the company.

d. Mixing – In this process, all materials are mixed (83.5% soil, 6.5% hydraulic lime and 10% of water). A diesel-powered tracked dumper does the mixture with a concrete mixer and max payload of 1500 kg (fuel consumption of 3.2l/h). The mixing time for 1200 kg is of 15 minutes. The mixture is unloaded next to the pressing machine.

e. Pressing – An automatic electric hydraulic press (power 9.54 kWh; productivity of 375 blocks/hour) is used in the process of casting and pressing the blocks. Although the equipment is automatic, two procedures are made manually, namely loading the hopper tank and removing the "fresh" blocks. The defective blocks return to the production cycle.
f. Drying – The "fresh" blocks are wet cured and dried under ambient conditions for at least 28 days. In the wet curing, 10 litres of water are consumed per cubic meter of CEBs. No energy input is required in this process.
g. Handling and packaging - After the blocks are dried, they are stacked on a wooden pallet and wrapped in a plastic film. The whole process is manual.
h. Storage – The pallets are properly stored for later shipment.

CONSTRUCTION STAGE SCENARIO | Module A4 – Transport

This module includes the transportation of the product, ancillary materials and equipment from the company's headquarters to the construction site. The travelling distance is variable, depending on the location of the construction site. Within the equipment frequently transported, a skid-steer loader, a telescopic handler and a mixer are included. Since the equipment returns to the headquarters, the travelling distance has to be doubled. For this transportation, the company usually rents a diesel-powered 32-ton lorry.

CONSTRUCTION STAGE SCENARIO | Module A5 – Construction

The construction process of a CEBs wall consists of laying the blocks with mortar. The mortar used is a mix of lime (usually 30% but the percentage may vary according to the type of soil) with soil and water. Regarding the finishing coating, there are several options since due to aesthetic properties of the product, the wall can be plastered, limewashed or just left with no finishing. Thus, the type of chosen finishing can vary the environmental impact of a CEB wall.

USE STAGE SCENARIO | Module B2 – Maintenance

In the use stage, only the information module regarding the maintenance of the product (module B2) was considered. The other modules of the 'Use Stage' were not considered since they do not apply to this case or are less frequent and difficult to estimate during the service life (e.g. the repair or refurbishment actions depend on the degree of severity of the damage or the type of intervention). Thus, maintenance is the only relevant periodical operation to take into account. This module includes the following processes:

a. Transport – it includes the transportation of building products and equipment from the company headquarters to the building, namely lime and some small equipment and objects. The transport usually used is a diesel-powered van.
b. Whitewashing – The whitewash is the most common maintenance procedure, but the type of maintenance could vary depending on the finishing. The whitewash is a mix of lime and water. Traditionally, the quantity of quicklime is of 1 kg for 5 litres of water and allows to whitewash around 10 m^2 of a wall with two coats. The wall must be wet in advance to the washing, but the quantity of water necessary may vary depending on air temperature and sun exposure. The period between whitewash is on average of 4-5 years but can be longer. The whitewash is applied manually, and it is not required energy input in this process.

END-OF-LIFE STAGE SCENARIO | Module C1 – Demolition

In the case of a CEB wall, the demolition process is no different from a conventional brick wall. In the process, a diesel-powered backhoe digger or a mini-excavator with a hydraulic hammer are usually used, and occasionally it may be necessary to use manual demolition equipment such as jackhammers. The time required for the demolition process depends upon the type and size of the structure to be demolished. In this process, an on-site sorting of the demolition waste is included.

END-OF-LIFE STAGE SCENARIO | Module C2 – Transport

This module includes the transportation of the demolition waste to the company headquarters to be processed. The most suitable vehicle for this transportation is a diesel-powered 32-ton lorry. The travelling distance is variable.

END-OF-LIFE STAGE SCENARIO | Module C3 – Waste processing

The waste processing is simple and has the purpose of recovering the material for a new product life cycle. It includes a process of crushing/milling the waste of the CEB wall (blocks and mortar). In this process, an electrical jaw crusher is used. The resulting material is forwarded to the process of recovery/recycling (module D).

END-OF-LIFE STAGE SCENARIO | Module C4 – Disposal

In the demolition process, the company claims that it is possible to recover near 90% of the waste material. Therefore, the other 10% are lost waste (e.g. small broken parts, dust from demolition, etc.) that it is left in the building site. Since the product is mainly made from soil, there is no significant impact in returning it to the natural environment.

BENEFITS AND LOAD BEYOND THE SYSTEM BOUNDARY | Module D – Recovery/Recycling

The process of recovery/recycling recovers the resulting material from waste processing (module C3) for a new cycle. The material is forwarded to the mixing process (Module A3) to be recycled into new CEBs. To be recycled, it is necessary to add 1%, in volume, of hydraulic lime to increase the amount of binder of the mixture and to guarantee quality properties. The value of 1% of lime was provided by the manufacturer, according to their current experience on recycling defective dried blocks or dismantled walls. The use of the recovered material has economic and environmental benefits and does not change the quality of the final product.

7.2.3.3 CUT-OFF CRITERIA

According to EN 15804, the cut-off criteria for unitary processes is 1% of the total energy inputs and 1% of the total mass but should not exceed a total of 5% of energy and mass flows excluded from the product stage. The following processes from the CEBs production stage were excluded:

a. Internal transport – since the manufacturing equipment is in a production chain, i.e. very close to each other, the contribution of internal transport to potential environmental impacts is considered negligible;
b. Manual work, as it does not cause impacts;
c. Environmental loads related to the construction of the industrial facilities and production of equipment;
d. Maintenance of building facilities and equipment – the impacts attributed to the maintenance of facilities and equipment were not considered since they are difficult to quantify and have a low contribution in life cycle inventory (LCI) [197];
e. In the administrative services the office consumables (e.g. office paper and tonners) were excluded since there was no purchase record history.

7.2.3.4 LIFE CYCLE INVENTORY

In the CEBs product stage processes, specific data such as physical characteristics (dimensions and weight of the blocks), materials and quantities, type of equipment used, extraction capacity, the time required for mixing, the production capacity of the press, the quantity of packaging products (European pallets and packaging plastic film), amount of waste and billing values (used for economic allocation) were provided by the company.

The fuel and electricity used by the equipment in processes like extraction, crushing, sieving and pressing take into consideration manufacturers technical sheets or data provided by them. The number of uses of a wood pallet took as reference the work of Bengtsson and Logie [198] and considered 87 trips/uses during its life span.

The inventory data regarding transportation, consumed fuel and electricity, and production of hydraulic lime and packaging products, is based on the generic life cycle inventory Ecoinvent v3.3 database.

Table 26 presents the inputs and outputs to produce 1 CEB. Figure 7.3 shows the raw materials flow to produce a CEB with 6,1 kg (Product Stage). Regarding the percentage of lime used, it should be noted that CEBs use more lime than rammed earth because the blocks need higher mechanical resistance to support handling and transportation after the curing process.

TABLE 26. Life cycle inventory per declared unit (1 CEB)

Inputs	Units	1 CEB
Soil	kg	7.05E+00
Lime	kg	2.51E-01
Water	L	5.81E-01
Electricity	kWh	3.26E-02
Fuel	MJ	3.27E-01
European pallets	un	1.15E-04
Packaging film	kg	7.50E-04
Transport	ton.km	2.57E-01
Outputs		
Waste soil (gravel, etc.)	kg	1.34E+00
Water (drying process)	L	4.32E-01

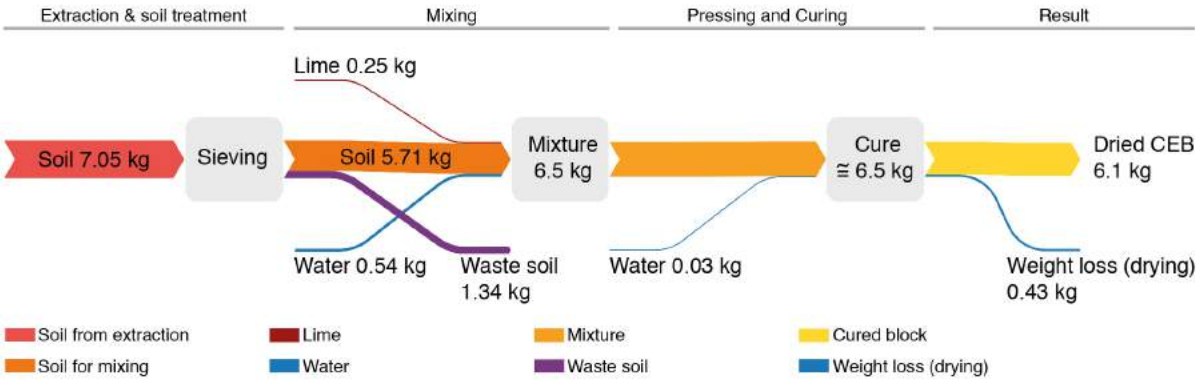


FIGURE 7.2. Diagram of raw materials flows per declared unit (1 CEB).

7.2.3.5 ALLOCATION PROCEDURES

The business activity of the company is not only related to the production of compressed earth blocks but also includes rammed earth, and conventional construction works. Thus, to take into account the impacts of the unitary processes that are common to the various business activities, the financial allocation was used. In this case, a percentage of the revenue generated by each activity was applied.

A common process to all business activities are the administrative services, and in this case, the electricity and water use in the office was considered. The information considered reports to the year 2016.

7.2.4 RAMMED EARTH

7.2.4.1 DECLARED UNIT

In this case, the declared unit is 1 m^3 of a rammed earth wall.

7.2.4.2 SYSTEM BOUNDARIES AND DESCRIPTION OF THE PRODUCTION SYSTEM

In the case of Rammed Earth, the study covers the stages from cradle to gate with options. As for CEBs, the company intends to close the loop of the product, but the necessary processes have not been implemented yet. Therefore, the company has no quantitative data for these processes, and it is difficult to predict the required time and resources. Moreover, even though it is possible to pre-cast rammed earth panels, the majority of this type of construction relies on the traditional way of on-site construction. Thus, in this study, some information modules in “cradle to gate” analysis are not applicable, and the modules of Construction Stage (A4-A5) had to be considered (Fig. 7.4). The environmental impacts were not quantified beyond the Construction Stage, and the modules were organised as follows: A1 – Raw materials extraction and supply; A4 – Transport of equipment and materials to the building site; and A5 – Installation/Construction. From information modules B – Maintenance to D – Recovery/recycling, the processes were described according to the scenarios provided by the company (Fig. 7.4), but the environmental impacts were not quantified. As already mentioned for the CEBs, this method is recommended by standard EN15804 to ensure a proper understanding of the function of a product. Figure 7.4 shows the diagram of processes and presents all the inputs and outputs for each process of the life cycle stages.

The composition of rammed earth walls varies from site to site according to the type of soil and its properties. Even in a region with adequate soils for rammed earth, sometimes there is the need to adjust the particle size distribution. If the soils to make this adjustment are sourced far from the building site, the overall environmental impacts will increase due to the impacts of the transportation processes. The company reported that when this adjustment is needed, the soils to do so are extracted as close as possible to the building site to minimise the transportation needs. Nonetheless, to consider these variables in this study would be complex since the adjustments may vary from site to site. Thus, in this study the common scenario of adequate soils available in the building site or nearby is considered, as reported by the company. Although it is possible to build a rammed earth wall without adding stabilisers, if the soil has good quality, in this study the most common scenario is considered, i.e. the addition of hydraulic lime. The conventional mixture used has the following percentages: 87% soil, 3% hydraulic lime and 10% of water.

PRODUCT AND CONSTRUCTION STAGES | Module A1 – Raw materials extraction and supply

The main raw material is soil and is extracted on-site by a diesel-powered backhoe loader, with an average consumption of 14.55 l/h at an average-load operation service. During the extraction process, the soil is sieved to reject rough materials like rocks. The “waste” from the sieving process is returned to the extraction site.

The hydraulic lime necessary in the construction process has its origin in production units as close as possible to the company’s facilities.

PRODUCT AND CONSTRUCTION STAGES | Module A4 – Transport

In the process of transportation of materials and equipment to the construction site, and since it is variable, based on the data provided by the company, it was considered that the average travelling distance from the company headquarters is 30 km.

In the equipment transported from the headquarters, a skid-steer loader, a telescopic handler, a portable air compressor, pneumatic rammers, the formwork panels and the rented backhoe digger are

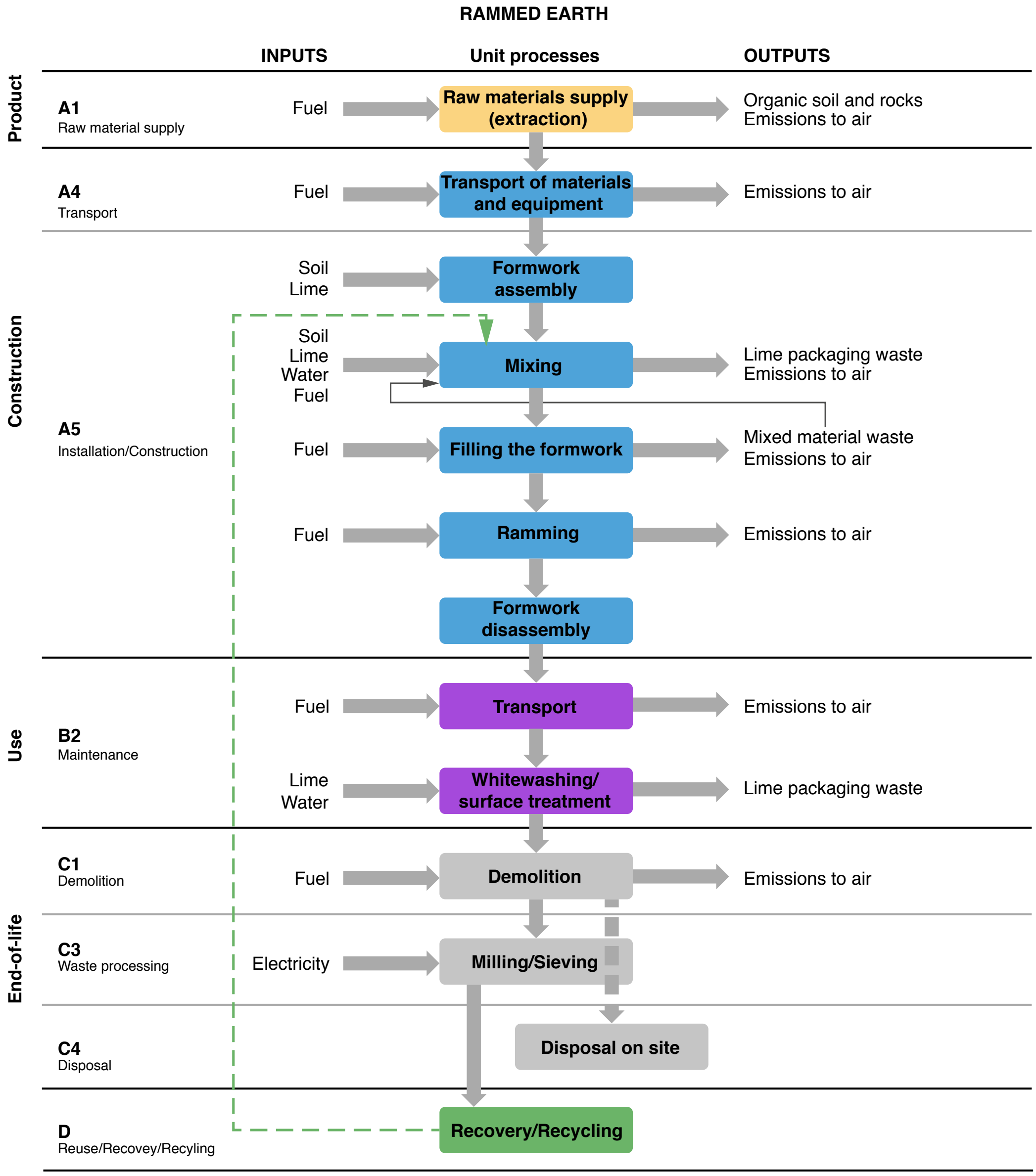


FIGURE 7.4. Diagram of inputs and outputs of processes to build a rammed earth wall.

included. Since the equipment returns to the headquarters, the average travelling distance considered was 60 km. The backhoe digger used in the extraction process is rented at an average distance of 5 km from the headquarters. This transportation is done by road using a diesel-powered 32-ton lorry that is rented to a company that provides this kind of service.

For the transportation of hydraulic lime, the distance from supplier to company's headquarters, and from there to the construction site (both are in a 32-ton lorry) was considered (Fig. 7.5). The environmental loads from the transportation processes are based on the generic inventory values from the Ecoinvent v3.3 database. The travelling distances and the type of transport considered for the equipment and materials are presented in Figure 7.5.

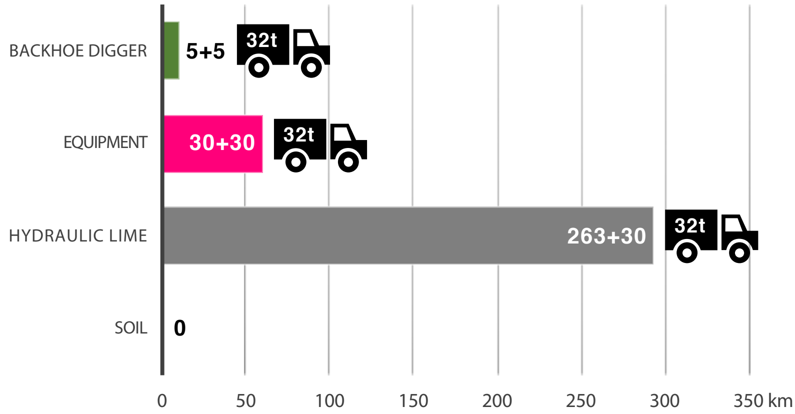


FIGURE 7.5. Travelling distances and type of transportation for each material/product of the rammed earth construction process.

PRODUCT AND CONSTRUCTION STAGES | Module A5 – Construction

In this module, the following unitary processes are considered:

a. Administrative services – This process includes the office activity necessary for the company's operation, i.e. water and electricity use in the office;

b. Formwork assembly – This process consists of assembling the formwork elements to cast the rammed earth. Although this process is mostly manual, in some conditions the telescopic handler to lift the formwork panels can be used;

c. Mixing – In this process, all raw materials are mixed (87% soil, 3% hydraulic lime and 10% of water). In the mixture, a diesel-powered skid-steer loader (fuel consumption of 6.8 l/h) is used. The mixing time for 2080 kg (approximately 1.66 m^3 of the mixture used to build 1 m^3 of rammed earth) is about 15 minutes;

d. Formwork loading – The mixture is poured into the formwork with a diesel-powered telescopic handler (fuel consumption of 9.12 l/h, considering a mixed-use of cargo, handling, etc.);

e. Ramming – This process is carried out by workers using pneumatic rammers driven by a portable diesel-powered air compressor (fuel consumption of 6.8 l/h, which is equivalent to 2.63 l/m^3 of rammed earth);

f. Formwork disassembly – This process consists of disassembling the formwork and is mostly manual with the occasional use of the telescopic handler. After this process, the rammed earth wall is naturally dried.

USE STAGE SCENARIO | Module B2 – Maintenance

In the Use stage, the company only provided data regarding the maintenance of the wall. As in the case of the CEB, the other modules of the 'Use Stage' were not considered. The following unit processes compose this module:

a. Transport – this process includes the transportation of building products and equipment from headquarters to the building site, namely lime and some small equipment and objects. The type of transport used is usually a diesel-powered van.
b. Whitewashing – Whitewashing is the most common maintenance procedure in this type of wall, but other types of surface maintenance are also applied, mainly when the wall surface is not covered by a finishing layer (e.g. render). The maintenance is usually carried out at 4-5 years interval but this can be longer if, for example, the wall is protected from the rain. The whitewash procedure is equal to the one mentioned for the CEBs. The whitewash is applied manually, and no energy input is required in this process.

END-OF-LIFE STAGE SCENARIO | Module C1 – Demolition

The demolition process of a rammed earth wall is very similar to a conventional wall. This process uses a diesel-powered backhoe digger or a mini excavator with a hydraulic hammer typically, and occasionally it may be necessary to use manual demolition equipment such as jackhammers. The time required for the demolition process depends upon the type and size of the structure to be demolished. In this process, the on-site sorting of the demolition waste is included.

END-OF-LIFE STAGE SCENARIO | Module C3 – Waste processing

In the case of rammed earth, waste processing is made at the building site. The process is simple and consists of crushing/milling the waste of the rammed earth wall (including renders, if applicable) to recover the material for a new product cycle. In this process, an electrical jaw crusher is used. The resulting material is forwarded to the process of recovery/recycling (module D).

END-OF-LIFE STAGE SCENARIO | Module C4 – Disposal

In the demolition process, it is assumed that near 10% of the material is lost and 90% is recovered. Therefore, 10% of demolition waste is left at the building site. Since the product is mainly made from soil, it is possible to state that there is no significant impact from returning this material to the natural environment.

BENEFITS AND LOAD BEYOND THE SYSTEM BOUNDARY | Module D – Recovery/Recycling

The process of recovery/recycling recovers the resulting material from waste processing (module C3) for a new product cycle. The material is forwarded to the mixing process (Module A3) to be reused in a new wall. The use of the recovered material has economic and environmental benefits and will not affect the functional performance of the new wall.

7.2.4.3 CUT-OFF CRITERIA

In the assessment of the environmental impacts of a rammed earth wall, and based in the EN 15804 cut-off rules, the following unitary processes were excluded:

a. Internal transport and equipment for formwork assembly – since the equipment is used in several processes almost simultaneously and in some cases just sporadically (as in the formwork assembly), the contribution of internal transport and equipment is difficult to quantify and, in some cases, negligible;
b. Manual work, as it does not cause impacts;
c. Environmental loads related to the construction of the industrial facilities and production of equipment;
d. Maintenance of building facilities and equipment – the impacts attributed to the maintenance of the facilities and equipment were not considered since they are difficult to quantify and have a low contribution to the life cycle inventory (LCI) [197];
e. In the administrative services, the office consumables (e.g. office paper and tonners) were excluded since there was no purchase record history;
f. The transport of employees to the construction site. Since it is difficult to determine the time required for the construction, the number of trips necessary to build the rammed earth walls were not considered.

7.2.4.4 LIFE CYCLE INVENTORY

In the Product and Construction stages, specific data such as physical materials and quantities, type of equipment used, extraction capacity, the time required to mix and to pour into the formwork, fuel consumption of the portable air compressor, amount of waste and billing values were provided by the company. The company also provided the average distance between the company headquarters and the construction site and the type of transportation used.

The fuel and electricity used by the equipment in processes like extraction, mixing and lifting, take into consideration manufacturers technical sheets or data provided by them.

The inventory data regarding transportation, consumed fuel and electricity and production of hydraulic lime are based on the generic life cycle inventory Ecoinvent v3.3 database.

The data regarding transport vehicles, fuel, electricity, water and hydraulic lime considered the processes predefined in the SimaPro and Ecoinvent database. Table 27 presents the inputs and outputs to build 1 m^3 of rammed earth wall. Figure 7.6 shows the raw materials flow to build a rammed earth wall with 1 m^3 (Product and Construction Stages).

TABLE 27. Life cycle inventory per declared unit (1m^3 of rammed earth wall)

Inputs	Units	1 m^3 Rammed earth
Soil	kg	1.98E+03
Lime	kg	3.27E+01
Water	L	1.56E+02
Electricity	kWh	1.59E+00
Fuel	MJ	2.56E+02
Transport	ton.km	1.70E+01
Outputs		
Waste soil (gravel, etc.)	kg	9.89E+01
Water (drying process)	L	8.92E+01

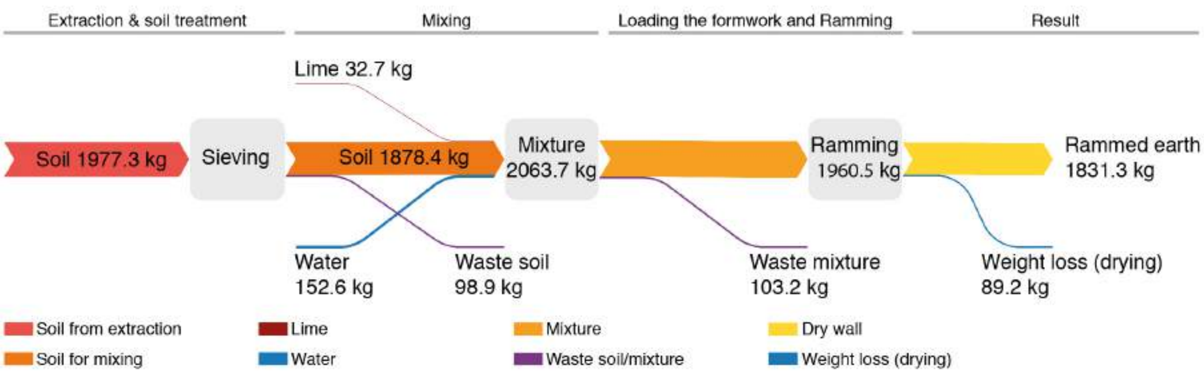


FIGURE 7.6. Diagram of raw materials flow per declared unit (1 m^3 of rammed earth wall).

7.2.4.5 ALLOCATION PROCEDURES

As mentioned before, the business activity of the company covers diverse types of construction works. Thus, as in the assessment of CEBs, a financial allocation was used to carry out the calculation, i.e. a percentage of the revenue generated by each activity. The allocation was used to estimate the environmental loads resulting from the annual consumption of electricity and water in the company headquarters that can be attributed to the rammed earth construction works. Data from the year 2016 were used.

7.3 LCA AND DISCUSSION OF RESULTS

In the following paragraphs, the LCA of earthen materials is presented. The analysis is divided into two parts. The first part is focused on the LCA of CEB and rammed earth materials, based on their respective declared units. Then, to highlight potential environmental advantages of using local earthen materials in relation to conventional materials, a comparative LCA is carried out based on a functional unit of 1 m^2 of a wall.

7.3.1 COMPRESSED EARTH BLOCKS

7.3.1.1 ENVIRONMENTAL IMPACTS

Table 28 presents the environmental impacts related to the product stage (cradle-to-gate) of the compressed earth blocks. To understand the dimension of the environmental impacts associated with each module, the contribution of each module to the overall impact is presented in Figure 7.7. From the analysis of the results, it is possible to verify that modules A2 and A3 are the ones that most contribute to the potential impacts (Fig. 7.7). In the ADP_ff category, modules A2 and A3 have almost the same contribution. In categories as ADP_elements and ODP, the module A2 has the highest weight. On the other hand, in categories as GWP, POCP, AP and EP, it is the module A3 that has the highest contribution.

Besides being relevant to understand the contribution of each information module in each impact category, it is also essential to identify the processes that contribute the most to the impacts within each module, to allow future improvements. Figure 7.8 identifies the processes/products which cause more

TABLE 28. Environmental impacts per declared unit (1 CEB)

Impact category	Unit	Total	A1-Raw material supply	A2-Transport	A3-Manufacturing
Depletion of abiotic resources – mineral elements (ADP_elements)	kg Sb eq	5.72E-07	5.32E-09	5.05E-07	6.11E-08
Depletion of abiotic resources – fossil fuels (ADP_ff)	MJ	3.58E+00	2.58E-01	1.67E+00	1.65E+00
Global warming potential (GWP)	kg CO_2 eq	3.88E-01	1.68E-02	1.07E-01	2.63E-01
Ozone depletion (ODP)	kg CFC-11 eq	3.46E-08	1.92E-08	1.92E-08	1.23E-08
Photochemical ozone creation (POPC)	kg C_2H_4 eq	4.92E-05	3.37E-06	1.86E-05	2.72E-05
Acidification (AP)	kg SO_2 eq	1.24E-03	1.28E-04	4.10E-04	7.01E-04
Eutrophication (EP)	kg $(PO_4)^{3-}$ eq	2.98E-04	2.93E-05	9.70E-05	1.72E-04

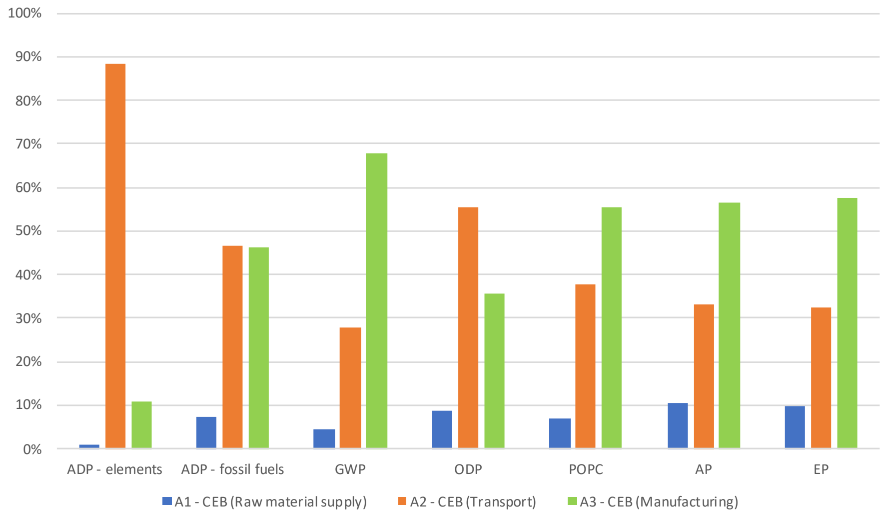


FIGURE 7.7. Weight of the modules on each environmental impact category, per declared unit (1 CEB).

impacts in each module. During the Product Stage, it is possible to verify that the processes with the highest impacts, more than 50%, in each module are the same for all environmental impact categories. In module A1, the extraction of soil using a backhoe digger has the highest impacts. In module A2, soil transportation from the extraction site to the manufacturing facility represents almost all the impacts associated with this module. Finally, in module A3, it was expected that processes such as the mechanical processing of the soil (crushing, sieving and mixing) and the pressing process would have the highest weight in impacts. Still, results show that it is the addition of hydraulic lime that contributes to more than 60% of the value of all impact categories. Although with a lower contribution, the processes of mixing (using a diesel-powered concrete mixer) and pressing also stand out in some categories. The process of pressing in categories such as ADP_elements and POPC represents around 10%, while the mixing process (concrete mixer) has some importance in more categories, namely, GWP (≈5%), ADP_ff (≈10%), ODP (≈20%), AP (≈15%) and EP (≈15%).

7.3.1.2 EMBODIED ENERGY

Table 29 presents the total embodied energy of 1 CEB. From the analysis of the results (Table 29 and Fig. 7.9), it is possible to verify that module A3 has the highest contribution to total embodied energy, followed by module A2.

TABLE 29. Total embodied energy per declared unit (1 CEB)

Total Energy	Unit	Total	A1-Raw material supply	A2-Transport	A3-Manufacturing
Embodied energy (EE, tot)	MJ	2.98E-04	2.93E-05	9.70E-05	1.72E-04

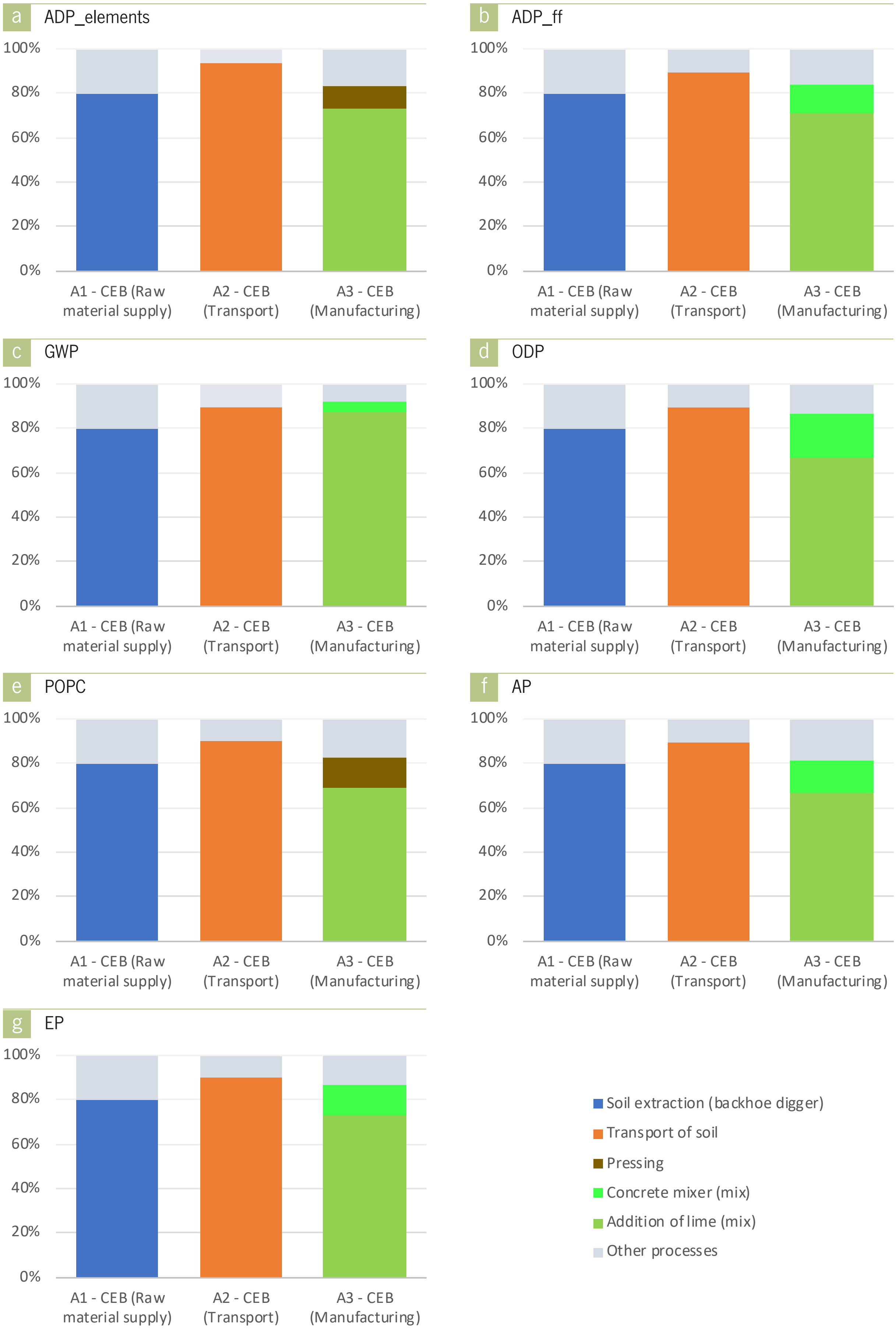


FIGURE 7.8. Processes with the highest impacts by module and category of environmental impact per declared unit (1 CEB).

As verified in the assessment of environmental impacts, three processes represent more than 60% of the total energy used in each module (Fig. 7.10). In module A1, the process with the highest use of energy is the extraction of soil using a backhoe digger; in module A2, it is the process related to the transport of soil; and in module A3 it is the addition of hydraulic lime to the mix. Thus, in A3 the use of lime as stabiliser represents a higher contribution to the total embodied energy than all the mechanical processes to obtain a CEB. The processes of mixing (concrete mixer) and pressing represent a contribution of approximately 10% each.

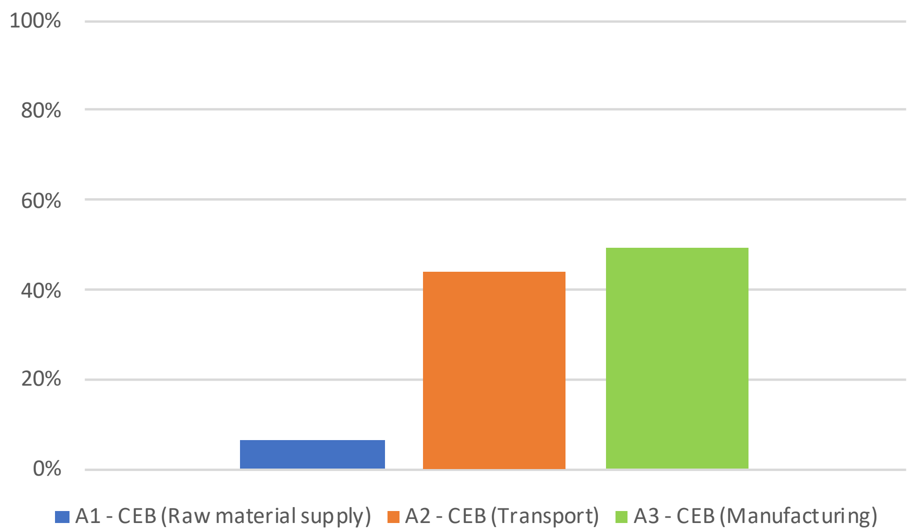


FIGURE 7.9. The contribution of each module to the total embodied energy per declared unit (1 CEB))

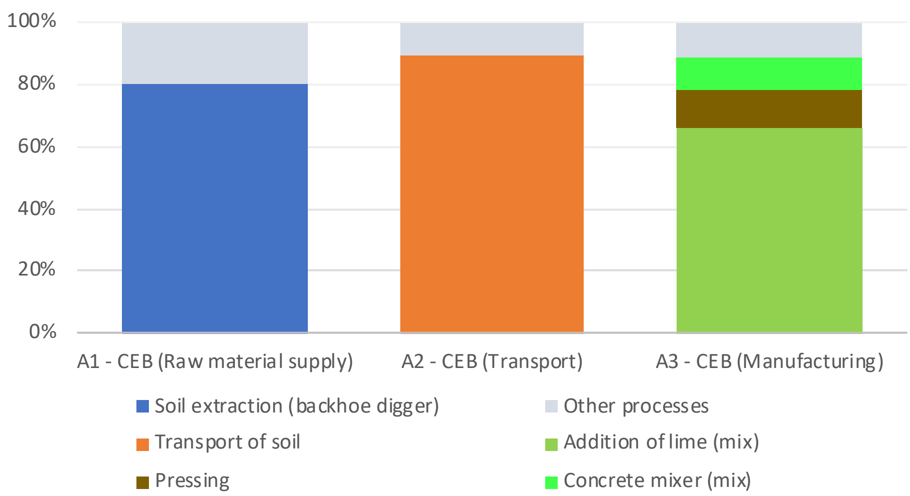


FIGURE 7.10. Processes of each module that contribute the most to the embodied energy of a declared unit (1 CEB).

7.3.2 RAMMED EARTH

7.3.2.1 ENVIRONMENTAL IMPACTS

As mentioned in previous sections, the construction process of rammed earth walls is entirely made on site, and therefore, the 'Construction Stage' also had to be considered. Table 30 presents the environmental impacts for each category. The percentage of the environmental impacts associated with each module, and the contribution of each module to the overall impact is illustrated in Figure 7.11.

From the analysis of the results, module A5 (Construction) stands out by contributing the most to all categories. Once the "material" is produced/built on-site, the number of manufacturing processes and respective environmental load are concentrated in this module. Regarding the other modules, A1 (Raw material supply) and A4 (Transport), they have a similar weight (below 10%) in almost all categories. The exception is category ADP_elements where module A4 weights more than 35%. In categories POPC, AP and EP, module A1 has a percentage slightly higher than module A4 but still below 10% of the total.

In order to understand which are the processes that have a higher contribution in each module, Figure 7.12 presents the results for the several environmental impact categories. Regarding module A1, since the extraction of soil was the only process considered, it represents the total impacts of all categories. In module A4 (Transport), the transport of the hydraulic lime is the process with the highest contribution, almost 60%, in all environmental impact categories. Lime represents only 3% of total rammed earth's weight. Still, the addition of this stabiliser has a significant bearing on the impacts of this module, which could be reduced with the use of lime produced locally, and if used only in situations in which the quality of the soil makes its use necessary.

TABLE 30. Environmental impacts per declared unit (1 m^3 of rammed earth wall)

Impact category	Unit	Total	A1-Raw material supply	A4-Transport	A5-Construction
Depletion of abiotic resources – mineral elements (ADP_elements)	kg Sb eq	2.15E-05	1.01E-06	7.63E-06	1.29E-05
Depletion of abiotic resources – fossil fuels (ADP_ff)	MJ	5.71E+02	4.88E+01	4.43E+01	4.78E+02
Global warming potential (GWP)	kg CO_2 eq	4.75E+01	3.18E+00	2.76E+00	4.16E+01
Ozone depletion (ODP)	kg CFC-11 eq	6.00E-06	5.82E-07	5.24E-07	4.90E-06
Photochemical ozone creation (POPC)	kg C_2H_4 eq	7.91E-03	6.39E-04	4.53E-04	6.82E-03
Acidification (AP)	kg SO_2 eq	2.58E-01	2.42E-02	1.08E-02	2.23E-01
Eutrophication (EP)	kg $(PO_4)^{3-}$ eq	6.12E-02	5.56E-03	2.43E-03	5.32E-02

In module A5, the addition of hydraulic lime to the mixture is responsible for the highest impacts in categories ADP_elements (≈45%) and GWP (≈ 58%), but also has significant impacts in ADP_ff (≈ 32%), ODP (≈22%) and POPC (≈36%), AP (≈27%) and EP (≈31%) (Fig. 7.10). The use of the skid-steer loader in the mixing process and of the air compressor in the ramming process, more specifically the fuel consumed, are also responsible for considerable impacts in module A3. The use of the skid-steer loader has high impacts in categories ODP (≈36%), AP (≈33%) and EP (≈32%), but also has significant impacts in ADP_elements (≈24%), ADP_ff (≈31%), POPC (≈29%) and GWP (≈19%) (Fig. 7.10). The contribution of the air compressor has a similar profile, with values between 19-30%, namely, ADP_elements (≈24%), ADP_ff (≈32%), GWP (≈19%), ODP (≈37%), POPC (≈29%), AP (≈34%) and EP (≈32%).

As observed for the CEBs, the use of hydraulic lime (3%) as stabiliser represents a considerable share of the environmental impacts in almost all categories. The use of fuel in mechanical processes of mixing and ramming also has a significant share of impacts in module A5.

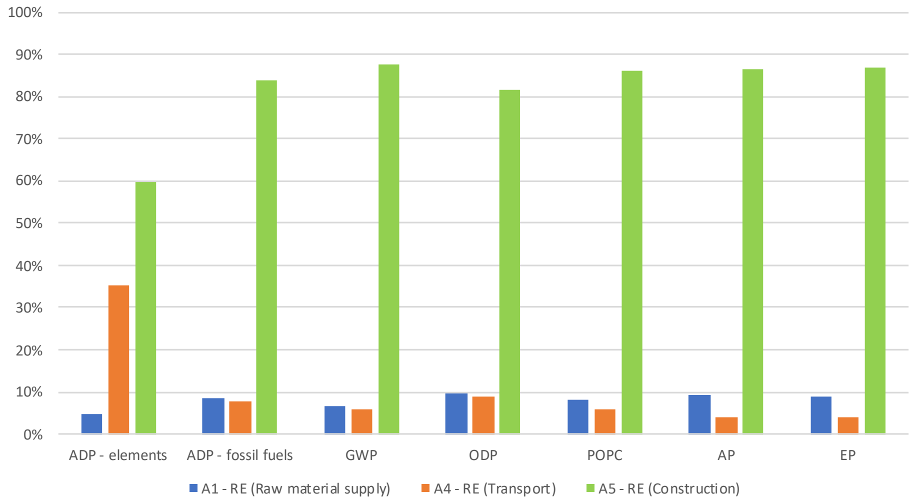


FIGURE 7.11. Weight of the modules on each environmental impact category, per declared unit (1 m^3 of rammed earth wall).

7.3.2.2 EMBODIED ENERGY

Table 31 presents the total energy consumed to build 1 m^3 of a rammed earth wall and the contribution of each information module (modules A1-A5).

From the analysis of the results, it is possible to verify that module A5 (Construction) has the highest contribution to total embodied energy, with more than 80%, following the trend verified in the environmental impact categories. Modules A1 and A4 have almost the same contribution, with less than 10% each (Table 31 and Fig. 7.13).

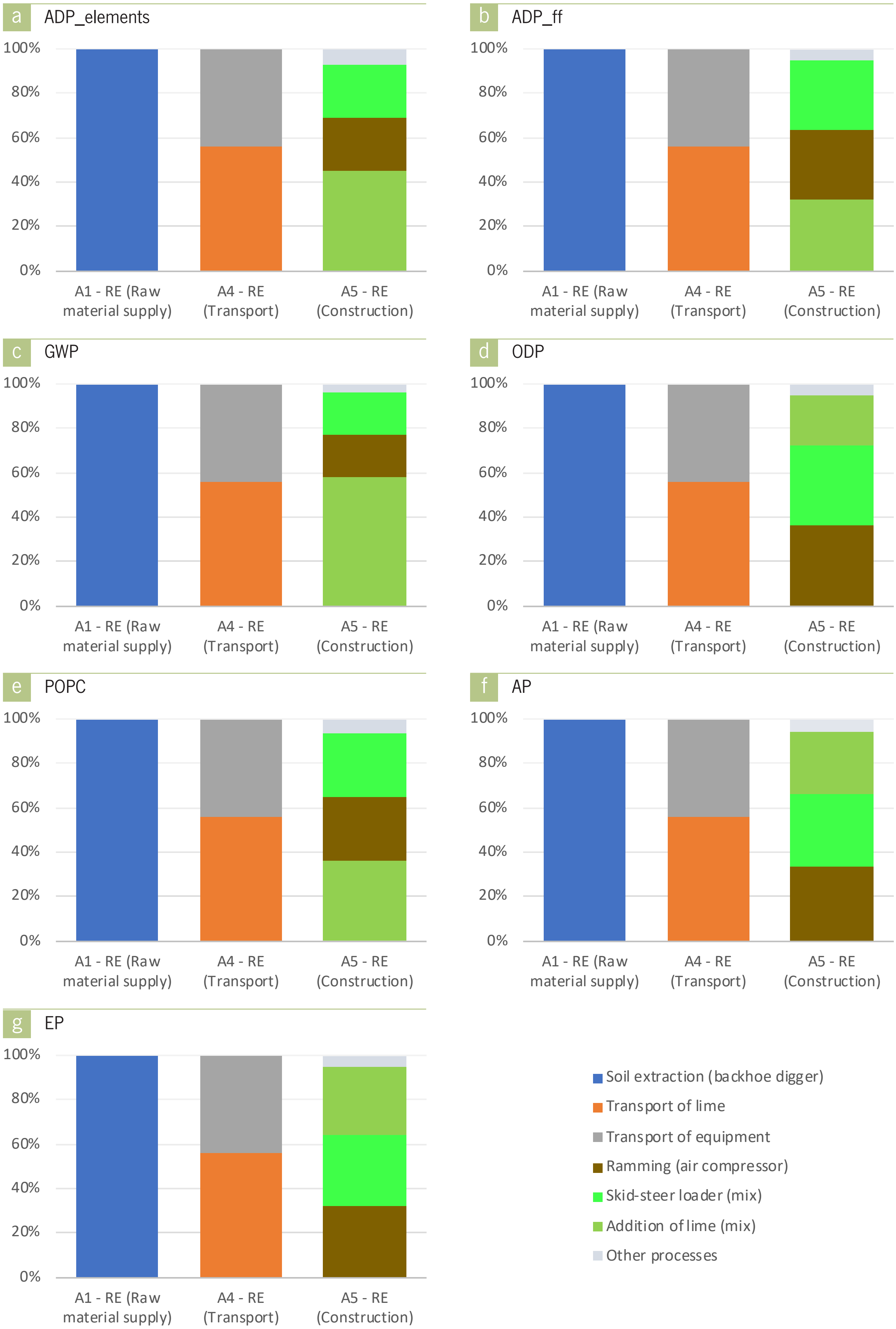


FIGURE 7.12. Processes with the highest impacts by module and category of environmental impact per declared unit (1 m^3 of rammed earth wall).

TABLE 31. Total embodied energy per declared unit (1 m^3 of rammed earth wall)

Total Energy	Unit	Total	A1-Raw material supply	A4-Transport	A5-Construction
Embodied energy (EE, tot)	MJ	5.96E+02	4.95E+01	4.61E+01	5.00E+02

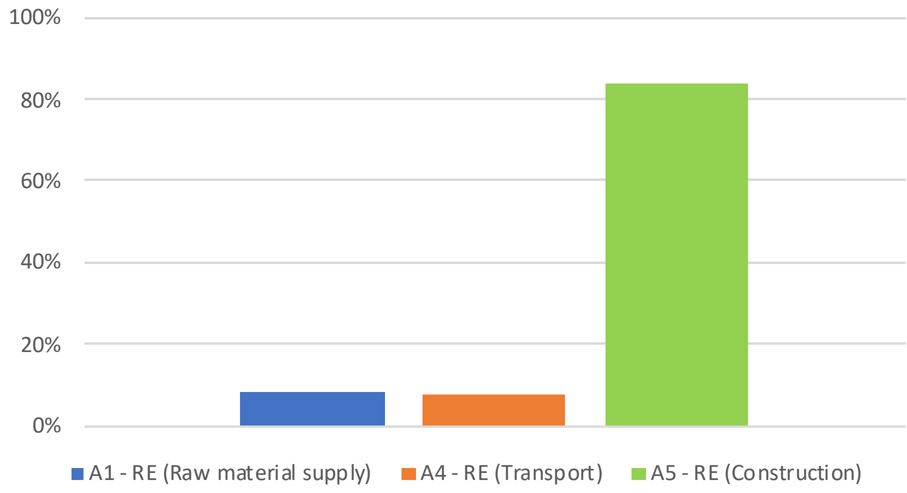


FIGURE 7.13. The contribution of each module to the total embodied energy per declared unit (1 m^3 of rammed earth wall).

Likewise, the processes with higher energy use in each module were highlighted (Fig. 7.14). The analysis of the results is similar to the ones reported regarding the environmental impacts. In module A1, the extraction of soil using a backhoe digger is the only process and so responsible for all the energy used in this module. In Module A4, the transport of hydraulic lime is responsible for almost 60% of the energy used in this module. As mentioned before, a small percentage of lime is responsible for considerable energy use. The other 40% are referred to the transport of the equipment, materials and other products. In Module A5, the processes with higher energy use are related to the fuel used by the air compressor and the skid-steer loader, and to the addition of hydraulic lime. The first two processes have almost the same contribution (around 30%), being the contribution of the lime slightly higher (33%) (Fig. 7.14). Once again, lime has the highest contribution. Lime is the only product that is not produced locally, and that has an industrially-based production, and therefore its contribution to the embodied energy is significant. The embodied energy of the rammed earth produced by this company can be reduced if they find an alternative material or a producer with a less energy-intensive production system.

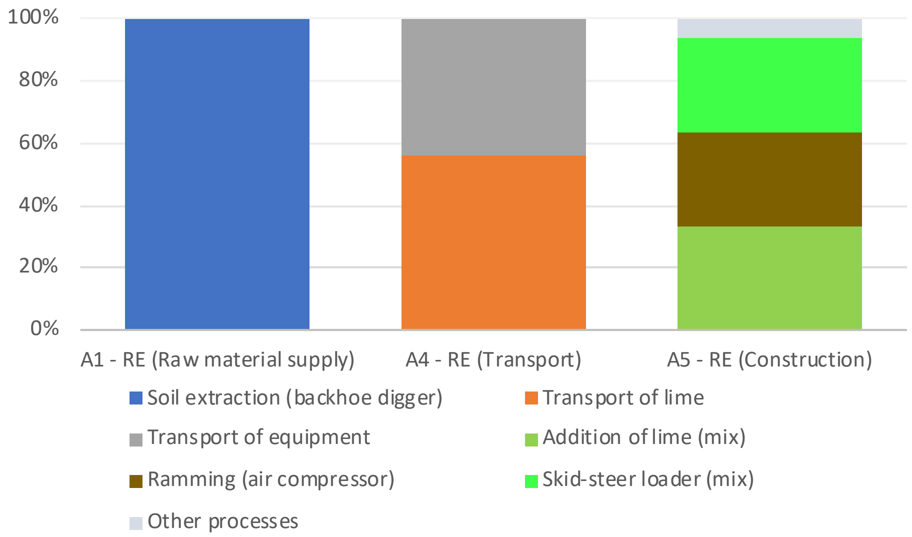


FIGURE 7.14. Processes with highest embodied energy by module and per declared unit (1 m^3 of rammed earth wall).

7.3.3 COMPARISON OF THE ENVIRONMENTAL PERFORMANCE OF DIFFERENT WALLS

This section is devoted to comparing different types of external and partition walls, using earthen and conventional building materials, to address the potential environmental advantages of using local earthen materials/techniques in the Portuguese context. The comparative analysis is made based on a declared unit of 1 m^2 of a wall, to compare the environmental performance of different building systems, in the same circumstances. In this analysis, only the cradle-to-gate impacts are considered. Transportation of materials was not considered since the travelling distance from the different manufacturers varies according to the location of the construction site, and the potential impacts of this module could distort the comparison and the goal of the analysis.

For the external walls, the considered functional unit is 1 m^2 of a wall that has the same U-value, according to technical data for the Portuguese context [136, 137]. Therefore, the external wall solutions considered have a similar U-Value (1,30 W/(m^2.°C)) and are the following:

i. Rammed Earth, without render, R=0,55 (m^2.°C)/W, total thickness of 60 cm;
ii. Clay hollow brick 22 cm thick, R=0,52 (m^2.°C)/W, considering laying mortar and render (sand and cement), total thickness of 26 cm;
iii. Lightweight concrete block 25 cm thick, R=0,54 (m^2.°C)/W, considering laying mortar and render (sand and cement), total thickness of 29 cm.

For indoor partitions, the declared unit is 1 m^2 of a wall that satisfies the national functional requirements for a partition wall inside a dwelling. Thus, the partition solutions considered are the following:

i. CEB, considering laying mortar (lime and soil) without render, total thickness of 15 cm;

ii. Ceramic hollow brick 11 cm thick, considering laying cement mortar in the joints and cement render as finishing layer, with a total thickness of 15 cm;

iii. Concrete block 10 cm thick, considering laying mortar and render (cement mortar), with a total thickness of 14 cm.

The calculation of the environmental impacts of the cement mortar was based on the generic inventory data from the Ecoinvent v3.3 database. The inventory of materials used in the different wall solutions is presented in Tables 32 and 33.

TABLE 32. Data inventory of the materials used in the different external walls per declared unit (1 m^2)

Inputs	Unit	Rammed earth (60 cm)	Clay hollow brick (26 cm)	Lightweight concrete block (29 cm)
Rammed earth	kg	1100	–	–
Clay hollow brick	kg	–	119	–
Lightweight concrete block	kg	–	–	112
Mortar	kg	–	110	107

TABLE 33. Data inventory of the materials used in the different partition walls per declared unit (1 m^2)

Inputs	Unit	CEB (15 cm)	Clay hollow brick (15 cm)	Concrete block (14 cm)
CEB	kg	246	–	–
Earth mortar	kg	44.5	–	–
Clay hollow brick	kg	–	63.6	–
Concrete block	kg	–	–	90.6
Mortar	kg	–	92.5	88.6

From the analysis of the results, it is possible to verify that earthen materials have the best performance by far, both in environmental categories and embodied energy (Tables 34-35 and Fig. 7.15-7.16). In some environmental categories, the differences are not higher due to the weight of earthen solutions that is considerably higher than conventional building systems (except for ODP and AP in which rammed earth has equal or slightly higher impacts than conventional solutions). However, the weight of these solutions cannot be seen as a disadvantage, since earthen materials are acknowledged by their thermal and hygroscopic inertia that has benefits in stabilising indoor relative humidity and air temperature.

Therefore, when compared with industrially produced materials, earthen materials have considerably lower environmental impacts and embodied energy, being an alternative for sustainable building. Moreover, and although it was not quantified, the potential of earthen materials to close the loop of materials and to be recovered and used in a new product cycle, with the same function, must be highlighted. Their low processing is an advantage since the waste treatment processes to recover the material are the same or similar to the ones considered to prepare raw materials. As an example of comparison, a brick wall does not have the same potential for being recovered/reused. The final disposal process for clay bricks after demolition consists in being used as filler material in the base of buildings or roads or landfilled as inert waste, as mentioned in the study of Almeida *et al.* [91] for the Portuguese context. So, there is a quality loss in the original material that cannot be recovered, and the demolition waste has a limited reuse potential.

TABLE 34. Assessment of the environmental performance and embodied energy of 1 m^2 of different external walls

Impact category	Unit	Rammed earth (60 cm)	Clay hollow brick (26 cm)	Lightweight concrete block (29 cm)
Depletion of abiotic resources – mineral elements (ADP_elements)	kg Sb eq	1.29E-05	8.21E-05	9.56E-05
Depletion of abiotic resources – fossil fuels (ADP_ff)	MJ	3.43E+02	4.61E+02	6.04E+02
Global warming potential (GWP)	kg CO_2 eq	2.85E+01	5.74E+01	8.26E+01
Ozone depletion (ODP)	kg CFC-11 eq	3.60E-06	3.87E-06	2.80E-06
Photochemical ozone creation (POPC)	kg C_2H_4 eq	4.74E-03	9.26E-03	1.97E-02
Acidification (AP)	kg SO_2 eq	1.55E-01	1.63E-01	4.19E-01
Eutrophication (EP)	kg $(PO_4)^{3-}$ eq	3.67E-02	4.53E-02	8.63E-02
Embodied energy (EE, tot)	MJ	3.58E+02	5.40E+02	7.23E+02

TABLE 35. Assessment of the environmental performance and embodied energy of 1 m^2 of different internal partition walls

Impact category	Unit	CEB (15 cm)	Clay hollow brick (15 cm)	Concrete block (29 cm)
Depletion of abiotic resources – mineral elements (ADP_elements)	kg Sb eq	2.34E-05	4.90E-05	4.95E-05
Depletion of abiotic resources – fossil fuels (ADP_ff)	MJ	1.50E+02	2.96E+02	2.05E+02
Global warming potential (GWP)	kg CO_2 eq	1.66E+01	3.91E+01	3.20E+01
Ozone depletion (ODP)	kg CFC-11 eq	1.44E-06	2.40E-06	1.54E-06
Photochemical ozone creation (POPC)	kg C_2H_4 eq	2.07E-03	6.08E-03	4.60E-03
Acidification (AP)	kg SO_2 eq	5.21E-02	1.13E-01	1.02E-01
Eutrophication (EP)	kg $(PO_4)^{3-}$ eq	1.26E-02	3.09E-02	2.82E-02
Embodied energy (EE, tot)	MJ	1.65E+02	3.49E+02	2.45E+02

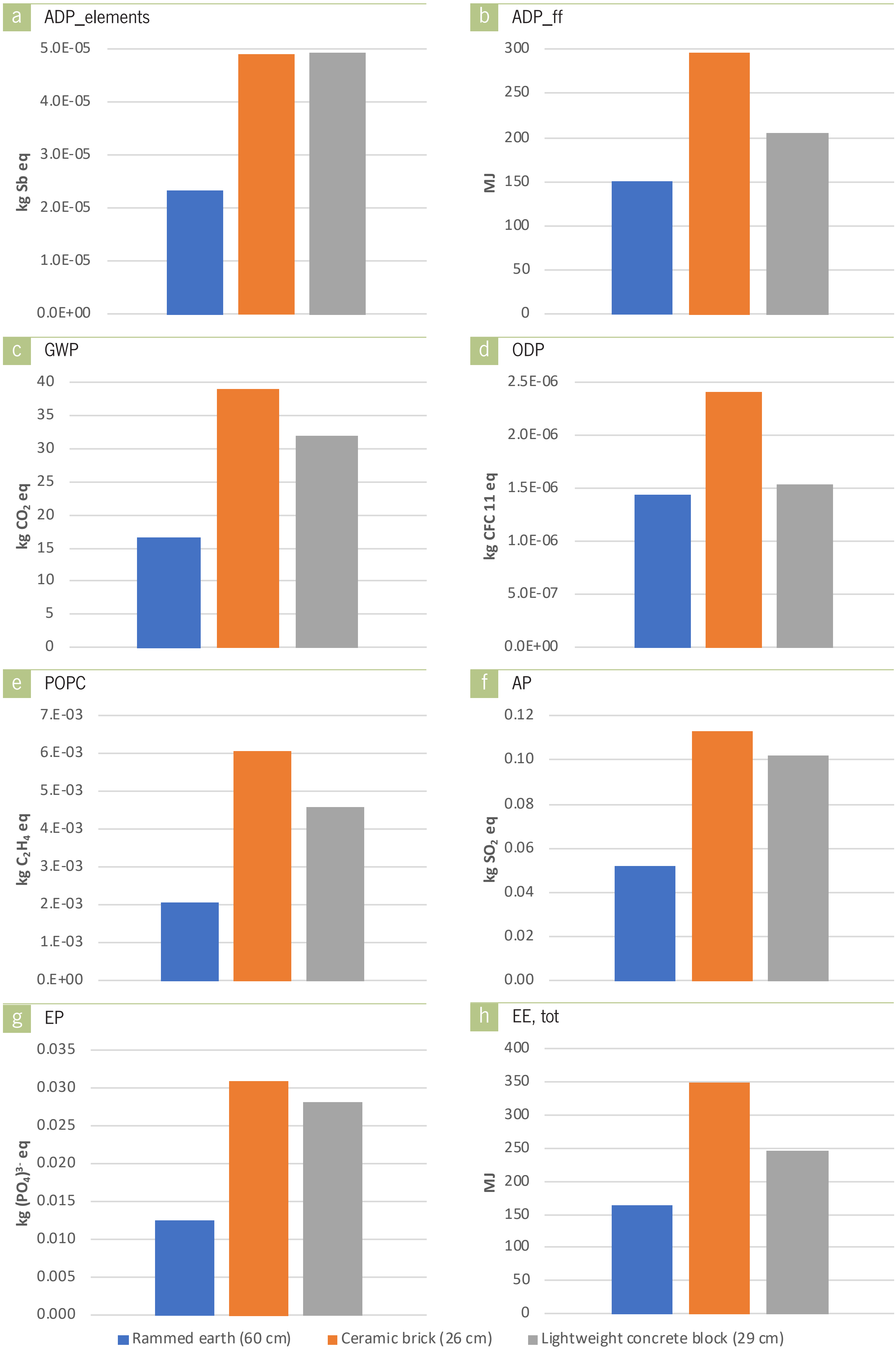


FIGURE 7.15. Assessment of the environmental performance of 1 m^2 of different external walls.

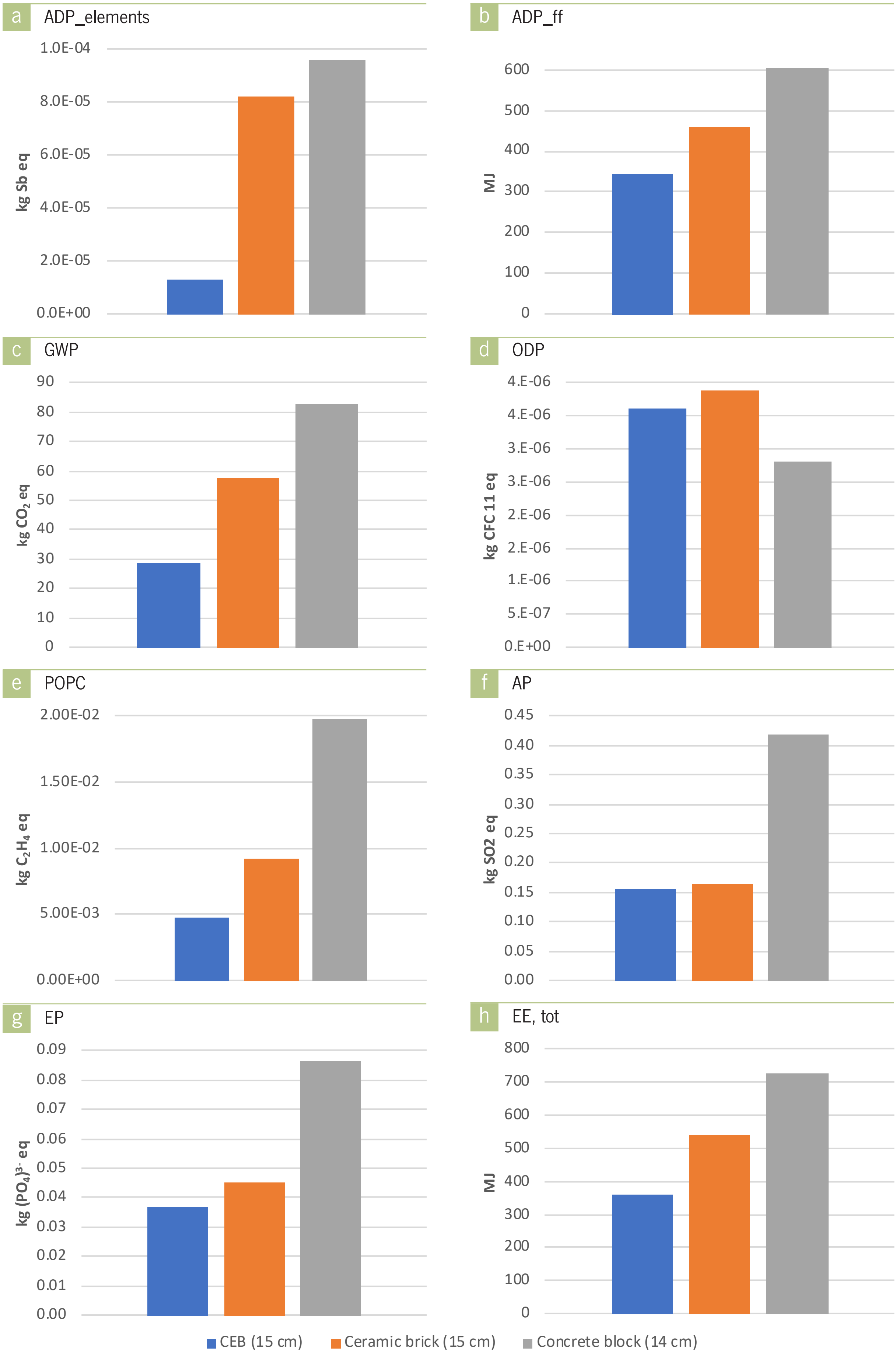


FIGURE 7.16. Assessment of the environmental performance of 1 m^2 of different internal partition walls.

7.4 CONCLUDING REMARKS

The life cycle assessment of earthen materials in the Portuguese context is a contribution to understanding the potential of these materials in current construction and more widely, in the scope of sustainable buildings.

Concerning compressed earth blocks, it was possible to verify that the modules of Transport (A2) and Manufacturing (A3) are the ones that most contribute to the environmental impacts and embodied energy. In module A2, the transport of soil represents more than 80% in all impact categories. Thus, choosing a closer extraction site will contribute to reducing the impacts of transportation. In module A3, the addition of hydraulic lime is the process with more impact, representing more than 60% in all categories.

In the case of rammed earth, the results show that the environmental impacts and embodied energy are above all related to the processes of module A5 (above 60% in all categories. The fact that the material is produced/built on site explains this concentration and the processes related to extraction (A1) and transport (A4) have a small contribution (around 10%). The use of hydraulic lime represents considerable impacts both in modules A4 (Transport) and A5 (Construction). In the latter, the use of fuel for the equipment is also responsible for considerable impacts in all categories and represents 60% of the total embodied energy.

For both materials, the use of lime, even in small percentages, stood out as having a high contribution to the environmental impacts and embodied energy. This is the only product used that is not produced locally, and that has an industrially based production. The impacts of both materials could be reduced if lime is sourced locally; or if an alternative material with a less energy-intensive production system could be used; and if the energy used could be reduced or offset through the use of more energy from renewable sources.

Even with the introduction of some mechanised processes, which significantly increased productivity and allowed homogenising the quality of the final product, the earthen materials studied continue to be low processing materials. This is visible when earthen materials are compared with industrially produced materials since they have a significantly higher environmental performance, with lower environmental impacts and embodied energy. Taking as an example two categories usually mentioned as the most important in the context of buildings, i.e., GWP and Embodied Energy, 1 m^2 wall of Rammed Earth and CEB have around half of the carbon emissions and embodied energy of clay brick or concrete block walls (Fig. 7.17).

Taking into account the sourcing of materials, additional benefits (e.g. social and economic) may be achieved by using local-made materials. Since these materials are locally sourced and produced, its commercialisation out of the regions of origin, or where they are typically used, can undermine the environmental advantages presented in this work. Therefore, more LCA studies on vernacular materials are needed to understand their environmental performance further, but also to allow transparent comparisons with other building materials. Additionally, it is perceptible that the impacts from the end-of-life of earthen materials can be lower than the impacts of conventional building materials. They can be easily recycled into a new material loop with the same function as the previous one or returned to the natural environment at a minimal environmental cost (Fig. 7.17). Nevertheless, more studies are needed to further assess further the real contribution of these materials to the promotion of a circular built environment.

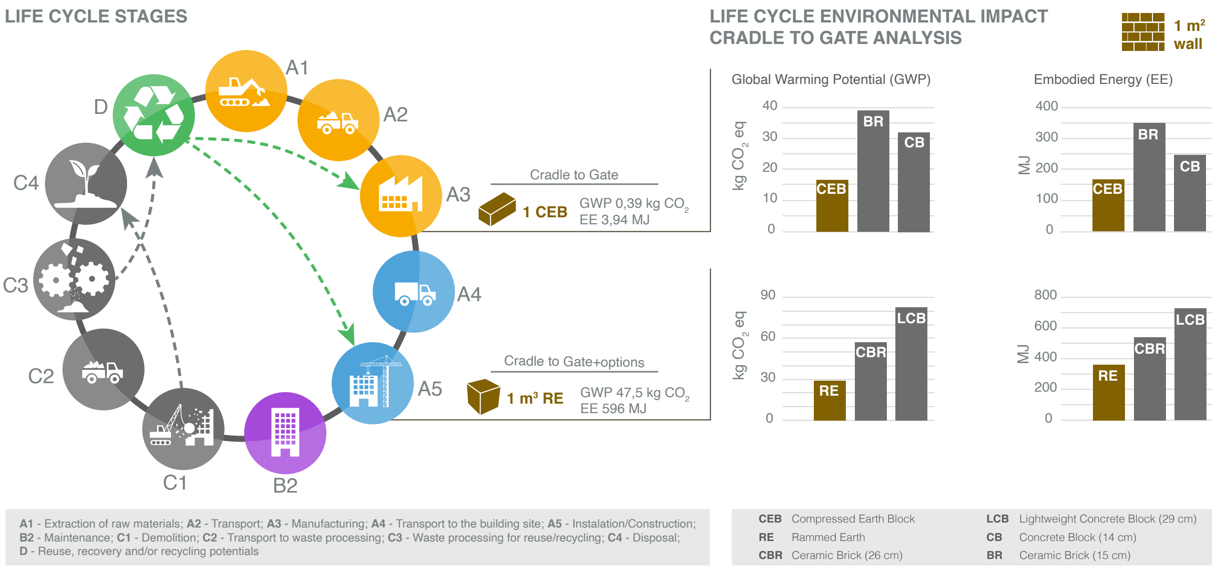


FIGURE 7.17. Life cycle stages of the materials and summary of the life cycle environmental impact results.

The contents presented in this chapter are, entirely or partially, published in the following publications:

Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks.
Journal of Cleaner Production 241 (2019) 118286. doi:10.1016/j.jclepro.2019.118286

CHAPTER 8

CONCLUSIONS

8.1 GENERAL HIGHLIGHTS

The conclusions of the different parts of this research work were presented in the respective chapter, so in this chapter, without intending to be repetitive, the main contributions of this work will be highlighted.

The interest in vernacular architecture within the broader scope of sustainability has been growing for the last three decades and is still rising. The main goal of this research work was to give a contribution to the field of knowledge of vernacular architecture and sustainability through a quantitative study on the thermal performance and comfort conditions of vernacular buildings, but also on the environmental performance of vernacular materials, in the Portuguese context. The aim was to overcome the lack of scientific data on the topic and so, to allow a fair comparison of vernacular strategies/materials *versus* conventional modern solutions. Thus, putting aside the subjectivity and the use of decontextualized data in comparative analysis. To achieve the goals proposed, this research was subdivided in two main steps: i) to evaluate the thermal behaviour, through the analysis of *in situ* monitoring, of three different case studies located in three different climate zones; ii) and to assess the life cycle performance of two earthen materials manufactured by a Portuguese private company.

In Portugal, as shown in the qualitative analysis (Chapter 3), the climate-responsive strategies found in vernacular architecture reveal a close relation with the local climate. From the examples shown, the division of the country and the purpose of the main strategies according to climate are clear. The strategies to promote solar heat gains are more concentrated the north while the south concentrates the passive cooling strategies. In the case of rainwater harvesting strategies, the specificity of local conditions is even more visible with a distribution that is mainly in, but not restricted to areas with low precipitation. Regarding materials, it has to be highlighted that there is an almost perfect correlation between the distribution of the construction materials used and the lithological diversity of the Portuguese territory, but also regarding the type of cereal harvest (thatch) and forest cover (timber). The simplicity of pragmatism of strategies and materials have significant potential to be improved and adapted to contemporary construction.

On the topic of thermal performance and comfort evaluation, in general, the case studies showed an adequate response to their specific environments, although in winter and during some periods of mid-seasons it was not possible to achieve thermal comfort conditions by passive means alone.

For case study 1, the timber building (*palheiro*) in Praia de Mira, although it does not have a high thermal inertia to stabilise indoor temperature variation, the mild local climate favours its thermal performance. The building has satisfactory comfort conditions during almost all seasons without using a heating/cooling system. A point that must be highlighted is the low variation of indoor relative humidity, considering that high values of humidity that characterise the local climate during the whole year. Notwithstanding some weaknesses of the building (e.g. air infiltrations), the thermal-hygroscopic performance of the case study shows that timber construction, if correctly designed and built, may have potential in the coastline environment. Additionally, this type of construction is better suited to respond to scenarios of coastal erosion and flooding due to sea-level rise, with the possibility of being moved or disassembled and relocated. Besides these site-specific advantages, there are also advantages of timber construction regarding environmental impacts, since this material is renewable, biodegradable and a reusable/recyclable resource that fits into a "cradle to cradle" life cycle perspective.

The glazed balcony, presented in case study 2 (Granja do Tedo), revealed to be an effective passive heating strategy in a climate with cold winters. Although in the renovation the balcony lost the "sunspace effect" and part of its effectiveness (due to the removal of the partition wall to increase the bedroom floor area), the contribution of solar gains through the balcony is visible in the indoor temperatures of the bedroom. In this particular case, the simulation with an energy model of the building allowed determining the effectiveness of the glazed balcony with the separation wall. The simulation results showed that the glazed balcony acting as a sunspace permitted increasing the contribution of solar gains, reducing heat losses and therefore reducing energy demand for heating. At the same time, during the summer, if ventilated, it also allows providing shading and reducing energy demand for cooling. Analysing the annual thermal monitoring, during the mid-seasons the rooms in the balcony had adequate comfort conditions when the building was occupied since the occupants controlled solar gains using the shading system (opaque curtains). Not controlling the solar radiation increases the risk of overheating periods even when the building is not occupied, as seen in autumn. During the winter, it was not possible to achieve acceptable thermal comfort conditions without an active heating system. Nevertheless, during the thermal comfort assessment of the bedroom with the glazed balcony, performed on a cloudy day, the operative temperature was close to the lower limit of the thermal comfort range. During sunny days, and even when the building was in free-running mode and with the shading device active, indoor air temperature increased considerably. During the summer, the results showed thermal comfort conditions within the comfort limits, but with the risk of overheating. The use of an external shading device and the promotion of ventilation will be more effective to reduce the risk of overheating, as demonstrated in the simulation.

Case study 3, the earthen building in Safara, revealed to be well adapted to a region with a hot summer climate. The high thermal and hygroscopic inertia of earthen building elements in the envelope, partition walls, ceilings, and floors, allowed stabilising and regulating temperature and relative humidity. The results of the indoor environment monitoring showed that the case study had good or satisfactory indoor thermal comfort conditions during almost all year by passive means only. As in the other case studies, during the winter, it was necessary to use an active heating system to overcome the periods of thermal discomfort. The building had its best thermal performance during the summer period, confirming that the strategies and earth construction systems were developed to deal with the scorching summer heat that characterises the region. These good results were confirmed by the application of the adaptive model of thermal comfort, with a comfort condition in the middle of the comfort range. Also, by applying the EN15251 methodology to categorise the quality of the indoor environment, the results showed that during most of the summer period the building had comfort conditions in Category I (the highest level of expectation). It has to be highlighted that these good results were achieved in a free-running mode for most of the time.

In all the case studies, surveys involving the occupants were carried out, using a Thermal Environment Survey, to assess occupants' thermal sensation in each season. The subjective results obtained validated the objective assessments, and these showed that the adaptive model of comfort adjusted to the Portuguese context is adequate to analyse the thermal comfort conditions in Portuguese vernacular buildings.

Although the strategies and construction systems applied in the case studies showed to be adapted and developed to specific contexts, these also have some performance weaknesses. Some of these weaknesses are because they are not optimised (e.g. reduced airtightness) or because they have a low thermal resistance, hindering the thermal performance during the winter. However, it has to be taken into consideration that these techniques were developed in times when the technological means and resources were more limited and when heating was done with simple solutions (e.g. fireplaces). In this sense, the simulation of building energy models (Chapter 6) allowed determining and comparing under the same conditions the influence of different solutions regarding annual energy demand for heating and cooling. The results showed that the scenarios with thermally insulated solutions had a better performance regarding the annual energy demand balance, mainly because energy needs for heating were significantly reduced. However, for the same solutions, energy needs for cooling increased. In the scenarios based on case study 1 (timber building), the main difference between solutions is in the energy needs for heating, while the energy needs for cooling are practically the same for all solutions whether they are insulated or not. In the scenarios based on case study 3 (earthen building), insulated walls, including an insulated rammed earth wall, allowed significantly reducing energy needs for heating. But, on the other hand, when compared with the non-insulated original rammed earth wall, the energy needs for cooling doubled. Thus, the simulation confirmed the good thermal behaviour of non-insulated rammed earth walls during the cooling season. In this case, the addition of an insulation layer to fulfil legislation requirements do not seem the adequate solution for a region with hot summers since heating needs were reduced but energy needs for cooling increased considerably up to twice the energy needs for heating.

The results obtained from *in situ* monitoring and energy simulation models show that vernacular strategies/construction systems, in comparison with conventional ones, have the potential to be used nowadays in their specific climates. Nevertheless, optimisation and improvement of the construction systems can increase their thermal performance, particularly during winter.

On the side of vernacular materials, these are frequently acknowledged as ecological, but currently, there is a lack of quantitative data about their environmental performance that can be used to support the building designers' decision-making processes. The life cycle assessment results (Chapter 7) showed that earthen materials produced in the Portuguese context have a better environmental performance than conventional industrially-based materials. In the two environmental indicators usually mentioned as important in the context of buildings, i.e. Global Warming Potential and Embodied Energy, 1 m^2 wall of Rammed Earth or CEB have around half of the carbon emissions and embodied energy of ceramic brick or concrete block walls. It must be highlighted that, for both materials, the use of hydraulic lime (an outsourced material), even in small percentages, stood out as having a high contribution to the environmental impacts and embodied energy. Additionally, the perceptible impacts from the end-of-life of earthen materials can be lower than the impacts of conventional building materials since they can be easily recycled into a new material life cycle with the same function and requiring low processing or returned to the natural environment at a very small environmental cost.

8.2 FURTHER DEVELOPMENTS

The study of vernacular architecture has still potential to grow within the broader scope of sustainability, and nowadays in the scope of the new concepts of restorative and regenerative buildings.

The research work presented gave a contribution to the field by carrying quantitative studies on some examples of Portuguese vernacular buildings and materials. However, the plurality of the Portuguese territory (mainland and islands) offers a vast research field, and multiple types of buildings and materials have not been studied yet in the scope of sustainability. And, as demonstrated in this work, the specific local conditions have significative importance in the way as buildings and strategies were developed and how they perform. Therefore, further studies are needed to complement the results presented in this work but also to create a database of the many types of climate-responsive strategies, and on the thermal and environmental performance of buildings and materials. Only with reliable data, it is possible to promote the use of vernacular strategies/materials in new buildings.

In the energy and thermal comfort performance topics, the simulation tools offer enormous potential for the research of vernacular architecture. In the study presented some difficulties were felt in simulations due to the lack of data on the thermal-physical properties of vernacular materials, which forced to simplify the approach and simulation conditions. In this sense, there is a need to develop specific studies on the physical properties of vernacular materials but also to measure weather data in a way that provide enough information to create reliable weather data files to use in simulations. With more accurate data, it will be possible to carry simulations and get more reliable and accurate results.

The research field of local and bio-sourced materials has the potential to grow. Thus, there is a need to develop more life cycle assessment studies on this type of materials produced in the Portuguese context to understand their environmental performance further, but also to allow transparent comparisons with other building materials. Nevertheless, more studies are needed to further assess the real contribution of these materials to the promotion of a circular built environment.

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APPENDIX

Universidade do Minho
Escola de Engenharia

Laboratório de Física e
Tecnologia das Construções

INQUÉRITO SOBRE:
PARÂMETROS DE CONFORTO

Este trabalho enquadra-se num projecto de investigação que se encontra a ser desenvolvido pelo Laboratório de Física e Tecnologia das Construções (LFTC) do Departamento de Engenharia Civil da Universidade do Minho.

Este inquérito tem como objectivo avaliar a opinião dos ocupantes deste espaço relativamente aos ambientes térmico, lumínico, acústico e de qualidade do ar, com o objectivo de identificar o modo como cada um influencia o conforto global percepcionado pelos ocupantes.

Os resultados deste inquérito complementarão a avaliação experimental de vários parâmetros ambientais que é efectuada em simultâneo.

A sua participação é fundamental para o desenvolvimento e conclusão deste estudo, pelo que se solicita que responda objectivamente e com franqueza às questões que lhe são apresentadas.

Os dados obtidos no questionário serão apenas usados para fins estatísticos.

Muito obrigado pela sua disponibilidade e colaboração!

Inquérito sobre a percepção da Qualidade do Ambiente Interior

Data:				Inquérito n.º:
Hora:				Auditor:
Nome do ocupante:				Posição do ocupante no compartimento
Idade:		Sexo:		
Peso:		Altura:		
Naturalidade:				
Existe algum motivo de ordem fisiológica que possa condicionar a sua percepção de conforto? Sim: Não:				
Temperatura aproximada do ar exterior: ºC				
Céu				Tipo de compartimento/edifício:
Limpo:	Sol e nuvens:	Encoberto:		
				Humidade relativa exterior (%):
Condições sazonais				Temperatura interior (ºC): Humidade (%):
Inverno:	Primavera:	Verão:	Outono:	
Equipamento (equipamentos presentes no compartimento que ligados contribuam para o aumento ou redução de calor ex: computadores, ventoinhas, TV, etc.)				
Item:		Quantidade:		Total de calor adicionado/subtraído
Nível de actividade do ocupante:				Metabolismo (met)
1. Reclinado				1. 0,8 met
2. Sentado, Quieto				2. 1,0 met
3. Escritório, Escola				3. 1,2 met
4. Em pé, relaxado				4. 1,2 met
5. Em pé, actividade ligeira				5. 1,6 met
6. Em pé, actividade média				6. 2,0 met
7. Actividade intensa				7. 3,0 met
Vestuário do ocupante: Assinale nos quadros da página seguinte todas as peças de vestuário que tem vestidas neste momento.				Isolamento térmico do vestuário Total Icl=________________clo

Vire a página por favor.

Camisa/Blusa

de verão, manga comprida	(0,15)	☐
de verão, manga curta	(0,20)	☐
de inverno	(0,25)	☐
de flanela	(0,30)	☐
T-shirt	(0,09)	☐
pólo de malha	(0,17)	☐

Calça

de verão	(0,20)	☐
de meia estação / ganga	(0,25)	☐
de inverno	(0,28)	☐
calções	(0,08)	☐
macacão	(0,30)	☐

Saia

de verão	(0,15)	☐
de inverno	(0,25)	☐

Sapatos

sola fina / ténis de pano	(0,02)	☐
sola grossa / ténis desportivos	(0,04)	☐
sandália / chinelo	(0,02)	☐
bota	(0,10)	☐

Roupa interior

camisola de alças	(0,04)	☐
camisola de manga curta	(0,09)	☐
camisola de manga comprida	(0,12)	☐
cueca / slip	(0,03)	☐
boxer	(0,04)	☐
sutiã	(0,01)	☐
combinação	(0,15)	☐
ceroula	(0,10)	☐

Vestido

de verão	(0,20)	☐
de inverno	(0,40)	☐

Camisola / Pulôver

de verão	(0,25)	☐
de inverno	(0,36)	☐
sem mangas	(0,22)	☐
sweat-shirt	(0,30)	☐

Meias

finas	(0,02)	☐
grossas, pelo tornozelo	(0,05)	☐
grossas, pelo joelho	(0,10)	☐
de nylon	(0,03)	☐
collants	(0,10)	☐

Blazer / Blusão

de verão	(0,25)	☐
de inverno	(0,35)	☐
colete	(0,12)	☐
casaco	(0,60)	☐
parka	(0,70)	☐

Outras peças de roupa

____________________________	☐
____________________________	☐
____________________________	☐
____________________________	☐

Sensação de conforto térmico no espaço onde se encontra o ocupante (indique o que é mais apropriado)	Escala de sensação térmica
1. Muito quente	1. +3
2. Quente	2. +2
3. Ligeiramente quente	3. +1
4. Neutro (confortável)	4. 0
5. Ligeiramente frio	5. -1
6. Frio	6. -2
7. Muito frio	7. -3

Vire a página por favor.

Por favor, assinale nas escalas seguintes (colocando um cruz sobre a escala [X]) a posição que melhor representa a sua sensação de desconforto no local onde se encontra e no período em que foram executadas as medições experimentais.

Considerando apenas a iluminação, como descreve a sua sensação de desconforto?

Luminosidade excessiva

Neutro | Ligeiramente desconfortável | Desconfortável | Muito desconfortável

Luminosidade insuficiente

Considerando apenas o nível de ruído, como descreve a sua sensação de desconforto?

Neutro | Ligeiramente ruidoso | Ruidoso | Muito ruidoso

Considerando apenas a qualidade do ar, como descreve o ambiente e a sua sensação de desconforto?

Inodoro | Odor intenso

Neutro | Ligeiramente poluído | Poluído | Muito poluído

Considerando os parâmetros de conforto avaliados nas respostas anteriores, indique como classifica a sua sensação de desconforto global.

Neutro | Ligeiramente desconfortável | Desconfortável | Muito desconfortável

Agradecemos o tempo despendido no preenchimento deste inquérito.

APPENDIX 2 | TABLE OF “BUILDING OCCUPANCY AND USE PROFILE”

Perfil de utilização do edifício

Data	Usou equipamento de aquecimento? (Qual? Entre que horas?)	Usou equipamento de arrefecimento (Qual? Entre que horas?)	Ventilação natural (ex.abertura de portas ou janelas)(Em que divisão? Entre que horas?)	Sombreamento (Em que divisão? Entre que horas?)
ex: 5 Janeiro 2014	ex: lareira. Das 20h às 23h	ex: Ventoinha. Das 21h às 22h	ex: Quarto. Das 20h às 22h	ex: Cortinas - varanda. Todo o dia.

REPÚBLICA PORTUGUESA
FCT Fundação para a Ciência e a Tecnologia
POCH PROGRAMA OPERACIONAL CAPITAL HUMANO
NORTE 2020 PROGRAMA OPERACIONAL REGIONAL DO NORTE
UNIÃO EUROPEIA Fundo Social Europeu