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Critical Early Inputs Towards Thermal Performance
in Architectural Design of Residential Buildings
in Temperate Climates – the Portuguese case

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Abstract

This research aims at giving a contribution on the critical issue of how to induce the convergence of architects towards the proper energy performance of residential buildings, since the early design stages, by playing with the sensible parameters and sufficiently upstream the use of current computing models or codes. The environment context is the one of temperate climates, departing from the Portuguese case. The vernacular architecture represented a strong statement on the need for the architect to design with the climate. It approached the building design as an exercise of complementing Nature, by providing some shelter and better comfort conditions, throughout the different seasons of the year. For some regions of the Globe, with severe climate, the comfort is very much dependent on the additional energy either for heating or cooling. In other climates, instead, the dialogue with the climate may lead to what Rafael Serra called the 'architecture of the complexity', meaning that through proper orientation, dimension and location of openings and thermal storage, it's possible to enhance the indoor thermal conditions.

During the first decades of the XXth century, independently from the place, the expectations of comfort led to a kind of uniformity of a paradigm of building with dual equipment both for heating and cooling, and associated ventilation. Later on, in the 70's, Energy has become a critical issue and more recently also an environmental issue, in what regards the use of fossil fuels, in which buildings have an important share. Everything seems to recall the regionalist approaches of the building design, in particular of housing buildings, by recovering the basic approach of the dialogue with the climate.

Currently the thermal analysis of buildings is carried out in the final stages of the building design. The ideal situation would be always the integration of a multidisciplinary design team, including an expert on building physics that could address the thermal design choices in the beginning of the building design. However, the practice reveals that many of the early decisive design options are taken by the architect alone, so reducing the potential of the contribution of the building physics for comfort and health before the appeal to the complementary systems.

This thesis aims to discuss the problematic of the early design stages and to identify the critical parameters that can be used as 'indicators' of the final performance of the building. The results demonstrate the high potential for the adopted approach. A methodology supported on an expert system allowed for the adoption of the proposed method. The expert system integrates the critical inputs with influence on the hypothetical thermal needs. Simultaneously, it provides qualitative recommendations with a user friendly language for architects, for a straightforward thermal assessment in the early stages of the building design. This way, this thesis contributes to a more effective approach towards sustainable, low energy housing buildings in Portugal.

Resumo

Este trabalho de investigação pretende dar um contributo para um maior envolvimento dos arquitectos na avaliação do desempenho energético dos espaços arquitectónicos, em particular, na fase inicial do projecto de Arquitectura, em que a escolha das soluções construtivas é na maior parte das vezes decisiva. O estudo centra-se na adaptação dos edifícios aos climas temperados, tomando como caso de partida Portugal. A arquitectura vernacular representa um testemunho notável da necessidade do arquitecto desenhar com o clima, abordando a prática de desenho como uma extensão do ambiente natural, com o objectivo de providenciar abrigo e condições interiores de conforto. Em alguns climas extremos, o conforto nas habitações é muito dependente da energia adicional para aquecimento e/ou arrefecimento. Contudo, noutros tipos de clima, mais amenos, como o Mediterrânico, as grandes variações de temperatura em curtos espaços de tempo traduzem-se no que Rafael Serra designou de 'arquitecturas de complexidade'. Nestes casos, as decisões de desenho relacionados com a orientação, assim como a localização de aberturas e de massas inerciais para armazenamento térmico, conduzem à optimização das condições térmicas interiores.

Durante as primeiras décadas do século XX, independentemente do lugar, as expectativas de conforto levaram a uma espécie de uniformização do paradigma de edifício com sistemas de aquecimento e arrefecimento. Entretanto, nos anos 70, a Energia tornou-se uma preocupação ambiental, sendo o sector dos edifícios um dos que têm um peso mais significativo no uso de energia. Tornou-se clara a necessidade da recuperação das práticas regionalistas, através do desenho dos edifícios adaptados ao clima.

Actualmente a análise térmica dos edifícios é realizada nas fases finais do projecto do edifício. A situação ideal traduzir-se-ia numa equipa de projecto multidisciplinar, com especialistas da Física dos Edifícios, em que as questões da térmica seriam abordadas nas fases iniciais do projecto. Contudo, a prática revela que a maior parte das decisões são tomadas numa fase inicial apenas pelo arquitecto, reduzindo o potencial do contributo da Física dos Edifícios para as questões de conforto, antes da necessidade de integração de sistemas de aquecimento e de arrefecimento.

Esta tese pretendeu discutir a problemática da fase inicial do projeto e identificar os parâmetros críticos, tendo em conta a influência no desempenho final dos espaços arquitectónicos. Os resultados demonstram o potencial da abordagem adoptada. A metodologia apoiou-se num sistema pericial, que permite a adopção do método proposto. O sistema especialista integra os parâmetros críticos de projecto com reflexo nas prováveis necessidades térmicas e simultaneamente fornece recomendações qualitativas, com uma linguagem 'user-friendly' para arquitectos, para um apoio expedito nas fases iniciais do projecto de Arquitectura. Desta forma, esta tese contribui para uma nova abordagem de desenho de edifícios residenciais sustentáveis e de baixo consumo energético em Portugal.

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List of Abbreviations

ACE/CAE	Architects' Council of Europe/Conseil d'Architects d'Europe
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
DGE	Directorate General of Energy (renamed DGEG in 2004 – Directorate General of Energy and Geology)
DHW	Domestic hot water
EC	European Community
EPBD	Energy Performance of Buildings Directive
ES	Expert system
EU	European Union
GLR	Gain-load ratio
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KBS	Knowledge based system
LT	Lighting and thermal
PV	Photovoltaics
RCCTE	Regulation of the Characteristics of the Thermal Behavior of Buildings
RECS	Regulation on the Energy Performance of Services Buildings
REH	Regulation on the Energy Performance of Residential Buildings
RPH	Renovation (of air) per hour
SLR	Solar load ratio
UN	United Nations

List of Symbols

A	Area of building components
A_e	Area of exterior elements
A_g	Area of glazing per orientation
A_{glz}	Total glazing area
A_h	Area of exterior horizontal elements
A_{int}	Area of interior elements in contact with non-heated spaces
A_p	Useful floor area
A_w	Area of exterior walls
e	Exterior element
E	Intensity of the solar radiation (solar irradiance) incident on glazing surfaces
f	Orientation factor
f_c	Factor of heat losses through thermal bridges
g	Glazing element
G_g	Average monthly solar gains
$g_{\perp}$	Solar factor
HDD	Heating degree days
I	Inertia factor of the architectural space (summer)
It	Useful superficial mass per square meter
K	Inertia factor of the architectural space (winter)
M	Average duration of insolation during the cooling season
M_i	Useful superficial mass of the element
N_i	Nominal heating needs
N_v	Nominal cooling needs
N_{ic}	Calculated nominal heating needs
N_{vc}	Calculated nominal cooling needs
P_d	Floor to ceiling height
Q_c	Conduction heat gains or losses
Q_e	Evaporative heat losses
Q_i	Internal heat gains

Q_s	Solar heat gains
Q_v	Ventilation heat gains or losses
S	Glazing solar factor summer – fraction of the incident energy on the glazing surface that is transmitted to the interior space
S_i	Element surface
S_v	Glazing solar factor winter – fraction of the incident energy on the glazing surface that is transmitted to the interior space
U	Coefficient of thermal transmittance
UA	Thermal conductance
$\Sigma UA/A_p$	Global thermal conductance per useful floor area
U_e	Coefficient of thermal transmittance of exterior elements
U_{glz}	Coefficient of thermal transmittance of glazing surfaces
U_h	Coefficient of thermal transmittance of exterior horizontal elements
U_{int}	Coefficient of thermal transmittance of interior elements in contact with non-heated spaces
U_w	Coefficient of thermal transmittance of exterior walls
ϕ	Obstruction factor – percentage of clear and not shaded glazing area that receives direct incident solar radiation
η	Utilization factor of solar gains
ΔS	Sum of all heat flow terms
ΔT_e	Effective temperature difference through the envelope
ΔT	Mean temperature difference

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1 Introduction

1.1 Motivation

Buildings sector is responsible for a relevant part of the energy use of a society together with transport and industry. In the case of Portugal, energy in buildings represents around one third of the primary energy use (IEA 2011). Most of it is under the form of electricity, substantially obtained from fossil fuels, with a thermal efficiency that represents, for the worst cases, around 30%. So, buildings are called upon to respond to the need to mitigate the global warming and to the reduction of energy imports, i.e., the fossil fuels. This can be achieved by reducing the energy needs through proper building design in tune with the climate. In addition, if it's the case, by allowing for the production of electricity from the Sun.



Figure 1 Houses in Janas, Sintra. Prize DGE 2003 (Mourão and Santa Rita 2003)

Recently, values of up to 60% of the electricity used in Portugal have been produced from renewable sources (APREN 2014). That trend expresses the progress in recent years towards a dominant share of electricity originated from renewable, while depending on the yearly changing meteorology, that will be the tendency towards the future. Yet, this effort from the energy supply side lacks the corresponding generalized approach from the demand side. That concerns obviously all major energy sectors, i.e. transportation, buildings and industry. According to the 5th Intergovernmental Panel on Climate Change Report, the building sector represents the most cost-effective potential for CO₂ mitigation, which is attributed for being achievable through good design

practices, among other means. Moreover, regarding different energy uses in buildings, the study of different scenarios by IPCC previews that the energy challenge will need to be mainly tackled at the level of the thermal energy. The IPCC report also indicates gaps in the knowledge of energy in buildings, pointing out that current indicators refer too much to 'efficiency' instead of 'sufficiency' (IPCC 2013). Through the latter perspective, built environment should not be regarded as a problem but as an opportunity to tackle energy challenges and to contribute for the aimed sustainable development.

The connection between energy efficiency and energy sufficiency is particularly challenging for the case of the building stock in Portugal. Recalling concepts, while energy efficiency is the result of an action that is undertaken to produce a service or a good, using less energy resource than before, sufficiency appears at an earlier stage. Sufficiency means that before the strategies for any target for energy efficiency, action must be taken to anticipate the strictly necessary end use or useful energy for the required service.

The concept above has definitely a great potential if applied to the building stock: to new buildings, obviously and, with some limitations, also to rehabilitation. To clarify that, there is a need to typify the end uses of energy in buildings. Broadly, two main categories of energy end uses can be identified: those related to the thermal comfort and health (daylighting, ventilation, heating and cooling) and those related to the activities undertook indoors (cooking, domestic hot water, audiovisual, various appliances, such as computing, copying, etc).

The first category of energy end uses bears its expression from the deep origins of humanity: the energy related to buildings as shelters against 'enemies', being the extremes of climate itself often part of those. So, architectural expressions throughout the World ended by reflecting some cultural specificity, all of them being shaped by climate and geography (rivers, endogenous materials, etc.). A building must be defined by two sets of conditions: its functional purpose and the climate context, while the ultimate criteria for any building is always to be healthy and comfortable (Figure 2). The response to the climate must come firstly from the building design itself, i.e., its architecture and its physics in terms of materials, thicknesses and physical integration. An eventual hiatus between the performance obtained through the dipole architecture-physics and the pre-defined comfort and health requirements shall then ask for the

contribution of additional technologies or equipment for lighting, ventilation, heating and cooling. The topic of this thesis is related with the building response to the climate in order to implement, if not exacerbate, sufficiency, leaving the role of efficiency for the cases where technologies are still to be involved.

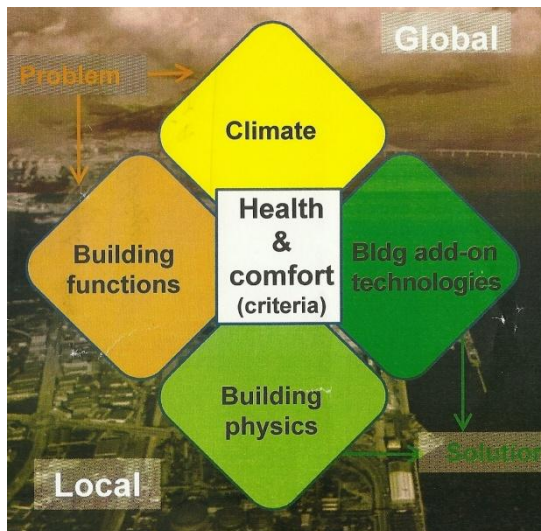


Figure 2 Approach of the building both as a shelter and as an energy system (Fernandes 2014)

Portugal has a ‘Temperate’ climate, according to Köppen-Geiger climate type classification, belonging to the subgroup of ‘Mediterranean’ climate (Peel, Finlayson et al. 2007). The coast receives oceanic influences, resulting in the amenity of temperatures. The interior has continental influences registering higher thermal amplitudes. The South, due to lower latitudes, registers higher temperatures, closer to those of the Mediterranean climate. Through all the territory, hot summers without rain alternate with mild seasons, in which rainy days succeed disorderly. Daveau refers that ‘the annual rhythm of the weather that characterizes Mediterranean countries is frankly original at a worldwide scale’. Besides this, Mediterranean climate is the only climate type in which the heat peak coincides with greater dryness (Daveau 1995), which means that the need for mechanical cooling, if any, is not justifiable, at least, by the high moisture levels.

The heating season in Portugal has an average duration of six months. Portuguese cities have quite less heating degree days in comparison with many other European cities. The heating degree days of Lisbon on a 20°C basis are 1600, which represent almost half of the HDD in London (2900) and one third of Stockholm (4400) (BizEE 2014).

Portuguese vernacular architecture of residential buildings represents a fine tuned relationship with both the function and the climate (Figure 2). Supplementary heating was traditionally obtained through fireplaces and hot water produced by wood burning. This was the existing context in the early 80's, when the need for the first regulation for energy in buildings for Portugal emerged, exclusively focused on housing buildings – the Regulation of the Characteristics of the Thermal Behavior of Buildings (RCCTE 1990). At the time, a worldwide blossoming of initiatives to elaborate codes to simulate building thermal behavior and passive solar approaches started being addressed, in response to the first oil crisis of 1973.

The type of regulation that was adopted for Portugal was inspired from the interpretation of the pre-existing situation of comfort in the building stock at the light of the concepts discussed below:

1. Heating or cooling residential buildings was a vestigial practice at the time, so there were no generalized actual levels of heating or cooling to be reduced through more efficient equipment;

2. The regulation to be created should not be based on the actual consumption for comfort, which was almost inexistent or quite meager, but should be expressed in terms of potential energy needs to satisfy pre-defined comfort targets. Those energy needs would be quantified as hypothetical values for each climate zone within the country. Reference levels stated in a grill of values would guide and led to excellence;

3. The climate was offering an opportunity to undertake new type of actions while designing housing buildings by putting the focus on the architecture and on the building physics before starting advocating added energy systems to fill in the gaps between the current bad architectural and physical design of the existing residential buildings and the minimal thermal comfort conditions, as defined for the designated adaptive comfort (ASHRAE 2004), definitely the most appropriate one in the case at study for housing in Portugal;

4. Fanger's comfort concept (Fanger 1972) is not to be applied to these buildings, as the adaptive comfort fits better the transition and 'adaptation' context described above.

The RCCTE was published in 1990 with almost one year in advance of its starting enforcement date (January 1, 1991), in order to allow for the preparation of public services and professional bodies for its implementation. What happened is that both

bodies, the services and professions, were slow. Namely, architects were not prepared for the application of the RCCTE, as their education in the Portuguese Architecture Schools and training was 'beaux arts' oriented, with little incursion into building physics, and engineers were not familiar with the buildings heating practice and even less with the exploration of the building physics for the sake of the enhancement of the building performance in terms of comfort. Yet, in reality, the majority of buildings built at the time were not even designed by architects. Even though, an intense new building construction program was underway in the country since the early eighties.

About ten years later, the first EU Energy Performance of Buildings Directive (EPBD 2002) was issued. Its message was, to say the least, wrongly understood by the services and professionals in Portugal eager to expand a market for heating and cooling appliances almost inexistent until then. The EPBD focus had in mind the current practice regarding the use of heating systems in residential buildings in Northern EU countries. That explains why the first attempt was to discipline the use of energy by reducing its consumption through energy efficiency. Yet, some energy sufficiency was also considered through more effective ways of insulating the exterior envelope, both the walls and the roof, as well as windows. However, the emphasis was more on the energy efficiency and reduction of heating wasted energy than on the sufficiency, through proper use of the building physics. The EPBD starting points were not the same of the RCCTE.

For the Portuguese case, as for other regions in the Mediterranean area, the generalized practice of heating through centralized systems did not exist. So, the strategy for Portugal, as for most of the Mediterranean countries, should start by emphasizing the role of the sufficiency at the level of the building architecture and physical construction (insulation, solar gains, etc.) to reduce the level of the energy needs for comfort. In such a context, the EPBD was not a timely reference for the proper management of energy use in residential buildings in Portugal and the RCCTE philosophy, more difficult to be understood and to be welcomed by professionals, started to be abandoned with the transposition of the EPBD in 2006.

In 2004 a new comfort concept, the adaptive comfort (ASHRAE 55-2004), emerged. In fact, it came in support of the RCCTE 1990 approach as it was calling upon the user to contribute by adapting the indoor climatic conditions to the outdoor ones. The adaptive comfort introduced some flexibility on the temperature settings requiring occupants to

adapt their clothing to the indoor climatic conditions to create favorable comfort conditions. Through sufficiency, the adaptive comfort, as well as RCCTE, was reducing the energy needs both in winter and in summer. The fact is that those principles of RCCTE regulation were waived by the engineering professionals, rushing for sizing heating and cooling apparatus. The regulation has been adjusted in that sense, i.e., the energy values of the RCCTE 1990 expressing hypothetical 'energy needs', not associated to the actual 'energy consumptions', were replaced by the updated RCCTE 2006 'actual energy consumption levels'.

Later on, a somehow misleading terminology appeared in Brussels. The 'net zero energy building' (NZEB) relates two energies that have nothing to do with each other – the so called 'production of energy' is connected with the outdoor conditions and the available surface on the roof, while the 'energy consumption' is related with targets associated to the building use indoors for its specific purpose, located in a specific climate, with its specific design and construction. Besides this, NZEB mixes up the two categories of energy end uses: the one related to physics that can and shall be exploited through architecture and construction in relation with the climate and the one connected to appliances and to the potential production of final energy locally, such as electricity by PV. The lack of theoretical consistency is such that while the solar energy through PV panels is accounted and valued, the process to value and to account the energy caught through windows, as daylight and solar heating energy, tends to be underestimated, when it should be not just taken into account but maximized in the winter season and retained outside in the summer.

In such a context, this thesis proposes to go back to the former RCCTE concept, exploring the approach of the building as a thermal system to enhance the contribution of the building physics for the comfort targets of residential buildings in Portugal in both winter and summer, at the light of the concept of 'adaptive comfort'.

The approach here is to explore the responsibility of the architect through his first gesture when designing a building, ensuring the continuity and integration of the built environment. The generation of interior comfortable spaces is the result of their creation/modification into the pre-existing natural environment – both of proximity and global – using the potential of the inexhaustible energy of the Sun. These procedures make clear the responsibility of architects for the sufficiency, before engineers will later come to tackle the efficiency. The specific motivation is, then, to be able to anticipate,

in the starting process of the design of a building, the use of the critical inputs to guide the architect in taking the most adequate move into the direction towards an energy sufficient building from the earliest stage.

1.2 Context

The connection of the Architecture with the Climate is inherent to the origin of shelters. The gregarious vocation of human beings has driven over centuries to the creation of 'human settlements' for defense, protection and mutual aid. In this process, local and environmental constraints have constituted conditions for the construction of urban artifacts different in forms and materials. Cities on the top of hills in Yemen valley and buildings in Cappadocia constitute examples of this differentiation such as houses with steep roofs in Austria mountains versus spherical or terrace roof types in Greece or Portugal.

In more recent times, with the explosion of the urban phenomena, the technological advances and the growing requirements for comfort and wellbeing led to the exploration of all forms of energy, mostly fossil fuels dependents. And so, such an intensity of energy use led to levels of energy consumption of oil equivalent per capita per year up to extremes as 8 ton or more which can be observed, for instance, in the paroxysm of American cities, and more recently, of Arabic as well as some Chinese cities, while the mean value for the World is barely above 1 ton of oil equivalent per capita.

That was the fundament for the alerts issued in the late eighties by the Gro Brundtland UN Report, putting into question the type of growth and the use of fossil energy sources (Brundtland 1987). That would lead to the global warming caused by the increase of concentration of CO₂ in the Atmosphere due to the emissions produced by the combustion of fossil fuels. The need for a new approach to the energy use emerged, as the energy environmental impact was no longer exclusively at a local pollution level but also at a global scale. The solution appeared formulated in two alternatives: a) at the energy sources levels to reduce the use of fossil fuels and to promote instead the use of renewable energy sources and, b) more relevant from the point of view of the society, to undertake all kinds of measures to reduce the energy demand both through energy efficiency and energy sufficiency, the latter owing to definitely precede the former.

Here, the alerts of the Brundtland report and, later on, of the UN Climate Change Commission, which 5th Report has just been issued in 2014 (IPCC 2014), are present in the scope of this thesis. The opportunities for comfort and health are to be met firstly through sufficiency by exploring the architecture and building physics potentialities. However, if that is not possible, then a technological energy system must complete the building task by fulfilling the needs of comfort and health through the best and more appropriate energy means. The ideal is that the technological part could be assumed by renewable energy sources. Nonetheless, there is a need to be also aware that other fuels may be used. In that case, eventual environmental/economic constraints shall inspire and support the priority to be given to the approach of the sufficiency.

At the building scale, as well as at the city scale, it is possible to identify the built environment as an energy system or conglomerate of energy systems, where functions of collection, storage and dissemination of energy received from the environment may coexist. That is the case of the free heating as well as the free daylighting, from the sun, and the free cooling from the wind. Obviously, there are regions where severe climates require energy solutions involving harder technologies and other types of energy resources. In Germany, residential buildings, not so long ago, used to require an order of magnitude of 150 kWh/m².year for heating, That is now under progressive drastic reductions down to 50 or 30 kWh/m².year mainly through strict insulation of the envelope, i.e. sufficiency measures.

The situation in other countries, such as Portugal, is quite different, as the climate conditions are much softer and the heating consumption would never need to reach values similar to those in Germany. In addition, there is not even a generalized practice of using centralized heating systems in Portugal, so far. Gas or electric appliances and fireplaces are currently used for heating. That does not prefigure significant actual current expenses on heating that could encourage the adoption of retrofitting measures in the existing building stock justified on economic terms by an effective return on investment as it occurs for Germany. Instead, that shall inspire the exploration of the potentialities of the architecture itself in tune with the environment (local and global) characteristics in order to get closer to comfort and well-being conditions corresponding to the adaptive comfort. This way, it will be possible for a residential building, or even buildings with other functions with low density of occupation, to create comfortable indoor environments without exacerbating the use of heating and even more of cooling

systems which, even if technologically efficient, would tend to lead to energy consumptions that could be dimed or even avoided.

Still with a proto scientific content, houses of the Vernacular Architecture and of regionalist styles are identifiable in the most diverse latitudes and longitudes of our planet, and presented in one of the first references to Architecture building design made by the roman architect and engineer Marcus Vitruvius Pollio in the 1st century B.C. In 'The Ten Books of Architecture', Vitruvius made several considerations about the adaptation of the building to the site context: 'If our designs for private houses are to be correct, we must at the outset take note of the countries and climates in which they are built. One style of house seems appropriate to build in Egypt, another in Spain, a different kind in Pontus, one still different in Rome, and so on with lands and countries of other characteristics. This is because one part of the earth is directly under the sun's course, another is far away from it, while another lies midway between these two.' (Vitruvius, Book VI, chapter I – 'On Climate as determining the style of the house' (Morgan 1914). Vitruvius outlines recommendations that begin with the most desirable orientation for streets regarding dominant winds. Later on, suggestions are made for the most proper solar exposure of different compartments of the house, concerning occupation patterns, with bedrooms facing east in order to receive the morning sunlight and the dinner rooms facing southwest for the light of late afternoon.

Vitruvius also addressed the relationship of the building with the place, local materials such as pozzolan, the proportions of buildings and defensive/protection aspects. Another relevant aspect is the strength of empiricism – 'We must, therefore, avoid mistakes in this matter and beware of the common experience of many communities. For example, Mytilene in the island of Lesbos is a town built with magnificence and good taste, but its position shows a lack of foresight. In that community when the wind is south, the people fall ill; when it is northwest, it sets them coughing; with a north wind they do indeed recover but cannot stand about in the alleys and streets, owing to the severe cold.' (Vitruvius, Book I, cap.VI) (Morgan 1914). Here, the influence of the building design and of the urban design in the healthy conditions is also underlined by Vitruvius.

The vernacular and empirical learning were an achievement of a long search for the building adaptation to the site, which was based in the knowledge through trial and error. This approach was applied not only for buildings but also for the territory

planning. Portuguese coastal cities are located in the northern shores of rivers, taking benefit of the southern solar exposure. Gaia, the twin city of Porto in the southern river bank of the Douro, is an exception as the urban fabric of the riverfront has been shaped by the storage of port wine which demands moist and cold conditions.

V. Olgyay and A. Olgyay advocated in the early 60's that thermal and daylighting comfort could be provided in some cases by a climatic understanding without the need for energy input (Olgyay and Olgyay 1963). The Figure 3 illustrates the scheme of Olgyay brothers' for passive building design complemented with a recent adaptation of the same scheme by Arup engineering group (ARUP 2011).

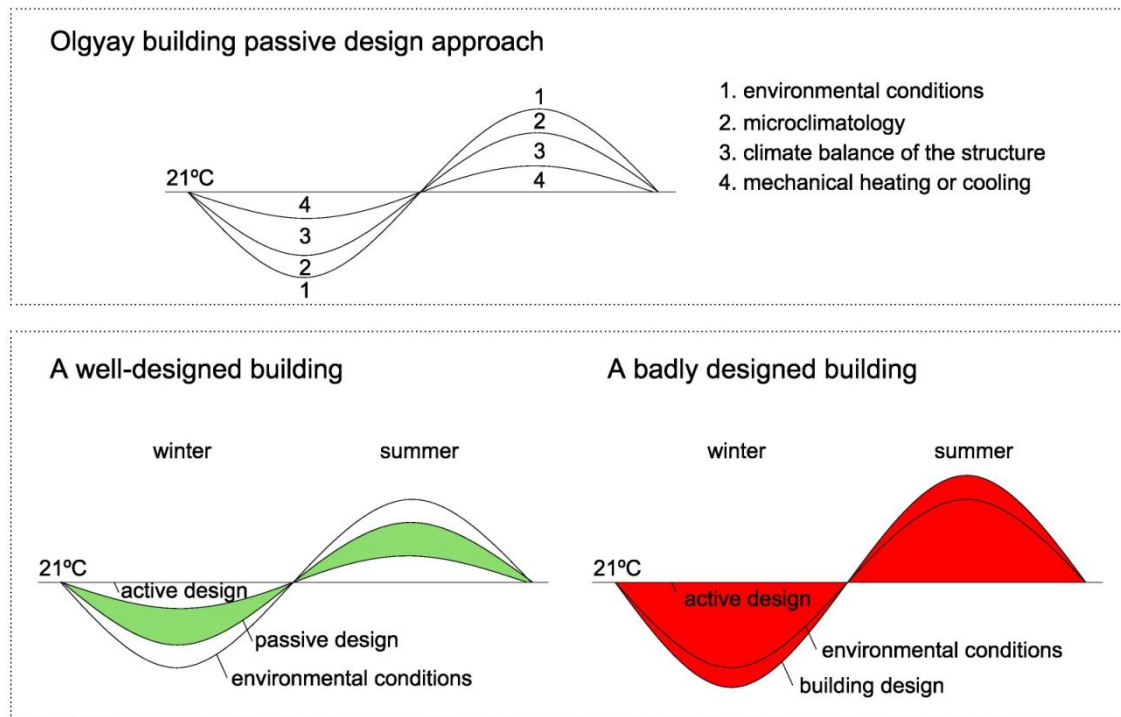


Figure 3 Definition of Building Passive Design (Olgyay and Olgyay 1963) (ARUP 2011)

The Arup scheme confronts the values associated to both buildings designed in harmony with the climate and those without climate adaptation which are called 'badly designed buildings'. Two different approaches of thermal comfort are addressed: the Fanger's and the adaptive ones. The line 4 of 'mechanical heating or cooling' represents the temperature 21°C. When the actual temperature of the interior space of the building is below 21°C, this should be heated and, if above, it should be cooled. The building designed with good construction options allows for the reduction in summer and increase in winter of the interior temperatures but it becomes evident that

temperatures close to line 4 only could be assured by the use of mechanical systems. Yet, the latter could even totally or partially be dispensed if the adaptive comfort conditions are assumed. On the other hand, the 'badly-designed building', with constructive choices that are indifferent to climatic conditions, needs to recur to heating/cooling systems in order to compensate for the consequences of the bad constructive choices. In the case of some buildings, as the so called 'net zero energy buildings', the building design disregards building physics potential in the Portuguese climate while putting all energy merit of the building on some external 'gadgets' of energy generation, as wind generators and PV solar panels.

In fact, and partly due to those misleadings, currently buildings are easily designed and built in opposition to the principles appealing for an architecture adapted to the climate. The two conditions or modes of interior environmental control vs the building interaction with the site were designated by D. Hawkes 'selective/regional' and 'exclusive/global' (Hawkes 1982). S. Yannas had defined those two building approaches by the 'modulator' of climate for the 'selective/regional' mode and the 'compensator' for the exclusive/regional mode (Yannas 1989), attributing the climate-modulating function to the architecture and the compensating function to the engineering.

The strategy of environmental control of the exclusive/global mode considers the human comfort as being the result of universal values for thermal, acoustic and lighting of buildings performance, disconnected from the climate specificity and being used anywhere and in any context. There are also cases of buildings designed without HVAC systems and also without any intention of adaptation to climate what results in buildings that 'behave worse than the climate' (Serra 1988). Many of these buildings subsequently call upon 'compensator' systems. This mode of intervention in the built environment had its maximum expression in the architecture of the International Style, during the years 30-50. The potential of the reinforced concrete was explored in buildings with weak thermal inertia, with large glazing areas and systematically using heating and cooling systems in order to 'compensate' for the energy needs resulting from those architectural and constructive options.

In Portugal, the regional architecture gained momentum, decades before, with the investigation on constructive solutions thought the 'Popular Architectural Survey' sponsored by the National Association of Architects in 1950's (SNA 2004). However, in Architecture, both at an academic and practical level, the knowledge of the architecture

adapted to the climate has been progressively abandoned since the appearance of the Modern Movement in the first decades of the 20th century, at a time when energy was cheap and environment was not even discussed. Only in the 80-90's decades of the XXth century, architects became aware of the sustainability challenge. Firstly, this was as a consequence of the implementation of the thermal regulation. Secondly, a few interesting cases of contemporary environmental conscious buildings were emerging in the country, mostly of them being a result of a team of both architects and engineers (Correia Guedes, Alves et al. 2009).

It was in the context above that emerged the RCCTE supported on the building passive approach to quantify the hypothetical heating and cooling energy needs, bearing in mind the capabilities of the dialogue of architecture and building physics (construction) with the climate. That way, instead of regulating the actual energy consumption which would have little meaning and, even less quantitative expression for Portugal, the RCCTE, in the early nineties, created an algorithm involving the most relevant physical parameters of the building. Giving appropriate values to parameters, such as the walls insulation and inertia, the openings area towards south according to the climate, expressed by the number degree-days, allowed to establish a grid of reference values for the heating and cooling seasons to which the actual buildings should be refereed to. And so a table of virtual building performance was created. In this way, the concept of sufficiency was fully implemented through promoting buildings that by their physics could end up by requiring less energy and making it easier to heat or cool the house, as the needs would have been reduced at the building design and construction phases.

Meanwhile, as already mentioned before, the recent evolution of the concept of comfort was also favorable to the RCCTE approach. The Fanger's statistical thermal comfort from the 70's was based in principles that were questionable from several points of view, namely, by Psychologists. Yet, it was unable to satisfy 100% of the occupants, always leaving a limit of 10% dissatisfied occupants. The concept of adaptive comfort, recently adopted by ASHRAE (55-2004) as an alternative, starts from the point that the building occupant is no longer a passive recipient of the given unique statistical indoor thermal environment, which must have a relationship with the outdoor climate but, instead must be the first actor regarding his own comfort.

The above shows the need and, also, the opportunity that can represent the anticipation during the building design, of what can determine/influence most of the

performance of the architecture in terms of the thermal comfort conditions in view of the adaptive comfort and, also, of the quality of the indoor air. Obviously there are numerous numerical codes created from 70's to simulate and to quantify the energy performance of buildings. However, for the building sketch, during the conceptual design, the most important proceeding is to calculate the potential energy needs to satisfy pre-defined comfort targets. Thus, under the adaptive comfort concept, the identification of the critical inputs and further the aggregation of the several values of Physics enables that the building design framework can anticipate the conditions in order to meet the 'climate modulator' function of the Architecture of the 'selective mode'.

1.3 Thesis Structure

The structure of this thesis, besides the introduction, is constituted by further seven chapters as follows:

Chapter 2, 'Definition of the problem', presents the context and the precise formulation of the research questions.

Chapter 3, 'State of the Art', describes in general terms the adaptation of the Architecture and the Construction to temperate climates, throughout the time, in particular since the seventies of the past century, when emerged the passive solar approaches. The problematic of the thermal performance of buildings, as well as, an overview of building design tools for architectural assessment are addressed.

Chapter 4, 'Methodology', presents the method adopted, setting out the basic steps supported in the order of priority of the essential design parameters which allow for bringing to the architectural practice an early and straightforward direction leading to a favorable thermal performance of architectural spaces.

Chapter 5, 'Thermal analysis', justifies and presents the calculation tool for sensitivity analysis, based on the RCCTE calculation approach and method. The application of the latter allows the generation and the organization of the data, as well as the graphic representation needed for the thermal assessment design tool.

Chapter 6, 'Results. Analysis and discussion', presents the results of the sensitivity analysis itself and their discussion. Relevant issues related with the interconnection of critical inputs and energy performance indicators, as well as physical values for integrating in building design, are obtained.

Chapter 7, 'Guided methodology – decision trees used to build the Expert System', describes how a system of decision trees is built with rules of thumb and key data, such as reference values and graphics of thermal needs, extracted from the sensitivity analysis in Chapter 6. In the end, the transposition of decision trees contents to an inference method is made through the *Exsys Corvid*.

Chapter 8, 'Conclusions and perspectives', presents the conclusions and final remarks. It also includes a complementary listing of issues to be considered in future work which could not be addressed in the context of this study.

2 Definition of the problem

The issue that makes the substratum of this thesis can be summarized by stating that, despite the emergency and generalization of the use of heating and cooling systems, and recognizing their relevance in some climates, namely those particularly cool or warm and humid, the alert issued by the United Nations and other political bodies to meet the reduction of the emissions of CO₂ calls for a reflection in what regards the energy use in buildings and the availability of alternative solutions focused in the residential buildings case, in particular, for moderate climates.

The approach, then, shall be a twofold one. Firstly, to treat separately housing buildings and office/institutional buildings where there may occur a higher occupation of spaces. Secondly, to distinguish between the two existing comfort types: the Fanger's comfort concept (Fanger 1973) and the adaptive comfort (ASHRAE 55-2004) and discuss where and in which conditions to use one or the other.

Commercial and institutional buildings with high density of occupation are likely to use heating/cooling systems managed and controlled under the Fanger's comfort criteria, while the adaptive comfort seems better fitting the current conditions of indoor environments in housing. In the first case, while buildings will be provided with the so called air conditioning, the potential to mitigate their energy uses for comfort will appear through some more or less extensive interventions in the envelope, mainly through shading, most probably through technology. In this case, the concern regarding the reduction of the CO₂ emissions will be mostly addressed through efficient technologies including ICT, i.e., information and communication technologies. Instead, housing buildings in temperate climates may respond to the CO₂ reduction challenge by doing as much as possible through building physics, in line with the concepts of the passive architecture (Figure 2). That would not exclude the support of some heating or mechanical ventilation systems, in which the levels of the energy required would be reduced to two steps: firstly, by sufficiency, i.e., by taking measures to reduce the basic needs, and, then, by energy efficient systems or just appliances in winter and proper management of the building (shading, cross ventilation, etc.) in summer.

The latter is ultimately an approach of the building taken as an energy system itself that owes to collect the energy from the Sun, stock it somehow in the walls and surfaces

backed by thermal mass and diffuse it through the surrounding places. That could seem to lead to a caricature of the building. That shall not be the case. Buildings are also cultural elements integrated in the environment with traditional contexts. The first role of the architecture is to respond to that challenge through the design of the building, while fulfilling its functions in a particular climate. However, the physical behavior of the building can only be tackled once the first sketch has been drafted. That happens commonly also for the structural design. For that reason, most of the decisions at the earlier stage of the design are of great influence in what concerns the future building thermal performance.

To make buildings a part of the environment and designing/building them to explore their dialogue with the climate, in order to approach the thermal comfort conditions, is what could be said to be the scope of the energy sufficiency. This thesis bears on the wide built experience since the early 80's regarding the passive solar approach to buildings design with so many different names such as solar architecture, passive solar architecture, bioclimatic architecture, etc. Yet, the need to be scientifically objective and consequent in terms of methodology and analysis of results require some confinement to the scope of this thesis which can be expressed in two questions:

1. Which are the critical parameters, aggregated or not, that can be used as design inputs anticipating the thermal enhancement of the project of a residential building from the beginning of the Architecture building design practice?
2. In order to advance in the approach to materialize the passive architectural design or the design with the climate, how to select, arrange/aggregate and integrate those critical parameters in a straightforward usable tool that takes into account the building design characteristics?

Explaining further:

- 1. Which are the critical parameters, aggregated or not, that can be used as design inputs anticipating the thermal enhancement of the project of a residential building from the beginning of the Architecture building design practice?*

A wide number of parameters influence the thermal performance of buildings, bearing in mind the environment indoors, i.e. at the level of conditions to assure the thermal comfort. As referred above, thermal comfort has been defined basically in two ways: the Fanger's definition (Fanger, 1972) and the adaptive comfort (De Dear and Brager

2002) (Roaf, Nicol et al. 2010). The theme will be addressed more in depth later on in this section. For now, adaptive comfort can be identified in simple words as based on the principle that people experience differently and adapt, up to a certain extent, to a variety of indoor conditions, depending on their clothing, their activity and general physical condition. Therefore, contrary to the conventional heating/cooling which is based on pre-set temperatures and humidity levels to be guaranteed by mechanical equipment in a rather strictly manner, the adaptive approach is based on a non fixed set of conditions, taking into account thermal perception and behavior of the user, requiring him to take an active role in controlling his indoor environment around values that are connected with the temperatures outdoors.

This requires the identification of the parameters that have a significant influence in the thermal response of the building as well as of those that are directly influenced by architectural design decisions. These parameters interact with each other, requiring sensitivity studies, given the climate specificity (Ellis and Mathews 2001).

A parametric study for residential buildings by Shaviv and Peleg aiming at to determine the critical input parameters (Shaviv and Peleg 1991) made progress in this domain. Their results allowed the distribution of architecture and constructive choices of the building design through the following categories:

1. Parameters which strongly influence the building thermal performance but that are not influenced by other design parameters, as it is the case of thermal insulation;
2. Parameters with strong influence on building performance and that are sensitive to other parameters, as windows size and orientation;
3. Parameters with weak influence on the building thermal performance and insensitive to other design parameters, as shape factor and absorptance of opaque surfaces.

This suggests at this stage that a reduced number of parameters are largely responsible for the building thermal performance. Thus, the architectural building design should be focused on design solutions for those parameters that have more influence in the energy behavior of architectural spaces. These findings represent a great contribution to a more straightforward assessment of architectural spaces. Yet, the determination of critical parameters shall take into account building design

constraints. It is important to clarify that the concept of ‘constraints’ in building design is very broad, as there are several types of constraints, linked with customer requirements and desires, with building functions, and many others.

The constraints that this thesis takes into account are of two types – the ones that are connected with the building integration in the site, e.g. building orientation, and the constraints driven by the building physics, e.g. the internal mass in interventions of building retrofit. The adaptation of the building design to the different constraints is a typical challenge of the architectural practice, being particularly relevant during the conceptual phase. This issue tended to be somehow disregarded by past thermal analysis studies, performed in the scientific field of building physics. In fact, past studies on the thermal behavior of buildings have been disconnected from the specific characteristics’ and phasing process of the architectural building design, with, obviously, some exceptions (Balcomb, Barley et al. 1980) (Serra 1989) (Torcellini 2008).

Thus, there is a different order of priority of parameters for a building with less constraints, in which all choices can be taken into account from the departing point, and for another building, namely if being retrofitted, in which the range of constraints can compromise the optimal thermal choices. This puts into evidence that optimized solutions are not always possible, namely for the building orientation. In these cases it is relevant to ask: Can we quantify the influence of the orientation in the energy needs? And what if the other design choices are optimized? To what extent is it possible to reduce the impact of the first choices regarding building site integration? Regarding the position of the thermal insulation, how to proceed in buildings in which thermal insulation cannot be applied by the exterior of façades? When thermal insulation is applied by the interior in all exterior walls is it possible to raise thermal inertia to a satisfactory category, using indoors some added elements which are both massive and with an appropriate visibility, i.e., exposure to the rest of the given space?

Yet, the adaptation of buildings to climate implies the introduction of thermal comfort criteria. In the Portuguese case, two relevant issues coexist:

1. The amenity of the climate has been leading to a frugality of Architecture solutions and consequently to an eventual default of sufficient comfort and healthy conditions;

2. The conflict between air conditioned and non air-conditioned environments has been dominating the debate on thermal comfort and on thermal regulation, but the opportunity represented by the adaptive comfort is already widely recognized.

The thermal comfort evaluation depends on climatic factors, such as air temperature and relative humidity, but also on cultural and technological issues. Moreover, the variations among the different comfort perceptions and the ways to respond from each individual occupant contribute to the complexity of the comfort concept.

In the Portuguese context, cultural issues have been playing a significant role. Testimonies of housing discomfort in nineteenth and twentieth centuries in Portugal were reviewed. Portuguese writers such as Eça de Queirós and Fialho de Almeida, as well as the geographer Orlando Ribeiro expressed the acceptance of low indoor temperatures during winter, as well as the high levels of solar radiation that allows to better stand for the low temperatures outdoors. With some irony, Fialho de Almeida in the first quarter of the twentieth century and Orlando Ribeiro in the twentieth century described that, in some cases, there was more thermal comfort outdoors than indoors. Orlando Ribeiro also highlighted the importance of solar radiation in the cold season.

A sample of texts from these three authors is presented below:

We took shelter in the library and we drank coffee near the warmth and joyful fire. Outside, the wind was roaring like it was in a deserted place in the middle of the mountains. And windows were shaking when the rain was angry. What a merciless night for those ten thousand poor people who wander in Paris without bread and home! In my village, between the hill and the valley, the storm may roar. But every poor, with their pot with sprouts, under the shelter of its not valuable tilt, finds comfort in his blanket near the warmth of the fireplace. And for those who do not have firewood or cabbage, there it is João das Quintãs or aunt Vicência, or the abbot, who knows all the poor by their namesakes, and always remembers them as if they belonged to him, when the car goes to the hills and the bread enters into the furnace. Ah, small Portugal, you still sweet to little ones! (Queirós 1901)

Yesterday cold tightened indeed in houses, so I decided to walk randomly around the outer boroughs of the city guided by my legs. (Almeida 1924)

Bearable in the street or in the countryside, winter is hard indoors, where cold builds up and remains; houses are poorly heated due to the lack of firewood, but also because severe cold is so rare that it does not justify preventing it. Thus, while cold in the middle Europe invites to intimacy within, here it is fought either by a sunbath or a quick walk.

(Ribeiro 1987)

The descriptions above put into evidence that the verified thermal discomfort in Portuguese dwellings resulted from cultural reasons, certainly associated to the relative amenity of the climate itself. But it also resulted from economic and technological limitations that, particularly until a relatively few years ago, were observed in Portugal. The Project 'EcoFamílias' which held a characterization of the built environment and the occupation patterns of energy consumption of 255 Portuguese families showed that houses built after 1991, i.e., after RCCTE was in place (RCCTE 1990), had a better thermal behavior than houses built in previous years as a result of the increasing use of thermal insulation in exterior walls, better sealed frames and double glazing (Ferreira, Antunes et al. 2008).

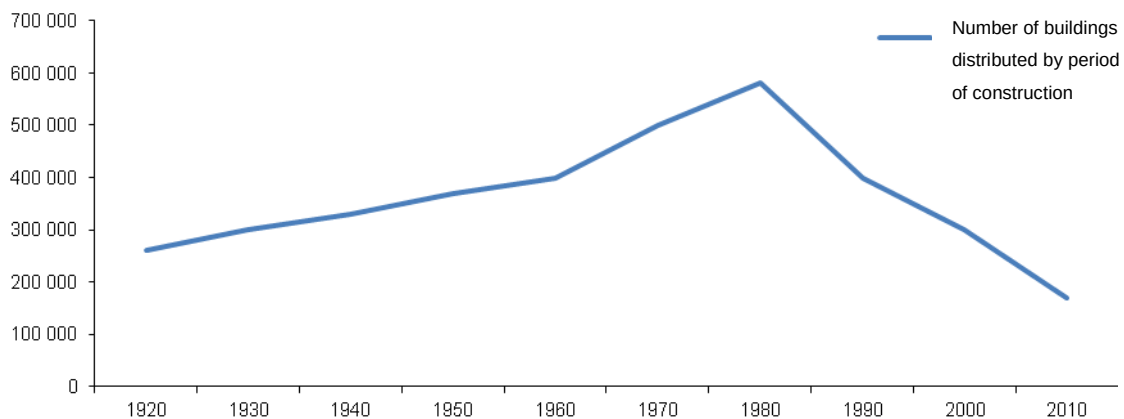


Figure 4 Number of buildings ordered by period of construction. Data source: Census 2011

Taking into account that around 70% of Portuguese buildings were built before 1990 (Figure 4), the year of the publication of the first thermal Regulation, most of the building stock has not benefited yet from the support of the Regulation neither from the later advances of the Physics of construction (INE 2011). Obviously some of the buildings built before 1990 benefited from retrofitting measures but these cases represent a minority. Thus the building retrofitting constitutes an opportunity for the improvement of the housing thermal comfort in Portugal.

More recently, the discussion has been focused in comfort and health in naturally thermal conditioned buildings *versus* buildings with technical 'add on' systems.

The concept that states thermal comfort as a 'condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation' was originated from O. Fanger's PhD Thesis (Fanger 1972) and became a standard for comfort (ASHRAE 55, 1992). More recently the standard ASHRAE 55- 2004 considers two different concepts of comfort: the Fanger's one and a new one called adaptive comfort based on the studies first of Nicol and Humphreys (Nicol and Humphreys 2002) and later of De Dear among others (Peeters, De Dear et al. 2009). The latter defines two comfort ranges, one, more inclusive, that corresponds to the range of operative temperatures with 90% of acceptability and another that corresponds to 80% of acceptability. A database was used with the results of field studies on 21000 sets of raw data compiled from 160 buildings located in four continents in varied climate zones since the mid-1980's (De Dear and Brager 2002) (Figure 5). The adaptive mode of ASHRAE is based on the principle of 'adaptive opportunity'. If discomfort occurs, people will react so as to restore their comfort. It is based on the fact that there is a linear correlation between the comfort temperature in naturally acclimatized buildings and outdoor temperature (Figure 5). In buildings with mechanical systems this relationship is not stable (Nicol and Humphreys 2002).

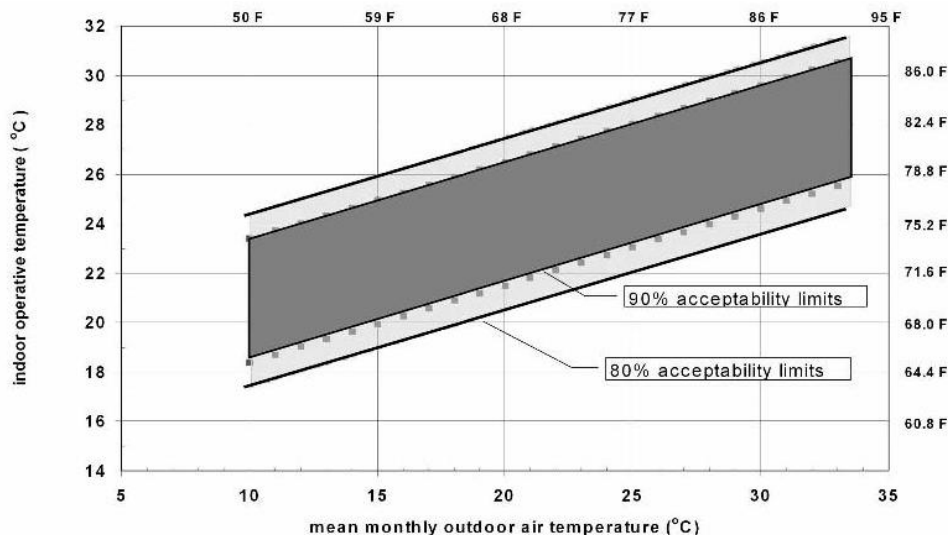


Figure 5 Acceptable operative temperature ranges for naturally conditioned spaces (ASHRAE 55-2004)

In many cases, legislations do not incorporate the adaptive comfort in their numerical calculations. Roaf, Nicol *et al* analyzed some of those cases and stated that many of the current legislative trends result in an increased energy use and therefore more CO₂ emissions from buildings (Roaf, Nicol *et al.* 2010). The European standard EN15251 also assumes the need for systems. Nicol and Wilson pointed out that the standard EN15251 goes against the spirit of the EPBD because the environmental control is too demanding and restricts the use of natural ventilation. The immediate result is the promotion of the use of energy by mechanical systems (Nicol and Wilson 2011). That was the consequence in the Portuguese legislation of 2006. A recent revision of the EN15251 has been in progress. The impression, however, is that the changes that will be adopted will end up by being rather mitigated and it seems that at the end not all potential of the adaptive comfort will be adopted (CEN/TC156 2014).

Several studies have shown that the perception and limits of thermal comfort are very different in naturally conditioned buildings and in buildings with systems. A much greater tolerance and acceptance of a wider range of temperatures was verified for naturally conditioned buildings in which occupants are able to control some of the building components such as windows and shading as well as to use different layers of clothes in order to achieve the desirable level of comfort (Brager and de Dear 1998) (ASHRAE 55-2004) (Bluyssen 2009) (Matias, Almeida *et al.* 2009) (Kordjamshidi 2011).

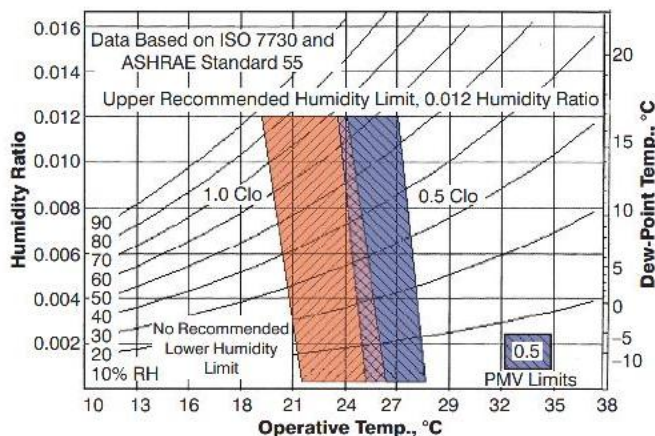


Figure 6 Acceptable range of operative temperature and humidity, ASHRAE 55-2004 (Olesen and Brager 2004)

Buildings without mechanical systems are not only recognized as being more comfortable but also as being healthier. The project 'Health optimization protocol for

energy efficiency buildings' (Roulet, Cox et al. 2005) points out three basic recommendations for the design of healthy, comfortable and energy efficient buildings: 'Prefer passive methods to active ones wherever possible; think about the user comfort, needs and behavior; adapt the building to its environment'. All studies so far have shown that naturally ventilated buildings have less symptomatic occupants than air-conditioned buildings (Bluyssen 2009).

Architecture plays an important role in the choice of constructive solutions allowing not only interior temperatures within or near the comfort zone but also avoiding asymmetries at the level of the thermal radiation as well as of the air movements. One of the most common causes of thermal discomfort in residential buildings is due to large glazing surfaces that origin overheating. Frames without thermal break and glazing surfaces that are oriented towards north also constitute situations to be avoided.

Szokolay defined the spaces in which local solar radiation or local air movements occur as 'non uniform environments' (Szokolay 2008). The standard ASHRAE 55 studied the level of discomfort of occupants caused by the local convective cooling and local differences of radiant temperatures in walls, floors and ceilings. The standard also considers the discomfort level due to the fluctuation of indoor air temperatures, both for a long period of time and in small time intervals (25m-4h). The graphic of Figure 5 already accounts for local thermal discomfort and for the possibility of occupants' adaptation (ASHRAE 55-2004).

One of the first approaches to thermal comfort has also taken into account the movement of air and radiation. Olgyay was one of the first researchers to study the design of buildings adapted to different climates and defined a comfort zone. The approach has been translated into a bioclimatic chart with dry-bulb temperatures on the vertical axis and the relative humidity on the horizontal axis. Figure 7 illustrates a metric version of the bioclimatic chart adjusted from the original graphic for warm climates. The aerofoil-shaped zone at the centre of this graph corresponds to the comfort zone. Subsequently Olgyay drew the movements of air in the upper level of the comfort zone and radiation in the below level, showing that air movements can extend the upper limit of the comfort zone and solar radiation can compensate lower temperatures (Olgyay and Olgyay 1963) (Szokolay 2008).

This approach is particularly relevant having in mind the specificity of building adaptation to temperate climates. Thus, a comfort approach in passive or climate responsive buildings cannot only take into account the interior air temperature and relative humidity. Factors as temperature fluctuations, radiant temperatures and local air differences by convection have a considerable importance. Yet, the fact is that the adaptive comfort that is taken into consideration allows for the user to accept those slight variations in the context of what is expected from adaptive comfort. And, then, if we wish to establish a relationship of those physical values with the architecture and constructive solutions, we have to refer to thermal inertia, glazing surfaces, shading and natural ventilation to help creating the conditions less extreme or harsh typical of those cases needing HVAC systems.

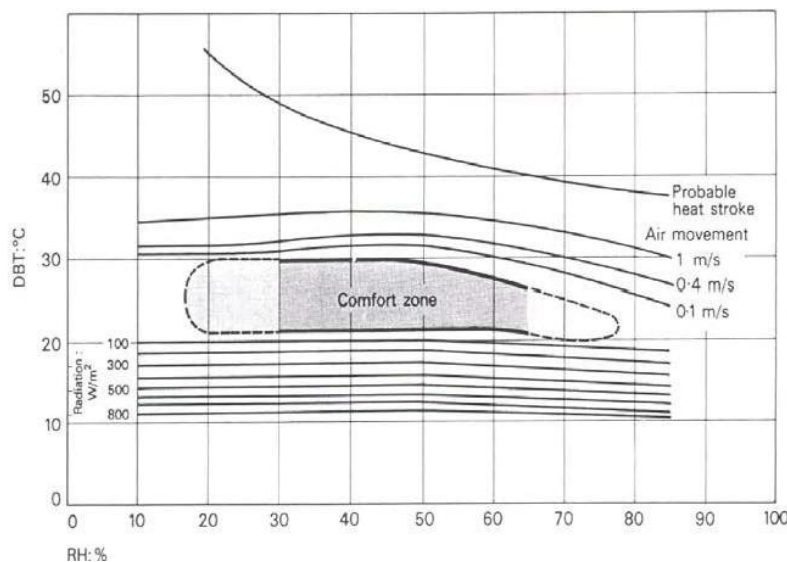


Figure 7 Metric version of the bioclimatic chart for warm climates by Olgyay (Szokolay 2007)

Studies have shown huge reductions in heating needs of German buildings achieved in last few years. However in Portugal, the reduction of heating needs is not the issue. The aim for comfort and for energy management for comfort in housing buildings in Portugal is to build or retrofit the building stock in such a way that adaptive comfort may be approached through the behavior of building envelopes, making them insulated from outside to retain the thermal mass effect both for winter and summer and accessible to the solar gains needed in winter and manageable in summer time.

This way, comfort will be reached most probably with more energy use for heating to have indoor spaces comfortable but not that much energy consumption as the envelope intervention under the strategy of sufficiency created the conditions to reach

the conditions of adaptive comfort with little energy use. So, the retrofitted buildings in Portugal will never have the same relevance in terms of energy, as the ones, for instance, located in a country like Germany. Even with the worst constructive solutions being chosen at the departure, heating needs and cooling needs won't be significantly high. The peremptory statement that HVAC systems are not needed at all in housing buildings in temperate climates, at least for cooling, is made by relevant studies (Fernandes and Maldonado 1987) (Roaf, Nicol et al. 2010).

2. In order to advance in the approach to materialize the passive architectural design or the design with the climate, how to select, arrange/aggregate and integrate those critical parameters in a straightforward usable tool that takes into account the building design characteristics?

Architecture plays a key role when it comes to the design of future low-energy (solar) buildings. For that reason, proper design tools and working methods should be available in order to aid architects in the design process.

The relevance of the assessment of design solutions during the early phases of building design deserves consensus among researchers.

Darke (1979) interviewed architects and observed that they carried out a limited set of aims or a specific solution concept for the initial solution. 'The greatest variety reduction or narrowing down of the range of solutions occurs early on in the design process, with a conjecture or conceptualization of a possible solution. Further understanding of the problem is gained by testing this conjectured solution.' (Darke 1979).

Rowe (1987) also considered that during the design process, professionals lie upon the first solutions: 'A dominant influence is exerted by initial design ideas on subsequent problem-solving directions... Even when severe problems are encountered, a considerable effort is made to make the initial idea work, rather than to stand back and adopt a fresh point of departure' (Rowe 1987).

This issue was also addressed by Marsh (1995) that pointed out the need of design tools, which language can be easily understood by architects: 'Environmental design is an extremely important aspect of architectural design, however, this is not evident in

the work of many architects...What is important is that the products of environmental science research be translated into a form easily assimilated into the design process. Only then will architects begin to use them early enough in their designs for such research to have any significant impact on the form of new buildings.’(Marsh 1995).

Achard, Baker *et al* (1992) approached the opportunity for energy savings when tackling the building design at earlier stages of building design: ‘If the designer does not realize the potential for energy saving during the initial phase the opportunity will be lost to make significant savings by relatively simple adjustments to the design. Increasingly sophisticated or costly efforts are needed to save energy at successive stages.’ (Achard, Baker et al. 1992)

The design of 'low energy buildings' has a multidisciplinary background that belongs to physics and architecture and so it is important to understand the characteristics and how the architectural building design is processed. Most tools do not take into account the characteristics of the architectural building design, including the sequence in the decision and its order of priority, but also the difference between the constraints and the choices of project (Alexander 1973) (Yezioro and Shaviv 1996) (Ellis and Mathews 2002).

Architects surveys have been conducted in order to understand how energy issues are integrated in the building design practice. Two recent surveys addressed to architects, both including Portugal, were conducted by two institutions – the International Energy Agency (IEA), in the scope of task 41 – ‘Solar Energy and Architecture’ (Wall 2010) comprising 255 architects from 14 countries and the Architects’ Council in Europe (CAE 2012) (CAE 2014) that represents the interests of 526000 architects of 33 countries in Europe.

The survey driven by IEA, comprised the question ‘In your current architectural practice, how would you rate the importance of the use of solar energy?’ About eighty percent of the architects rated the use of solar energy as important. Besides this and regarding the integration of solar issues in the building design process, and not only systems as solar panels but also constructive features as thermal inertia, results from IEA survey indicate that passive solar components are added *a posteriori* as current design tools are considered too complex and not proper for the Architectural assessment (Kanters 2011). These facts put into evidence that the profession is not

prepared to integrate energy issues in the architectural building design process, even though the recognition of the importance of designing with the Sun and the climate.

The IEA survey also allowed finding that methods for thermal aid mostly used by architects are rules of thumb, design guidelines, experiences and expert systems (44%). Simulations are up by 12%, the collaboration with other professionals by 15% and in the remaining cases thermal choices are a result of the interaction with customers or occupants (Kanters 2011). Several years before, in the early 80's, Balcomb, Barley *et al* had also considered design guidelines as being the most adequate method for thermal assessment in early design stages in architecture (Balcomb, Barley *et al.* 1980). However, the disadvantage of this type of methods is the lack of quantification that is essential for the building design (Yezioro 2009) (Kanters 2011).

Surveys driven by CAE in 2012 and 2014, 'The Architectural Profession in Europe', covered 95% of the profession in Europe and aimed to comprise questions related to unemployment, income among others. The section of the survey about Energy in Buildings was entitled 'Energy Efficiency'. A definition of Energy Efficiency was not provided. Yet, not even it was clear that interlocutors knew what energy efficiency actually meant, given their lack of knowledge in Physics, neither to what extent solar passive technologies were simple gadgets or could, in a quantified way, be called upon at the building process. In fact, questions of this section belonged to the engineering scope (CAE 2012). Additionally, ambiguous expressions were used in questions such as: 'To what extent are you currently being asked to design energy efficiency as a retrofit service by your clients?' (CAE 2014).

Not only surveys but also scientific studies give evidences of problems, barriers and opportunities of design tools. The literature points out some of the tool features or characteristics that are obstacles to their application in the architectural building design. The main feature is that existing tools are 'too complex' and are not integrated in the 'workflow' of architecture (Weytjens, Macris *et al.* 2012) (Donn, Selkowitz *et al.* 2012). As a result, most of buildings have their thermal assessment by physicists and engineers, if any is made, at a rather later phase of the architectural building design when most of the building design choices have already been made, and so creating difficulties to the proper integration of the thermal issues. Architects need thermal aid

tools during the sketch of the building in the conceptual design stage. Therefore, methods that require a detailed description of the building are not appropriate.

The tool to be used during the conceptual design phase of the building should be simple, with a user friendly language and inputs should match the critical parameters of architecture and construction (Shaviv and Peleg 1991) (Mathews, Richards et al. 1994) (Farkas, Probst et al. 2010) (Weytjens, Macris et al. 2012).

The energy signatures by Balcomb and the LT method by Baker and Steemers showed the effectiveness of the aggregation of design parameters in user-friendly graphics for architects. (Balcomb 1986) (Baker and Steemers 1990).

The building design that integrates properly physical values requires that architects use their normal procedures, but being supported by a method for thermal assessment. So, methods that are 'transparent' to users, such as rules of thumb, recommendations and expert systems (ES) contribute to give to users an explanation regarding the choice of certain options, with tangible and understandable explanations. Proceedings of these tools are transparent to users, and not like black boxes that rely on internal proceedings opaque to users (Gagne and Andersen 2011)

Thus it seems that the type of method adequate for the thermal assessment of architectural building design that best suit the local climatic conditions and the most significant site constraints is a tool that stores design guidelines and incorporates procedural steps and quantification called upon when it is needed. In quantitative terms, key data for each type of climate should result in a straightforward encapsulation of the critical inputs.

3 State of the Art

3.1 General Approach

The universe of this thesis is the one of residential buildings taken as energy systems in themselves with capabilities for capturing, storing and distributing heat from the Sun and the environment in cooler seasons and for preventing solar gains or limit their impact through free cooling strategies such as shading and appropriate ventilation in the warmer season.

The target of this study is to identify simple but sound tools that might be made accessible to the architect in order to support a first approach to the architectural design with relevant information on some specific critical indicators that will anticipate the fulfillment of a proper passive thermal behavior by the prospective building. To reach this end, it is necessary to look back to the last 40-plus years of science regarding passive buildings, without forgetting the whole history of human settlements and the climate inspired solutions that made cities like Seville so different from others such as Genova just to mention those two.

The Greeks were among the first users of solar energy in buildings. By the Hellenic period (5th to 3rd centuries before Christ) it became common to utilize the sun's energy for both heating and cooling buildings. The Greeks developed basic principles of solar architectural design. Aeschylus, Aristotle, Socrates and Xenophon outlined principles of using the sun's heat in winter. They pointed out that the main rooms of a house should face south while the north side of the building should be sheltered from the cold winds. To minimize solar heat gain in the summer, trees on the south side should provide shade to keep out the hot sun. Later on, the Romans developed the use of solar heating in homes, baths and greenhouses built between the 1st and the 5th centuries AD. They invented the glazed window and already knew about the greenhouse effect. The three most influential Roman architects – Vitruvius, Palladius and Faventinus emphasized the importance of proper solar orientation for private villas and public baths. Roman law took into account the solar rights of the citizens (Butti and Perlin 1980).

The lessons inherited from the classical traditions as well as the autonomous intuition and observations of later builders led to many other buildings and cities in the Northern

latitudes that are laid out facing south. In Portugal, there are a remarkable number of cities that face the sunny south while shunning the Northern winds, such as Viana do Castelo and Figueira da Foz.

The fact is that until the XIX century the sun radiation was, with the biomass, the major renewable energy source available and explored by mankind, in particular for lighting, heating and drying, with 'muscle power', wind and waterfalls providing quantitatively smaller but qualitatively significant sources of energy for any industrial uses. The invention of the four stroke thermodynamic engine and of the electric bulb in the XVII century opened up the door to the exploration of fossil fuels, the Industrial Era and today's Civilization.

Interestingly, a few specifically called solar houses were built and tested in the USA in the end of the 30's and beginning of the 40's, in connection, namely, with the MIT and the Boulder University, Colorado. At that time, the concern was mostly focused on the technologies associated with the heating and cooling functions in residential buildings. In the years 40-50's also Frank Lloyd Wright developed the 'Hemicycles' houses, which even today constitute references for passive solar houses.



Figure 8 Herbert Jacobs House, Solar Hemicycle, 1943-1948, F. L. Wright (Smith 1998)

About thirty years later, in 1973, a wider interest and more consistent movement was sparked by the oil crises and led to the development of a wide spectrum of potential technologies for solar energy conversion in passive solar buildings. Around the 70's some architects start expressing interest into the design of passive buildings – E. Mazria, among others (Mazria 1979) (Andersen and Wells 1981). In the early 80's the Journal of the ASES (American Solar Energy Society, the American Subsidiary of ISES) published a short article about three passive houses rendered as pioneering 'Solar Houses in Europe', The CTO - Casa Termicamente Optimizada, a project of INETI-FEUP in Porto designed in 1981 and completed in 1984 was among them (Godolphin 1984).

The above shows that, at the time, solar architecture still remained very much as an uncharted territory. The applications of solar energy in buildings can be made through two different paths: a 'technological' one, somehow extrinsic to the building itself, devoted to all kinds of solar conversion and management technologies and processes to capture and manage the solar radiation, be it for lighting, electricity production, storage or heating and cooling, etc.; and, an intrinsic path related to buildings physics considered themselves as energy systems exposed to the climate and to the cascade of effects caused by the radiation received on Earth on a daily cycle.

The aim of this thesis, as already stated in Chapters 1 and 2, is to facilitate the creation or design of buildings – new or retrofitted – that respond to the challenge expressed in Figure 2, which is to create buildings that fulfill the basic criteria of constituting healthy and comfortable spaces by playing with the Sun and the climate, and that by using as basic supporting design tools the form (architecture) and the physics of the building.

Buildings as energy systems can be quite complex. As shown in previous sections several vernacular architecture approaches attempting to respond to the challenge of climate with the means available at the moment in time can be identified. The question today is how to make new and retrofitted housing buildings answering with aplomb that challenge in all kinds of climate but in particular in the case of temperate climates where comfort can be addressed successfully in all seasons without substantial support from 'add on' heating or cooling systems.

Recalling that, to some extent, all buildings are or might be solar buildings, we can identify at least four major vectors of potential development regarding the application of

solar energy to buildings in order to assure comfortable and healthy conditions indoors based essentially on the architecture and the building physics:

1. The architectural composition, very much supported on currents such as the bioclimatic approach and the regionalism, as well as on the solar passive approach and technologies, seems to have a great potential for development, not yet explored, at the country dimension (E. Mazria, J. Cook, V. Olgyay, B. Givoni, S. Los, P. Frampton, etc.);

2. Passive construction components started being developed, in parallel with the passive solar houses, as an approach to the substitution for oil, under study in many research institutions, particularly by D. Balcomb - a visitor and friend of CTO - at the Los Alamos Laboratory in New Mexico, USA, and by F. Trombe and J. Michel, scientist and architect who created the celebrated Trombe wall at the Odeillo Laboratory in the French Pyrenees;

3. Several solar technologies were developed through research into solar houses in many places, including sophisticated devices for Sun capture and management, storage and related thermodynamic processes;

4. The holistic approach through modeling came later in the 80's and had led to the assessment of the performance of individual parts as well as the whole buildings through computer simulation codes, scale models, or even using full scale models, such as the CTO – Casa Termicamente Optimizada in Porto (Gonçalves 1990).

The literature review in the context of this thesis puts the focus in two out of the four bullets above, i.e., on the whole problematic of the architectural composition in its geographical context trying to underline the importance of the bioclimatic; and, on the issue of the passive construction and building physics in the interface between the sufficiency or 'energy conservation', according to Balcomb's terminology, and the solar technology in what regards the exploration of technology of capturing, storing and managing the light and the heat from the solar radiation.

The progress in computing for simulating the thermal behavior of solar buildings led to the production of quite a number of computer codes becoming available in the 80's, mostly originated in the USA. Meanwhile the then Directorate for Research of the

European Commission promoted the EC own code (i.e. ESP). With the time the building modeling issue became stabilized and generalized.

The use of those modeling tools applied to the design of new or retrofitted buildings still entails issues of practicality that cannot be neglected and that are part of the larger problem that very few architects have enough intimacy with building physics and with complex modeling tools. Moreover, due to technical and economic reasons, it is not easy to include a fully multidisciplinary design team, from the beginning of each residential building project.

As a research topic, as it was explained in Chapter 2, this issue may, perhaps, seem to be too modest. But, in fact a major contribution can be given by handling the opportunity to promote the intimacy of the Architecture professionals with the truly critical thermal design parameters, from the very beginning of the building design.

3.2 Passive or Climate Responsive Architecture for Temperate Climates

In 1978 the climatologist Givoni, regarding the adaptation of buildings to different climates, wrote that buildings in Mediterranean basin, should be designed and built in order to assure a protection against heat in summer and cold in winter, without recurring to expensive heating and cooling systems (Givoni 1978). Frampton, in 1980's called to a return to the local Architecture, built with respect for the Sun and endogenous materials, claiming for the regionalism and the reinterpretation of the traditional Architecture as the pathway to be followed by the Contemporanean Architecture (Frampton 1983).

Earlier, Olgyay (1963) highlighted the relevance of carefully choosing solutions that satisfy all seasons requirements, in order to find a combined strategy for a balance between conduction losses through the envelope, solar radiation gains through the glazed surfaces and convection losses through openings in the envelope, be them either temporary or permanent. Some specific proposals were: a) windows facing south should be chosen but always with seasonal protection i.e. assuring shading in summer time; b) windows facing west should be small for summer and winter comfort; c) the roof should be ventilated during summer but protected during winter and d) building

settlements organization and vegetation should be used as a solution for shading, especially in west and east orientations and for northwest winds protection (Olgyay and Olgyay 1963).

In the 80's, S. Los brought up the issue of 'the architectural design directed towards improving both the environmental quality of urban spaces and their surrounding buildings, and the use of energy resources at a micro-urban scale', advocating that 'the architectural design should be multi-scale; that distinctly separate levels of scale do not exist, but each project itself should define its own scales and relationships.'

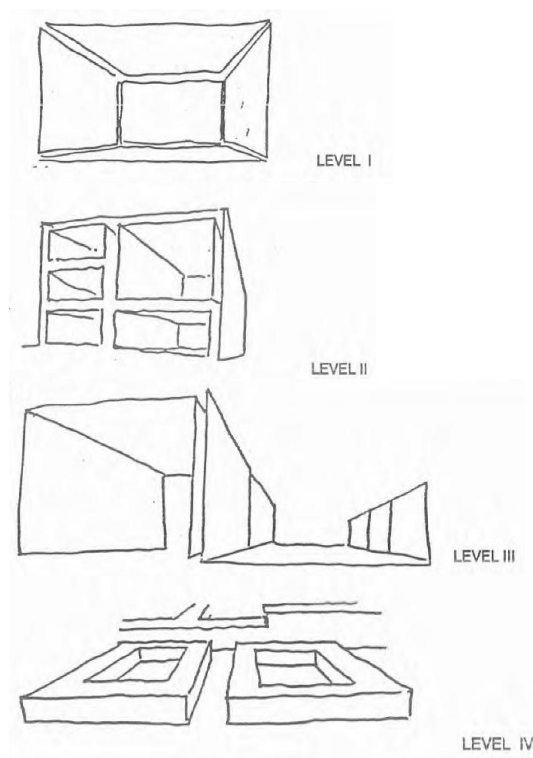


Figure 9 A typological grammar (Los 1988)

Los was inspired by the writings of the architect L. Kahn that advocated that it was possible to transpose the spaces of the building to the city (i.e. a square can be regarded as an exterior room), highlighting the relevance of the element wall as a boundary. So, the importance of design languages shall take into account the two 'faces' of the building – 'the façade presented towards the exterior, which belongs to the urban space, and is internal to that space rather than external to the building; and the face presented on the interior, which follows the logic of the building, and is internal to its space'. The different scales of project – the room itself, the building, the square

delimited by the building façade and the ‘homogeneous city part’ – should have the same design language, being all spaces defined by the same building elements. Los advocated that this architectural language should be translated into building design tools for energy assessment, through a specific repertoire of the grammar of the form (Los 1987).

Cook (1998) introduced new cultural and economic points to the discussion of buildings in temperate climates. The emergence of modern typologies of construction, as multistory buildings, should be integrated with the *urban tissue* of traditional buildings in order to ensure a ‘cultural continuity’. Addressing economic issues, energy passive architecture in temperate climates can be regarded as a contribution for the reduction of the import of foreign fuels. ‘Over dependency on imports can be avoided by coupling low energy use with low cost local technology’ (Cook 1998).

Serra (1988), a researcher from the Polytechnic University of Catalonia, was particularly concerned with the complexity of temperate climates, anticipating it clearly when underlining its complexity: ‘What distinguishes temperate climates further from other climates is the wide variety of weather conditions one can expect within the same season. (...) Accordingly when we consider the particular style of bioclimatic architecture which these temperate climates require, we are justified in using the terminology ‘architectures of complexity’. It is particularly difficult to solve problems caused by these rapid successive climate changes and therefore this field of design poses a greater challenge to architect’ (Serra 1988). Without recurring to very sophisticated constructive solutions, temperate climates with mild winters and dry and hot summers may allow thermal comfort for both summer and winter. Despite this, temperate climates require a wider range of constructive solutions than extreme climates, as it can be observed through many examples in vernacular or popular architecture. Addressing solutions, Serra proposed design flexible features which can respond as required to changing climatic conditions – movable shading devices, intermediate spaces between interior and exterior and some form of practicable openings for ventilation control with possibility of alternating total free passage of air and the prevention of even the slightest heat dissipation (Serra 1988).

Alvarez (2006) considered useful solar gains as one of the main contributions for thermal comfort of mild and sunny climates. Solar gains in winter can compensate for a significant part of heat loss through the envelope and assure free heating through

useful solar gains. The author establishes that for Mediterranean climate 'rules for an energy conscious design of building design envelope are' 'merely' to minimize losses and maximize free (solar) gains in winter, and minimize gains and maximize free losses in summer', stating also that 'the climatic conditions in the Mediterranean area - high availability of solar radiation in winter and low high-time outdoor air temperatures in summer - promote the existence of low energy buildings which do not differ significantly from current buildings'. More than increasing the insulation level of the envelope elements, energy issues in buildings of Mediterranean climates should focus on the design of more sensitive parameters – exterior envelope surfaces, the orientation and window size and thermal inertia (Alvarez 2006).

Szokolay (2008) also underlined that in most temperate climates the night-time temperatures are too low even in the summer, justifying the choice of heavy constructions. The author defined the time lag of a solar heated massive wall as 'to be set to equal the time difference between the maximum of solar input and the time when heating would be welcome'. Thermal insulation should be less strict than in cold climates. Besides thermal inertia and thermal insulation, south windows, horizontal shading devices and ventilation were pointed as being relevant. Overheating is a potential problem in temperate climates referred by Szokolay. The author recalled the relevance of south facing windows for winter solar heating but also the overheating that large south facing windows may cause in summer, that call on the need of exterior shading devices. One of possible solutions for overheating that can occur in temperate climate buildings in summer is ventilation that can be relied on to dissipate the unwanted heat, as air temperatures are unlikely to be too high (Szokolay 2008).

Szokolay addressed the conflicts regarding the influence of certain design choices at the level of different physical values. The example of the roof insulation in warm climates is given. Increased roof insulation can reduce daytime (solar) heat gain, but it will also reduce night-time dissipation of heat. The researcher also highlighted that a given choice can be limited in its influence on the building thermal behavior by the interaction of another parameter. Here the example of south facing windows interaction with thermal mass is addressed. If the building is lightweight, without adequate thermal storage mass, the resulting heat gain may produce overheating during the day; the user will be tempted to open windows, so there will be no heat left to soften the coldness of the night. However if the thermal mass is high it will allow the heat storage that will be dissipated during the night (Szokolay 2008).

Specifically, in what regards the aggregation of parameters, Shaviv and Peleg went further by performing a parametric study for buildings in Jerusalem, in the early 90's. The main finding about interaction between parameters was the loss of relevance of some design choices in well-insulated buildings. If the building is well insulated, colors have a negligible influence on its thermal behavior; hence the designer is free to choose any color for the walls. Also, buildings proportions do not have influence on the building thermal balance if it is well-insulated, as long as the area of windows on each orientation is kept as default and the suggested area of windows on the southern elevation can be achieved. Another finding, but now related with ventilation, is that even if light colors are always advisable for summer comfort, this issue is not significant in a well-ventilated building (Shaviv and Peleg 1991).

Some researchers translated these synergies in design methods with graphics/nomograms that encompassed relationships between parameters and related physical values. The LT method and the 'Energy signature' were the methods more focused on this approach (Balcomb 1986) (Baker and Hoch 1988). These will be addressed later, in the Subchapter 3.4. of the literature review.

Fernandes, Maldonado *et al* (1998) selected four main design features for building design in temperate climates also taking into account the 'climate complexity': enough south glazing for winter gains; adequate shading and ventilation for summer control; dynamic shading control for middle season and massive construction for both summer and winter comfort. During winter, mass allows a better distribution of solar heating through the day while in summer and middle seasons it favors a very small temperature fluctuation indoors (Fernandes, Maldonado et al. 1988).

Monitoring of climate-designed buildings in Portugal, in CTO case as well as for several others, showed that indoor temperatures can be within the comfort levels almost throughout the year and with minimal temperature fluctuations. That is particularly true if the adaptive comfort concept is adopted, which appears to be the one more adapted to the housing conditions in the Portuguese climate. The analysis of those results allows understanding how the holistic approach of buildings design can lead to low heating and cooling needs and low temperature fluctuations indoors (Subchapter 3.3.).

Specifically for Portugal, some studies developed sensitivity analysis and established the architectural and constructive parameters that most influence the building thermal behavior, either for summer, either for winter.

Fernandes, Leal *et al* (2009) proposed a thermal performance analysis of models, using different methods, RCCTE 2006 and ESP-r. Nominal needs and real needs obtained using the two methods were compared. Results revealed that there is a close correlation, being results obtained through RCCTE 2006 about 20% higher regarding the ones obtained through dynamic simulation. The disaggregation of heat losses and solar gains allowed identifying differences between them. Major variations are due to the envelope conduction and to useful solar gains.

Table 1 Proposed default values for the construction and architecture parameters in Portugal

Parameters from Construction and Architecture	Gonçalves, Panão et al. 2010			Fernandes, Leal et al. 2009		
	Low	Medium	High	Low	Medium	High
Thermal inertia It [kg/m ²]	weak It <150 ¹	medium It >150; <400 ¹	heavy It >400 ¹	weak It <150 ¹ It <100 ²	medium It >150; <400 ¹ It >100; <300 ²	heavy It >400 ¹ It >500 ²
U-value opaque elements [W/m ² .°C]	0.34 walls 0.40 floor 0.39 roof	0.50 walls 0.57 floor 0.53 roof	0.57 walls 0.88 floor 0.77 roof	0.3 average value	0.6 average value	0.9 average value
Position thermal insulation in walls	middle	middle	middle	interior	interior	interior
Solar factor of shading/ Position and type of shading device $g_{\perp}$	0.07 exterior	–	0.47 interior	0.07 exterior	0.38 interior	0.56 interior
U-value glazing [W/m ² .°C]	3.1 double	–	5.2 single	1.0	2.0	3.0
Air tightness/infiltration Ventilation rate [RPH]	1.0	1.05	1.10	0.6	0.9	1.2
Absorptance opaque surfaces (color)	light 0.4	medium 0.5	dark 0.8	–	–	–
Window area/floor area	–	–	–	0.05	0.15	0.3
Window orientation	–	–	–	N	E/W	S

¹ Useful superficial mass – It [kg/m²]. Default values for Portugal based on RCCTE steady state calculation

² Useful superficial mass – It [kg/m²]. Default values for Portugal obtained through dynamic simulation with ESP-r

In a second phase, a sensitivity study has been developed with different design alternatives of buildings located in Maia, Guarda and Faro. The calculation of the influence factor of each parameter was performed. Most sensitive parameters for

winter were the U-value of opaque elements (27% Faro, 24% Maia, 22% Guarda) and building orientation (17% Faro, 15% Maia, 12% Guarda). For summer, glazing area/floor area (59% Faro, 152% Maia, 121% Guarda), thermal inertia (41% Faro, 117% Maia, 70% Guarda) and shading devices (33% Faro, 53% Maia, 50% Guarda) were indicated as the most sensitive issues. This study showed that the most sensitive parameters for winter are the same for the different studied locations. The same was verified in the most sensitive parameters for summer (Fernandes, Leal et al. 2009).

The study from Gonçalves, Panão *et al* also used the RCCTE 2006 and concluded that the primary energy index used for energy certification labeling is mainly established by the efficiency of systems, including the certified solar panels. Passive strategies like adequate thermal insulation and windows sizing have a much reduced influence on the building label. However, this influence is determinant on heating and cooling needs (Gonçalves, Panão et al. 2010).

The fact that everything in a passive building is called upon to play a role in the future passive building, i.e. the architectural form, the orientation, the dimension and the orientation of the fenestration, the thickness and location of the thermal insulation, the thermal mass of all structural components, etc., may not exclude to explore the possibilities for the identification of some aggregated critical parameters with physical meaning and relevance for the thermal performance of the building.

At this point, it is possible to state that studies of buildings in temperate climates put into evidence that critical inputs for the building design are the ones that directly interfere with:

1. the architectural space thermal balance: thermal conductance, windows, shading, thermal inertia, ventilation and building orientation
2. useful solar gains - windows, thermal inertia and building orientation

bearing in mind that architectural constraints, as site integration, and the interaction between parameters, can limit the extent of the relevance of some or of all parameters.

Bellow, some approaches aim to address the quantification of the two issues above.

The equation of the thermal balance of energy fluxes for the building or for the architectural space at study is (Szokolay 2008):

$$Q_i + Q_c + Q_s + Q_v + Q_e = \Delta S$$

Where ΔS is a change in the heat in the building or in the architectural space.

A few parameters and considerations can be obtained by the discussion of the graph model (Figure 10) and the balance equation:

1. Thermal balance ΔS

The thermal balance is verified when the sum of all heat flow terms, thus, ΔS is zero (Szokolay 2008). Otherwise if ΔS is higher than zero it has a positive balance and the building/space stores heat. If ΔS is negative, as a consequence of those fluxes, the building/space loses heat and cools down.

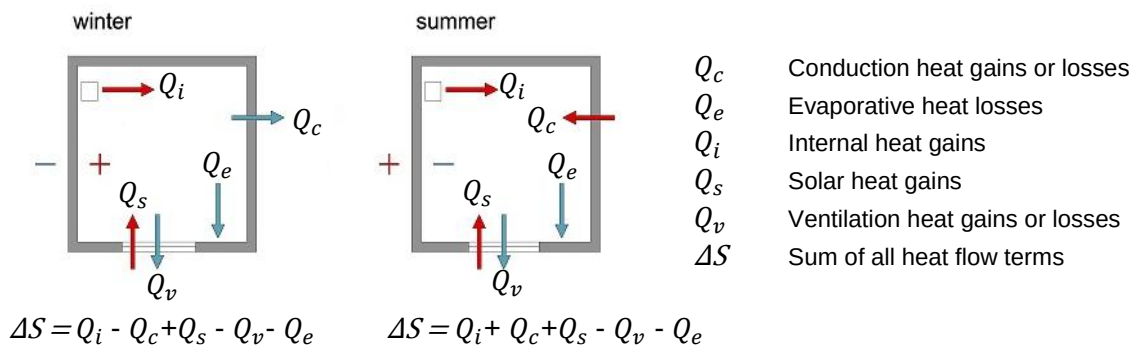


Figure 10 Building thermal balance in winter and in summer

2. Gain-load ratio

In direct gain solutions, the calculation of useful solar gains can give the result of the combination of the gains through south window surfaces and thermal storage mass that will contribute to the minimization of the purchased space heating energy. The calculation of useful solar gains is dependent on the ratio of gross solar gains and gross heating needs through its interaction with the interior inertia. It is expressed by the following equation (RCCTE 1990):

$$GLR = \frac{\text{Gross solar gains}}{\text{Gross heating needs}}$$

Where GLR means gain-load ratio, which means that it expresses the part of the solar gains that covers the heating needs. The relation of this expression with the level of internal thermal inertia determines the utilization factor of solar gains.

A study for Portuguese buildings (Maldonado, Fernandes et al. 1987) showed that the SLR (solar-load ratio) method developed by Balcomb and Wray (Balcomb and Wray 1987) is less precise than the GLR method developed by Barakat and Sanders (Barakat and Sander 1982). In fact SLR predictions led too less massive systems. This gain-load ratio differs from the solar load ratio, as the GLR includes heat losses through windows while the SLR does not (Barakat and Sander 1982).

The RCCTE 1990 method calculation adapted the gain utilization factor of the GLR method. The RCCTE 1990 approach will be addressed in the methodology chapter (Chapter 4).

Yet, it is needed to state that the quantification of useful solar gains is simplified in the RCCTE 1990, as it only quantified the contribution of useful solar gains for glazing facing south, southeast and southwest orientations, as well as for horizontal glazed surfaces (Table 2). In fact, geometry of solar radiation shows that there are useful solar gains for all the azimuths. The RCCTE 2006 and the Regulation on the Energy Performance of Residential Buildings (REH/RECS 2013) (Table 3) considers very near values of solar radiation measured in Portuguese cities.

Table 2 Orientation factor considered by the RCCTE 1990 (RCCTE 1990)

	N	NE and NW	E and W	SE and SW	S	Horizontal
Orientation factor	-	-	-	0.70	1	0.85

Table 3 Orientation factor considered by the RCCTE 2006/REH 2013 (RCCTE 2006) (ITeCons 2013)

	N	NE and NW	E and W	SE and SW	S	Horizontal
Orientation factor	0.27	0.33	0.56	0.84	1	0.89

In Figure 11 the contribution of all solar radiation directions is reported by Alvarez, evidencing the useful solar gains per orientation for Seville, a city in south Spain.

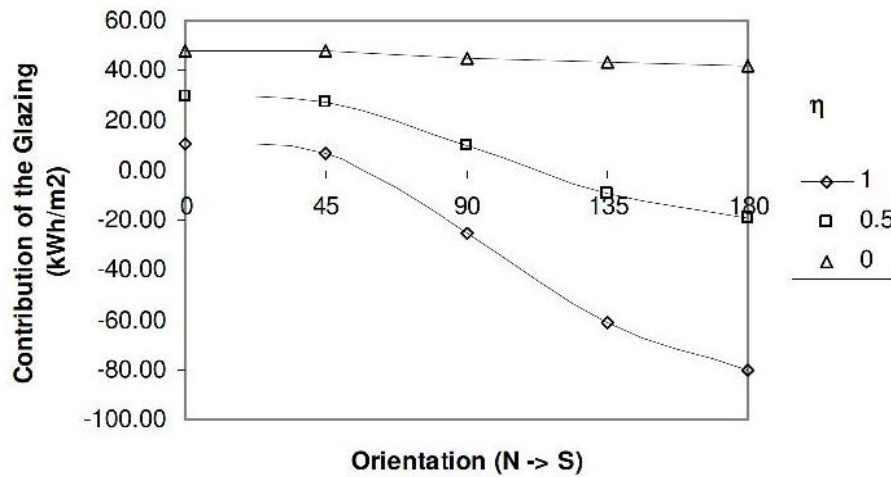


Figure 11 Net contribution of a double glazing (Alvarez 2006)

Additionally, some relevant updates based on the literature that approach the quantification of constructive solutions in building design are addressed below. Two questions that this thesis must address are also raised.

Thermal conductance

The thermal conductance states the relevance of the envelope (seen here as just the opaque envelope) and is expressed by the product UA which is given by the sum of all thermal losses obtained by multiplying each conductance by the surface of the corresponding part of the envelope skin.

$$q_c = \sum U_e \times A_e \quad (W/^{\circ}C)$$

U_e - represents the coefficients of thermal transmittance of exterior elements ($W/m^2.^{\circ}C$)

A_e - represents the areas of external elements (m^2)

Thermal inertia

Massive construction of vernacular architecture, as well as, in passive solar is of great interest. Yet, the research at CTO showed that there are limits for the benefit of the massive characteristics. Fernandes, Maldonado *et al* (1998) stated that despite modern construction technologies, buildings in moderate climates should be massive, but don't need to be as massive as in traditional architecture (Fernandes, Maldonado *et al*. 1988). Nowadays, there is the practice of applying the insulation externally to the

massive walls, this way confining the thermal mass that is sensed to play its storage role on the heat balance of the space.

Gonçalves (1990) and Fernandes and Maldonado (1987) studied the importance of the mass related with the area of solar openings. It was found that after a certain value for the relation between the solar gains and heat losses, the effectiveness of additional mass is gradually reduced. As an indication, up to 10cm of mass thickness the thermal inertia increases almost proportionally to the thickness (Gonçalves 1990).

Shaviv (1988) reached the same conclusion beforehand as a result of a parametric study for concrete buildings in the Mediterranean climate in order to study thermal mass. She had shown that when the thickness of the internal thermal mass changes from 10 to 40cm the building performance during winter and summer remains practically unchanged. For residential buildings, a thickness of 15cm was recommended (Shaviv 1988).

The location and distribution of mass was also studied by other researchers (Givoni 1978) (Sander and Barakat 1984) (van Hattem 1987) (Oliveira 1989) (Wall and Hastings 2007). Sander and Barakat (1984) refer the distribution and location of mass as the 'mass & glass' approach. The use of large areas of south-facing glass is needed to collect solar energy and heavy internal construction is needed to store the excess of heat collected during the day for later use at night (Sander and Barakat 1984).

The precise location of massive materials is where sunlight falls (Wall and Hastings 2007). This issue was also reported by van Hattem: 'Also the thermal mass must be placed in such a way that it absorbs the heat there, where the overheating occurs and at an adequate rate. So the thermal mass which is of interest must be an 'effective thermal mass, not just all the mass of the building.' (van Hattem 1987).

Addressing now the thermal inertia quantification, reference values were attributed by RCCTE according to the sum of the thermal mass of interior partitions and insulated exterior walls and their degree of exposure.

Interior thermal inertia, which is the useful superficial mass per square meter of floor (It), is defined by the following expression (RCCTE 1990):

$$I_t = \frac{\sum M_i S_i}{A_p} \quad (Kg/m^2)$$

This is a simple and user-friendly expression even for architects. Recently the REH presented a simplified process of setting the thermal inertia category for a given set of combination of constructive solutions for building elements. However, it is considered here that the simplified process of REH is quite broad, leading in almost all cases to medium inertia. Thus, that suggests that it would be desirable to perform a parametric study to build a thermal inertia decision tree, which would allow a much more straightforward interior thermal inertia assessment for architects.

Window orientation, size and shading

As it has already been referred, window size cannot disregard the thermal inertia in the space served by that window or windows glazing area. For direct gains in concrete constructions it was found that the importance of inertia rises with the increase of the glazing area. The area of south glazing surfaces per useful floor area can be at least 40%. For higher ratios there is some risk of overheating (Gonçalves 1990) which calls for the intervention of effective shading.

In the scope of this thesis, it would be desirable to know up to what values windows should be sized always taking into account the space inertia and orientation. Complementarily, these values will be very different for windows without protection and windows with shading devices

Ventilation

Ventilation is needed to ensure the indoor air quality (IAQ) by diluting pollutants - at least, those generated by human metabolism (breathing and sweating) - both in winter and in summer and might be needed for summer comfort taking advantage of the added cooling effect of the air movement. Levels of ventilation for metabolic activity and health needs (indoor air quality) must be wisely established as the ventilation with outdoor air in winter may increase heating needs.

The conditions of the site, where the building is located, and also the openings on the façades and roofs are determinant for air circulation strategies and consequently for

the proper natural ventilation in buildings. Unfortunately, the high dependency of the microclimatic conditions of the site limits the universality of the theoretical models (Cusido and Puigdomènech 1987). In this context, and given the numerous constraints that define the air circulation and velocities, qualitative solutions might be much more effective on building design than quantitative data that needs a high number of inputs for sizing ventilation inlets and outlets. Thus, available design guidelines and recommendations seem to be the most adequate method to address ventilation in early building design assessment. In Portugal in the 70's values of 2 renovations or air changes per hour were common. Since then, with better windows and doors the envelope has become tighter and those values have come down to 0.6 renovations per hour (value of the EH) and even less.

Obviously, there is a need to guarantee a minimum ventilation level, better expressed in liters per second per person than in ach (air changes per hour). The latter does not take into account the density of occupation. The new patterns of building occupation trends shows that for housing the number of square meters per occupant is growing through the time, as families are smaller. All this leads to more floor surface and therefore more volume available per capita.

A quite recent study sponsored by the EC DG HEALTH (DG SANCO) called 'Healthvent' showed the need for a holistic approach to the management of IAQ based on source control if it is possible. If yes, ventilation that remains the last resort solution for good indoor air quality and can have values as low as 4 Liters/second per person just to cope with the human effluents. Then, the value 4 l/(s.person) is proposed as the minimum health-based ventilation rate guideline to be applied when previous conditions are met (Fernandes 2013).

3.3 Case studies of Architectural building design of residential buildings in Portugal

In this subchapter two sets of buildings built in the last 40 years are presented. The reasons for the selection of case studies can be understood during the presentation of each case. Yet, a few general introductory considerations are still needed.

As it has already been referred in Chapter 2, two issues need to be addressed when establishing critical input parameters for the architectural design (Shaviv and Peleg 1991). The first one, which has been introduced in the previous subchapter, consists in determining whether the parameters have a significant effect on the thermal response of the building. The second that is driven in this subchapter deals with parameters that are directly influenced by architectural design decisions. In reality, all parameters are influenced by architectural decisions, but some of them are more dependent on other factors, some external as it can be the case for ventilation. In the latter case, the design can only ensure the location and type of openings and anticipate the phenomena of convection resulting from these options. Other parameters as the exterior area of the building, the windows sizing and the choices of constructive materials, are almost always entirely controlled by the architectural building design.

The characterization of construction choices of existent buildings, that have already been occupied and in some cases monitored, allows for the evaluation of their thermal performance and also to understand the context in which more relevant parameters are chosen. Two groups of buildings are considered:

1. Passive solar houses recognized by the scientific community by its good thermal behavior (CTO, Vale do Rosal, PLEA 88, Green Tower, Oásis, Janas) and
2. Other houses with building design features chosen for their adaptation to the climate and with respect with local resources (Beires, Elemental, Utopia, Beja and Lóios).

Moledo house has been chosen as a particular case in which thermal comfort indoors was jeopardized because priority was given to other values, such as the privileged view.

Buildings within the 1st group present more passive building design features than the 2nd group (Table 4), especially integrating indirect and isolated solar gains strategies. Buildings of the second group have more constraints, namely site integration constraints. Both attempt to respond adequately to sustainability and thermal comfort challenges by choosing building design features adapted to the climate and with respect with local materials.

A succinct description of each building is made as well as a table with the constructive and architectural solutions. The Table 4 shows that some building design characteristics are commonly used. Many buildings are S, SW or SE oriented. With the exception of two cases, buildings are characterized by having heavy inertia. Besides heavy inertia, for several cases additional thermal mass is embedded in interior elements in order to maximize the heat storage. Trombe walls without ventilation seem to be one of the passive features more used, particularly in contact with spaces with nocturnal occupation.

In the cases in which temperatures were measured, very stable interior temperatures were observed, within the range of acceptable temperatures determined by the adaptive thermal comfort concept (Simões 1986) (Maldonado, Fernandes et al. 1987).

Complementarily, in some cases, namely in Green Tower and Janas Houses, occupants were asked about thermal sensations indoors. In these cases, occupants had very satisfactory answers, reporting that during building occupation, heating and cooling systems were never used as they were not needed (Roulet, Cox et al. 2005) (Nascimento and Gonçalves 2005).

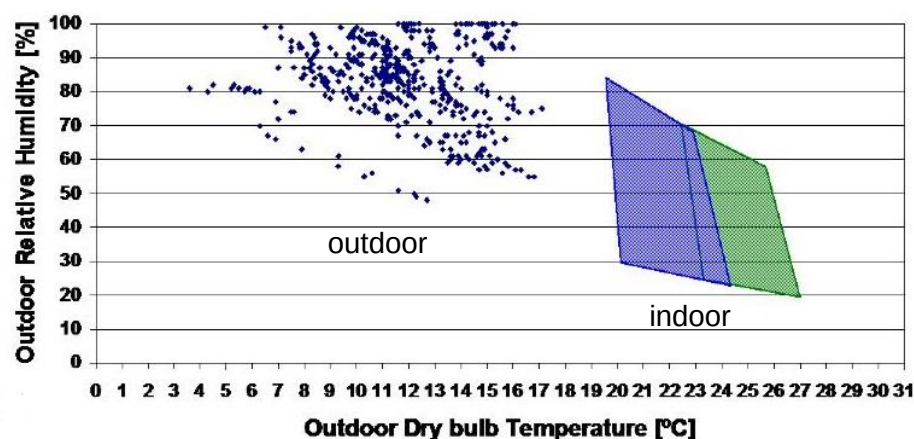


Figure 12 Green Tower building. Differences between indoor temperatures and outdoor temperatures for one winter month (L.Tirone, Lisboa 2001)

In what regards solar protection measures, buildings do not present a single solution for shading, but two or even three – for instance, a combination of interior curtains with exterior shutters and structural exterior devices. These are ‘elements that can change easily its environmental action depending on the climatic circumstances’ (Ganem and Coch 2004).

Another very recurrent architectural solution was the use of intermediate or buffer spaces between interior and exterior, as courtyards, that can originate favorable microclimates, and which occupation can also depend on the season and on the hour of the day. (Fernandes, Cortesão et al. 1986) (Nascimento and Gonçalves 2005).

Regarding site constraints, the case of the retrofit of House Lóios (12) puts into evidence that optimized solutions are not always possible. In these cases it is important to study all constraints upfront carefully. The optimization of solutions according to the site constraints variables is also approached in the case of House in Moledo.

The building in Moledo (4) oriented towards west is an example that, in some cases, factors as the landscape view are considered so relevant that become dominant. That can lead architects to take initial choices that are not the best regarding the thermal performance. In these cases it is relevant to ask: Can we quantify the influence of orientation in energy needs? And what if the other possible design choices are optimized to what extent is it possible that the building achieve a good thermal performance even if the first choices regarding the site integration, such as the building orientation, were not the best ones?

Energy requirements for winter and summer of these buildings were calculated using the RCCTE 1990 method (Figure 13). Besides the nominal needs for heating and for cooling, the sum of both needs was calculated. While nominal needs for heating and cooling are indicators of thermal comfort without either heating or cooling, the sum of both is basically an energy indicator of the maximum energy invoice per year for comfort purposes, as it is the real number of how much energy is required to be supplied yearly in order that a temperature of comfort can be achieved, being in this case 18°C for winter and 25°C for summer.

Almost all cases are below the limits imposed by the RCCTE 1990, which means N_i/N_{ic} and N_v/N_{vc} are lower than the unity. Two buildings are exceptions. The first

exception is the House Beires. The house was designed and built between 1973 and 1976 thus the construction did not take thermal insulation and double glazing into consideration. As most Portuguese buildings from that period of time, this building is quite massive, with double masonry walls and concrete slabs, but not insulated at all. If the building would have been built nowadays probably with exterior thermal insulation, the heating needs would suffer a reduction from 52kWh/m²year to 10kWh/m²year and could meet the regulation requirements. With the exception of lacking thermal insulation and exterior shading, all other solutions are optimized, from the maximization of the southwest façade to obstructions through vegetation.

The second exception is the House Moledo that presents large glazing surfaces facing west and east and maybe not that strangely performs better in summer than in winter. The east glazing façade is shaded by rocks during the most part of the day and the west façade has a projecting eave that also provides some shading, partially attenuating the solar radiation exposure in summer time.

During winter, the large area of glazing leads to high thermal losses by conduction and the window oriented towards west does not favor useful solar gains that could supply the space with some free heating. Yet, it should be underlined here that the useful solar gains in west glazing are not quantified by the RCCTE 1990, as it was already referred before. If the main façade of the building was south oriented, heating needs would have a reduction from 61kWh/m²year to 24 kWh/m²year and the regulation requirements would be met.

Regarding cooling needs, exterior obstructions from rocks in the eastern façade contribute to reduce the effect of the large glazed area, but the extension of the eave in the west façade is not enough for summer control. If the building had exterior shading devices, cooling needs would be reduced from 11kWh/m²year to 3kWh/m²year and would have met regulation requirements. The glazing surfaces are clearly oversized and even if glazing area had a reduction of 50%, the building would not perform significantly better in winter. Clearly, the orientation and the large area of glazing are the reasons for the high heating needs. This example shows that a solution for a space that does not take properly into account glazing orientation and the ratio glazing surface/attended floor surface will tragically compromise its thermal performance. This cannot be significantly improved even if other design choices are thermally optimized.

Only the solution of recurring to mechanical equipment can cope with the difficulties identified above.

The most challenging case for the thermal assessment in Architecture is the case of retrofitted buildings. The case of retrofit integrated in this study has a general good thermal behavior, even without thermal insulation in the main façade. House Lóios retrofit is an example that constraints related with the opaque exterior envelope where it is not possible the application of thermal insulation in one façade does not have such a high influence in the building thermal performance if other constructive choices are optimized.

Remaining buildings present fewer constraints. Essential or critical input parameters, the ones that guarantee thermal balance and optimization of useful solar gains, are carefully chosen – heavy inertia, exterior thermal insulation, and high areas of glazing surfaces facing south, southeast or southwest, exterior shading and few openings in other orientations, additional massive solutions, and natural ventilation strategies. CTO and Vale do Rosal, detached houses, and Janas House, semi-detached houses, are the ones that have a better thermal behavior and comfort conditions, being confirmed by building occupants.

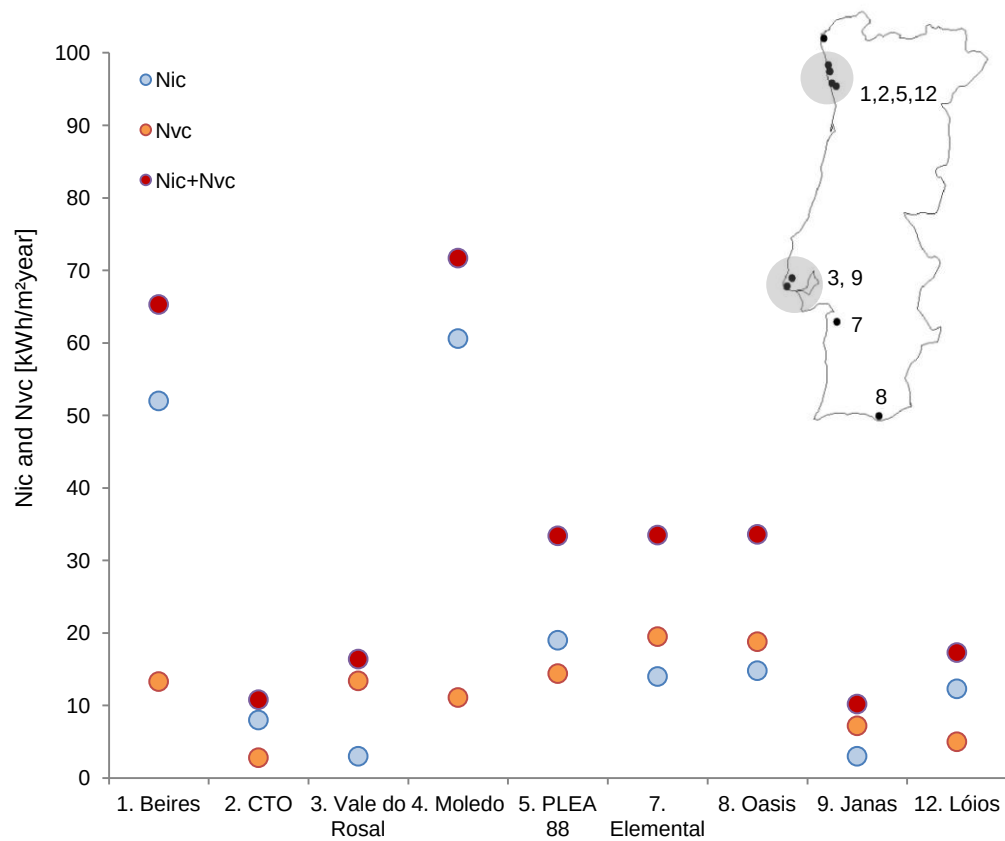


Figure 13 Thermal needs of some residential buildings in Portugal calculated through RCCTE 1990 method ¹

¹ Nominal needs of CTO, Vale do Rosal and PLEA 88 were calculated by Gonçalves, Oliveira

Table 4 Main features of Architecture and Construction of some cases of residential buildings in Portugal

<i>Main features of Architecture and Construction</i>	1. Beires 1973-1976	2. CTO 1980-1984	3. Vale do Rosal 1986	4. Moledo 1991-1998	5. Multif. PLEA 88 1996	6. Green Tower 1996-1998	7. Element. 2000-2002	8. Oásis 2003	9. Janas 2003	10. Utopia 2006	11. Beja 2006-2008	12. Lóios 2011
	A=167m ²	A=135m ²	A= 150m ²	A=180m ²	A=75m ²		A ±196m ²	A=195m ²	A= 110m ²	A=120m ²	A=550m ²	A= 356m ²
<i>Internal thermal inertia</i>	Heavy	Heavy	Heavy	Medium	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy	Medium
<i>U-value walls [W/m².°C], thickness [cm], position</i>	Double walls	U = 0.6 5 walls exterior	U = 0.55 6 walls middle	4 walls middle	4 walls	U= 0.4 6 walls exterior	Double walls	U = 0.6 3 walls middle	U = 0.5 6 walls exterior	No data	U value earth =0.7-1.4 Walls with 50 cm	Backyard façade and roof with exterior thermal insulation
<i>Thermal insulation slabs</i>		5 roof exterior 5 floor	10 roof exterior 3 floor	3 roof	5 roof 3 floor	8 roof		6 roof exterior 3 floor	10 roof exterior 4 floor	3 walls in contact with the earth		
<i>Additional massive interior elements</i>	No data	Water columns + floor S	Ceilings	No data	Concrete portico SW	Floor + concrete seats near S windows	No data	Floor+ walls + beds + flowerpots	Party walls	No data	Floor + water system roof	Granite walls
<i>Position and type of shading device</i>	Interior curtains + vegetation	Exterior blinds + others fixed + vegetation	Specific shading solutions for different glazing	Interior curtains + exterior horizontal overhangs	Exterior shutters + wooden pergola	Exterior blinds + structural exterior horizontal overhangs	Interior (glazing is in contact with interior patios)	Exterior blinds + structural exterior horizontal overhangs	Interior wooden shutters + exterior canvas + struct. ext. horizontal	Interior shutters	Exterior structural horizontal overhangs + interior curtains	Interior wooden shutters
<i>Type and U-value glazing [W/m².°C]</i>	Simple	Double	Simple/ Double	Double	Double	Double	No data	Double U = 1.7	Double U = 2.4	No data	No data	Double
<i>Air tightness/ Natural ventilation solutions</i>	Openable windows	Crossed ventilation	Crossed ventilation + upper windows	Stack effect	Buffer space + crossed ventilation	Crossed ventilation	Interior patios	Crossed ventilation + buried pipes	Crossed ventilation	Interior patios	Crossed ventilation	Interior patios
<i>Window size. Aglaz/ Ap</i>	No data	31%	32%	Around 45% E+ 45% W	15%	More than 20%	No data	33%	23%	Less than 10%	Less than 10%	No data
<i>Window orientation</i>	Mainly SW	Mainly S	Mainly SE	Mainly W	Mainly SW	Mainly S	Mainly SW	Mainly S	Mainly S	Mainly SW	No data	Mainly SE

Table 5 Main features of energy valorization of some cases of residential buildings in Portugal

Main features of energy valorization	1. Beires 1973-1976	2. CTO 1980-1984	3. Vale do Rosal 1986	4. Moledo 1991-1998	5. Multif. PLEA 88 1996	6. Green Tower 1996-1998	7. Element. 2000-2002	8. Oásis 2003	9. Janas 2003	10. Utopia 2006	11. Beja 2006-2008	12. Lóios 2011
	A=167m ²	A=135m ²	A= 150m ²	A=180m ²	A=75m ²		A ±196m ²	A=195m ²	A= 110m ²	A=120m ²	A=550m ²	A= 356m ²
Obstructions	SW and W	None	Fences and vegetation SW	Façade E obstructed by rocks	NE slightly obstructed	None	None	None	Vegetation N and W	More than 45° W and SW	None	SE façade 45° horizon angle
Vegetation in building elements or near buildings	Near - in the patio	Near - N	Near and covering the greenh. in summer	Near	Near	In a platform basis	Near	Near	Near - N and W	Near and in the green roof	Near	Near - in the patio
Buffer spaces	Semi-enclosed openspace	Shaded terrace S façade	Patios	Narrow void space E oriented	Sunspace +balcony	Balcony	2 loggias entrance + 4 patios	Terrace	Loggia entrance	Patios	Terraces	Internal courtyard
Others innovation daylight/ventilation	Pattern fix/openab glazing	Skylight; door heads without glazing	Clerestory	Chimney stack and lantern lights	Ventilation through the sunspace	None	Diffused light through patios	Transp. bricks in slabs	Mezzanine living room S	None	Clerestory	Skylight above the common staircase
Indirect gains	None	Trombe wall A= 7.5m ² .+ water columns	Trombe wall SE A=3.5 m ²	None	None	Trombe walls S	None	Thermal storage wall S A=37 m ²	None	None	None	None
Isolated gains	None	None	Greenh. SE	None	Sunspace SW	None	None	Greenh. for heating air pipes	None	None	None	None
Auxiliary systems												
Heating	No data	Fireplace	Fireplace	No data	None	Central solar water heating - natural gas boiler	No data	Earth tube heating associated to a greenh.	Fireplace	None	Central heating with a boiler with diesel	None
Cooling	No data	None	None	No data	None	None	No data	Earth tubes	None	None	None	None
DHW	No data	Solar panels	Recovery system heat firepl+ Solar pan.	No data	Solar panels	The same system used for heating	No data	None	None	None	Solar panels	None

**1. House Beires, Siza, Póvoa do Varzim
(Cianchetta and Molteni 2004)**

This house is also known as the 'bomb' house as it results from the explosion of one of its edges. The aim of this fragmentation was energy oriented as it increases the SW exposed area. The slice gives place to a patio-garden with vegetation that shadows SW facing windows during summer. The glazing area is mainly oriented towards SW. Vertical sliding movement of some windows is alternated with other fully openable windows. Interior light curtains protect it from solar radiation. This glazing area opened to a balcony retrieves the fully S glazed balconies of vernacular Architecture of the north of the country.

2. CTO, Carlos Araújo, Santiago Boissel, Eduardo Oliveira Fernandes, Rafael Ribas, Porto (Fernandes and Maldonado 1987) (Gonçalves, Oliveira et al. 1998)

The thermal optimized house is located in Porto and resulted from a research project in thermal comfort of residential buildings.

This massive two storey house combines traditional Portuguese constructive methods with passive solar technologies as a Trombe wall and water wall systems. Low temperatures fluctuation indoors is a result of a holistic strategy of energy conservation measures, such as orientation towards S, exterior thermal insulation, double glazing, window sizing according to orientation and exterior shading devices. Internal mass for heat storage and later diffusion are accomplished through the following solutions:

- The floor of the ground floor is massive with ceramic finishing and exposed to a high area of S glazing;
 - In the first floor a Trombe wall per room faces S;
 - Six water cylinders black painted (low coefficient of solar radiation absorption) are placed directly behind the larger glazing surface in the ground floor;
 - Interior walls are thicker than the usual and one of these walls integrates the firewood channel;
- Interior temperatures of the house were measured by a research team that occupied the house during the working hours.

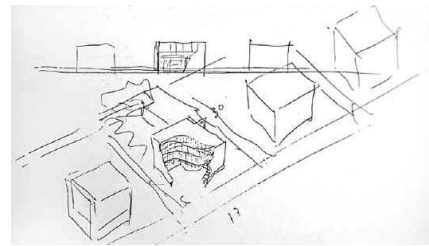


Figure 14 Beires House. Sketch (Cianchetta and Molteni 2004)



Figure 15 Beires House. Street view (Cianchetta and Molteni 2004)

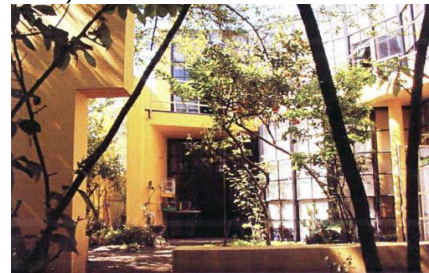


Figure 16 Beires House. Patio-garden (Cianchetta and Molteni 2004)

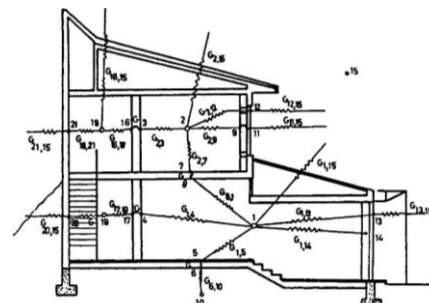


Figure 17 CTO. Thermal network of the Porto solar house (Balcomb 1984)

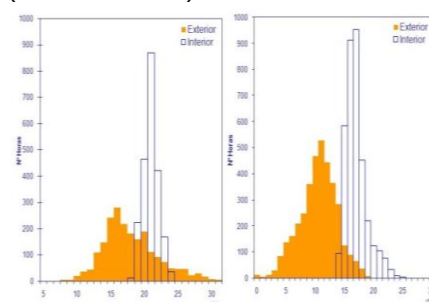


Figure 18 CTO. Cumulative temperature distribution in winter and in summer (Fernandes 1987)

Figures 18 - 20 show temperatures measured within CTO.

The figure 18 shows the accumulated frequency temperature distribution indoors (white) and outdoors (yellow) in summer and in winter, in free-float mode. The distribution confirms that interior temperatures were on average much higher than outdoor temperatures.

The figure 19 presents the thermal behavior of CTO in winter under thermostatic control and shows temperatures in a south oriented space and in a north oriented space. It also shows that during the day, temperatures higher than 18°C in the south oriented space are verified due to free solar gains. The figure 20 shows that auxiliary heating is almost not needed in the colder months of the year.

3. House Vale do Rosal, Fausto Simões, Almada (Simões 1986) (Gonçalves, Oliveira et al. 1998)

The main passive strategies of this house are the unvented trombe wall, the greenhouse and massive elements carefully chosen for increasing the thermal mass in strategic places. The trombe wall has 40 cm of thickness. Its simple glazing traps solar gains and also the heat of the fireplace, which is in the same structural line. The attached greenhouse in the entrance is shaded in the summer by a deciduous vine. Glazing surfaces are mainly SE oriented. Clerestories provide daylight to some compartments of the house, namely the kitchen that needs controlled daylight. There are some windows, namely in bedrooms, with single glazing but with tight insulating inside shutters. The exterior walls are constituted by double brick with thermal insulation in the middle layer. The sunspace inner walls, the fireplace back wall, the trombe wall and another wall in the kitchen are massive. The floor to ceiling height is higher in the living room and in the kitchen than in remaining spaces. The house has no auxiliary systems with exception of the fireplace in the center of the house that provides the auxiliary energy of nearly 2500 kWh for heating (Simões 1986). The fireplace has a device that recovers firewood energy to heat domestic water notwithstanding the use of solar collectors.

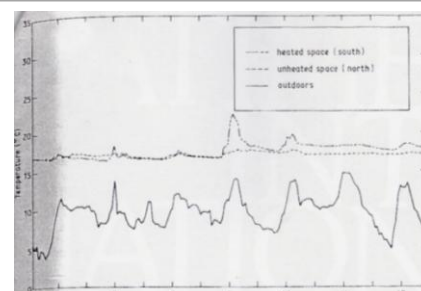


Figure 19 CTO. Thermal behavior in winter under thermostatic control. January 1986 (Maldonado, Fernandes et al. 1987)

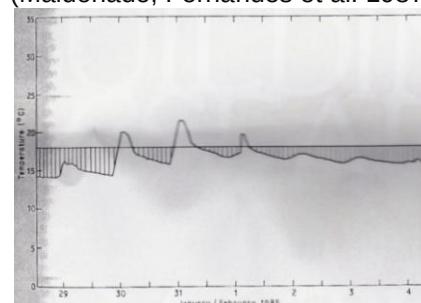


Figure 20 CTO. Calculation of auxiliary energy in free-floating mode. January-February 1986 (Maldonado, Fernandes et al. 1987)

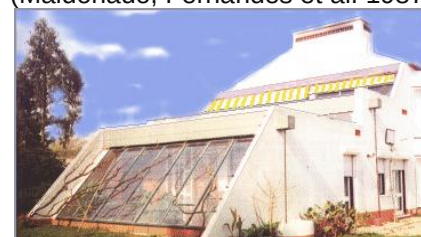


Figure 21 Vale do Rosal. SE view - winter (Simões 2007)



Figure 22 Vale do Rosal. SE view - summer (Simões 2007)

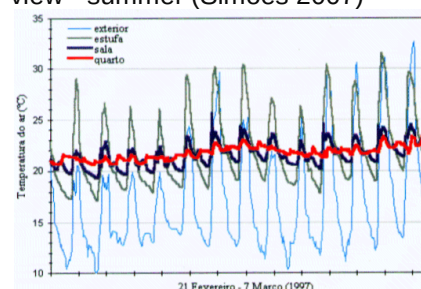


Figure 23 Vale do Rosal. Interior temperatures during 21 February-7 March 1997 (Simões 2007)

The monitoring conducted in 1996-1997 showed that during 21 February-7 March the variation of temperatures was very low (bedroom and living room) inside the thermal comfort zone, while high temperatures variation occurred in the exterior, most of the time outside the comfort zone – figure 23.

4. House in Moledo, Souto de Moura, Caminha

This house is embedded in a slope and its main façade is turned to W, as it is integrated in a landscape of slopes and the view to the sea is W oriented. The E part is fully glazed and a narrow space separates it from an irregular wall of rocks. In the interior, a corridor is turned to this fully glazed façade. The N and S walls are in contact with the earth. These double stone walls were insulated with 4 cm in the middle layer. Above it is displayed a flat roof with exterior thermal insulation. The W façade is fully glazed with sliding glass and shaded by a horizontal overhang that is an extension of the roof.

5. Multifamily house, Tombazis, Vila do Conde. Prize PLEA1988 (Gonçalves, Oliveira et al. 1998) (Fernandes, Moita et al. 1988)

This building won the contest sponsored by PLEA 88, an international design competition for multifamily housing with controlled costs. The main façade is SW oriented and the access stairs are NE oriented. Floors are massive and the exterior building components have exterior thermal insulation. Besides this, the building has a second façade, allowing the creation of a middle void space for natural ventilation. The glazing of the sunspace is simple and shaded by a wooden pergola; other glazing surfaces are double and protected with exterior shutters. The roof has solar panels as well as a common covered and naturally ventilated laundry. The building does not have cooling systems and almost does not require additional energy for heating, only 2382 kWh. The temperature fluctuation indoors is 3.5°C (Fernandes, Moita et al. 1988).

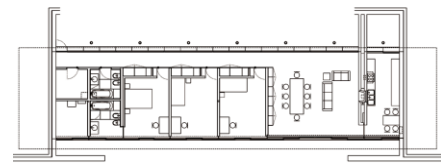


Figure 24 House in Moledo. Floor plan (Corrêa 2011)

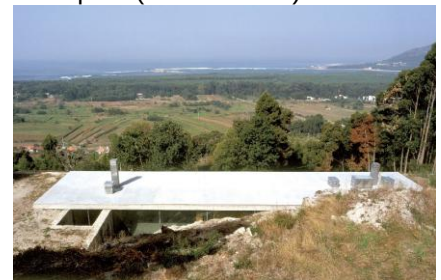


Figure 25 House in Moledo. Site integration (Corrêa 2011)



Figure 26 House in Moledo. East façade (Corrêa 2011)



Figure 27 Multifamily house in Vila do Conde. Southwest façade (Roulet, Cox et al. 2005)



Figure 28 Multifamily house in Vila do Conde. Northeast façade (Coelho 2007)

6. *Green tower, Livia Tirone, Lisboa (Gonçalves, Oliveira et al. 1998) (TironeNunes) (Roulet, Cox et al. 2005)*

The Green tower is one of the passive solar buildings that are integrated in the energy strategy defined at the level of urban planning of EXPO site in Lisbon. The urban plan for this zone defined that buildings should follow privileged orientation towards south and determined the nonexistence of projected shadows. The building has exterior thermal insulation, double glazing and movable blinds. A green area is defined in the basis of the building and a common terrace is located in the roof. All apartments have their main spaces S oriented. For cooling, the building relies only on natural ventilation strategies, including crossed ventilation. Mechanical ventilation is used in bathrooms and in kitchens for IAQ. The auxiliary energy system installed for heating and DHW is a central solar water heating system with a natural gas boiler for both hot water and heating. Seven years after the occupation of the building, about half of the apartments did not connect to the central heating system pre-installed in the apartments (Roulet, Cox et al. 2005).

7. *Elemental House, Aires Mateus, Grândola (Cecilia and Levene 2011)*

When regarded from the exterior and with closed shutters, this house has the appearance of a cube. In fact, this strategy can be regarded as an interpretation of vernacular Architecture in Alentejo. Given the intensity of the solar radiation and high temperatures variation, houses in Alentejo have a massive construction and small windows. The elemental house presents two sliding wooden doors or heavy panels. When the panels of the entrance loggias are opened, this monolithic structure opens almost totally to the exterior; when it's closed the house is opened to its interior patios. The central sequence of courtyard spaces brings additional light into the very deep (14 m) ground plan. Patios increase the area of the building that is possible to ventilate and daylight naturally.



Figure 29 Green Tower. South façade (Tirone Nunes 2013)



Figure 30 Green Tower. Site integration (Roulet, Cox et al. 2005)



Figure 31 Elemental House. Floor plan (Cecilia and Levene 2011)



Figure 32 Elemental House. Entrance (Cecilia and Levene 2011)

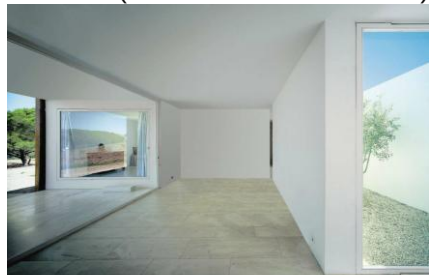


Figure 33 Elemental House. Interior space (Cecilia and Levene 2011)

8. *Casa Oásis, Cândido de Sousa e António Santos, Faro (Nascimento and Gonçalves 2005)*

The House Oásis has two levels and it is located in the south of Portugal in an isolated rural area.

The house is integrated in a slope towards S and the N part is buried taking benefit from the contact with the temperature and the mass of the earth. Additionally the house takes advantage of the temperature of the earth through buried pipes for heating and cooling. During the winter, the buried pipe outlet is inside a closed greenhouse where the air is hot. In the summer the greenhouse is disabled and opened for avoiding overheating.

A thermal storage wall facing S contributes to the relatively low temperatures in bedrooms during winter. In spite of glazing, polycarbonate surface was installed and the wall was not painted in the usual black color of thermal storage walls but in brown. Exterior shutters have thermal insulation of 3cm in its interior, providing more insulation to glazing especially during the winter. Massive interior elements - walls in concrete blocks, internal flowerpots and beds in concrete masonry with water storage - increase even more building thermal inertia. This building has no heating or cooling systems.

9. *Houses in Janas, João Santa Rita, Filipa Mourão, Sintra. Prize DGE 2003 (Nascimento and Gonçalves 2005)*

The strategy for the site integration of the building aims to protect it from dominant winds from NW, recurring to vegetation in the N and W. These three semi-detached houses in Janas take advantage of the S orientation by installing a considerable amount of glazing surface in the S façade. These openings are the key element of the building passive design strategy along with the inertial mass of the building. The shading strategy of the S façade relies on three different solutions – horizontal overhangs, internal wooden shutters and exterior light canvas that are activated during the summer.



Figure 34 Óasis House. East façade (Nascimento and Gonçalves 2005)



Figure 35 Óasis House. West façade (Nascimento and Gonçalves 2005)



Figure 36 Óasis House. Thermal storage wall (Nascimento and Gonçalves 2005)



Figure 37 Houses in Janas. South façade (Mourão and Santa Rita 2003)

Regarding heat losses, all the opaque exterior components of the building are insulated by the exterior. The thermal inertia of the building is heavy with massive walls separating the three detached houses and remaining interior walls in perforated brick with stucco. A fireplace in the living room assures the few heating needs during the winter. The building has no mechanical ventilation neither other systems for cooling. Regarding thermal comfort, occupants from two houses (west and central) have shown their satisfaction. None of users recurred to any type of auxiliary heating during the first year of occupation neither to any type of auxiliary cooling system.

10. House Utopia, Atelier Utopia, Provesende, Sabrosa

This house is integrated in a vineyard slope in the region of Douro classified as World heritage by UNESCO. The contact with the earth allows a delay of the heat transfer. All rooms are oriented towards S, also allowing the view both to the valley and to the river. Fenestrations are small, with exception of the ones in the kitchen and in the hall that connect to the two interior courtyards. A local construction material, the shale, is used for the walls and the floor. The roof is covered with earth and grass. Auxiliary systems for heating and for cooling were not needed considering the low variation of temperatures indoors.

11. House in Beja, Bartolomeu Costa Cabral, Beja (Cabral 2009)

In the south region of Portugal the earth was the most used material of construction until around 1950. This recent building near Beja uses rammed earth, which comes from the dig. The thermal quality of the earth is recognized and its U-value is around $0.7\text{--}1.4\text{ W/m}^2\cdot^\circ\text{C}$ (Simões 2006). The structure of the building, including the roof slab, is built in concrete. The thermal control of the roof is assured by a water mirror of 5cm with a pane protection. A system with a fan is used for increasing the process of water evaporation during the summer for cooling. During the winter this void space is closed in order that the thermal insulation of the pane contributes to less heat losses.



Figure 38 Houses in Janas. North façade (Mourão and Santa Rita 2003)



Figure 39 House in Provesende. Green roof (Ramos 2007)



Figure 40 House in Provesende. Southwest façade (Ramos 2007)



Figure 41 House in Provesende. Interior patio (Ramos 2007)



Figure 42 House in Beja. Exterior view (Cabral 2009)

Glazing surfaces are protected through horizontal overhangs and clerestories bring light into the living room through the top part of the wall. The building has its own water through a water well, photovoltaic panels for electricity, solar panels for DHW, septic tank for sewage and central heating boiler with diesel. It also has a cistern to collect rainwater for the irrigation network and for store it.

12. House Lóios, Floret Arquitectura, Porto (Floret)

The building Lóios is located in the historical core of Porto, classified by UNESCO as World heritage. The ground floor allocates services and the three upper floors have residential functions. The 1st and 2nd floor have two T0 (openspace) with 61m² and the 3rd floor a T1+1 (two rooms) with 111m².

The building with an L shape is integrated in a city block and only two of its façades have contact with the exterior. The backyard façade is turned to an interior patio oriented towards NE and the main façade is turned to SE. The distance to the three storey building in front is around 7 meters, which corresponds to the street width and the horizontal angle of obstruction of 1st floor windows is around 45°.

This architectural building design is a retrofit. A structural evaluation was performed before the intervention proposal. For heritage reasons the main façade is turned to the street, and could not be intervened. So the building design did not integrate exterior thermal insulation in this wall. Thermal insulation was installed by the exterior in the roof, in the backyard façade, in party walls and in the space between intermediate slabs and false ceilings.

The existent simple glazing was replaced by double glazing and the skylight above the staircases was maintained. This element is essential as the passive zone of the house, which is the zone in contact with the exterior, is reduced.



Figure 43 House in Beja. Interior view (Cabral 2009)

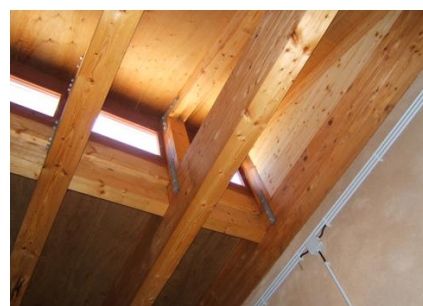


Figure 44 House in Beja. Clerestory (Cabral 2009)



Figure 45 House Lóios. Main façade (Floret 2011)



Figure 46 House Lóios. Internal courtyard (Floret 2011)

3.4 Progress on thermal assessment design tools and their integration in the architectural building design

3.4.1 Characteristics and specificities of the architectural building design

The first part of the literature review was focused on the review of the literature of buildings for temperate climates in order to find critical inputs for architectural design and their interconnection. Complementarily, the analysis of passive solar houses in Portugal recognized by the scientific community and also other residential buildings 'climate responsive' allowed to better address the identification of particularly advantageous solutions for temperate climates in terms of thermal comfort. The analysis of building cases also allowed understanding that not choosing building azimuths that favor useful solar gains can tragically compromise the building thermal behavior. In fact, analysis of the design of buildings already built provide a better understanding of how site constraints drive the design process and limit the extension of action of the thermal assessment.

Broadly, design tools for thermal assessment in Architecture disregard the main characteristics and specificities of the design process and most users of design tools lack expertise in thermal issues. These seem to be the main reasons why most thermal assessment tools in architectural building design have a weak acceptability by their users.

The five paragraphs below present five considerations that allow the understanding of the architectural building design methodology and practice as it was taken in the context of this thesis.

1. For most design researchers, the definition of the design as a process encompasses three relevant issues: goals, constraints and sequence of actions (Alexander 1979) (Coyne and Gero 1986) (Coyne 1990) (Cross 2006). The definition of design by Gero makes comprehensive what is at stake in the design process: 'Design activity can be characterized as a goal-oriented, constrained, decision-making, exploration, and learning activity that operates within a context that depends on the designer's perception of the context '(Gero 1990).

2. As it was already referred, an order of priority should precede the sequence in the decision-making (Alexander 1979) (Yezioro and Shaviv 1996) (Ellis and Mathews 2002). Christopher Alexander exhaustively studied the design process stating that it is 'a system of simple rules not complicated, patiently applied that gradually give origin to the design'. 'The sequence of the patterns for a design - as generated by the language - is therefore the key to that design'. The creation of coherent objects depends on the use of an order, the correct order. However, the author warns: 'You cannot create a design until you understand which features are dominant and which ones secondary' (Alexander 1979).

3. Considering the whole building design process, there is a consensus among researchers about the need of integrating elements that influence buildings thermal performance in the very beginning of the design process, in the Conceptual Design, with an architect-friendly language and anticipating the energy issues integration in the design (Balcomb, Barley et al. 1980) (Torcellini, Pless et al. 2005) (Yezioro 2009) (Kanters 2011). Four stages are overall considered in the architectural building design process. The first one, the Base Program, corresponds to the identification of constraints and allows the elimination of design options that are not possible for a specific building design, leading to the production of more realistic design alternatives (Panão, Gonçalves et al. 2008) (Yezioro 2009) (Cavieres, Gentry et al. 2011). Conceptual Design consists in the definition of the main decisions regarding spaces configuration and building elements materials and geometry. Formal design is the phase of communication of the main decisions and in which these can be fine-tuned. Detail design is the phase of detailing building components and in this phase no changes can be made on the main decisions.

4. The new paradigm for future tools are design tools that can help design teams to answer quantitative questions quickly, early in the conceptual design (Donn, Selkowitz et al. 2009). Usually, at early design stages, only conceptual sketches and schemas are available, often rough and incomplete. Still at early stages of design most important decisions have to be taken. Donn *et al* (2009) proposed 'the access to the power of simulation tools, at a stage in design when little is known about the final building, but at a stage also when the freedom to explore options is greatest', through the 'building performance sketch'. Design team needs tools that analyze specific ideas and issues. In fact, the study of design alternatives in Architecture is quite different from the study of alternatives in Physics and Engineering. While engineers and physicists want to

simulate several scenarios in a perspective of optimization, Architecture as a synthesis need to provide answers for specific dilemmas that appear frequently during the development of their building design (Venâncio, Pedrini et al. 2012).

5. Finally, black-box tools seem not adequate for thermal assessment because do not allow design professionals to learn with their use. The task 41 - IEA survey showed that Architects lack of Physics knowledge (Kanters 2011). Gagne and Andersen (2012) research aimed to understand how users would react to the use of an expert system that guides them through explanations during the design process. It was found that this type of tools not only enhances users' decision-making, but even develops their intuition (Gagne and Andersen 2012).

3.4.2 Tools to assess and to support design of low energy buildings – barriers, needs and opportunities

During the third International Congress on Building Energy Management (ICBEM) in Lausanne, requirements of tools for Architecture assessment were summarized in the following points (Barakat 1987):

1. The design tool should be user-friendly and easy to use
2. Input formats must be user oriented, with building materials language, rather than thermal properties
3. Solutions must be obtained quickly, in minutes rather than hours. This is more important than the accuracy of the tool
4. It should be able to handle alternatives 'what if' readily.

Recently, the IEA-SHC Task 41 international survey, already referred in Chapter 2, questioned architects how the integration of solar energy technologies was handled in the design process. Most of the respondents said that handled it by themselves. When questioned about the methods used in the design process 21% were marked as experiences, 17% as interactions with the owner, 12% use of design guidelines, 9% with computer simulation, and 6% answered 'rules of thumb'. This survey also aimed to identify needs related to methods to support the integration of solar systems. Results showed that most architects require simple and systematic methods to use in earlier design phases – improved tools for preliminary sizing of solar energy systems and for providing key data about solar energy (Kanters 2011).

Table 6 considers five types of tools for thermal assessment - steady state calculations, simulations, design guidelines/rules of thumb, graphical tools as shadow masks and nomograms, knowledge based systems (KBS)/expert systems (ES).

Tools that do not match all desirable requirements for design tools in Architecture are simulation codes being complex and time consuming. These require too many inputs not available in conceptual design and users' expertise for output analysis. What really happens in simulation is that it treats each building design process as a new problematic task and most buildings are answers to problems and needs that are not significantly different from the problems and needs that both contemporary and earlier buildings have already solved. There are some building design problems that are entirely new, 'that need to be solved in creative or inspirational ways but design of the bulk of building types, while still benefiting from creative thought, benefits most from accumulated knowledge and experience' (Lutton 1995). Besides this, the accuracy of simulation is not needed for early phases of the building design.

Table 6 Characteristics of different types of tools for the thermal assessment in building design taking into account users' background in Architecture

Type of tool and characteristics	Complexity	Time/easiness	Accuracy	Number of inputs	Outputs analysis
Steady state calculations	Complex	Time consuming and difficult to use	Some accuracy	Small - medium number of inputs	Outputs analysis does not require users expertise
Design guidelines/ rules of thumb	Straightforward	Easy to use	Some accuracy	No inputs	Outputs are straightforward
Simulation	Very complex	Time consuming and difficult to use	Very accurate and complete	Detailed description	Outputs for detailed analysis, but that require users expertise
Graphical tools as shadow masks and nomograms	Straightforward	Moderate time and easy to use	Some accuracy	Small number of inputs	Outputs are easy to analyze, but very focused on a specific issue
KBS/ES	Straightforward	Quick analysis, user friendly and easy to use	Some accuracy	Small number of inputs	Outputs are simple yet informative and easy to analyze

Steady state calculations are also complex and their application needs time as most users do not know how to apply them. Most straightforward methods are design guidelines/rules of thumb, graphical tools/nomograms and KBS/ES, with a small number of inputs appropriate for early phases of building design. Moreover, outputs are easy to analyze. A KBS is a computer program that uses a knowledge base and heuristic rules to solve complex problems. The boundary between a KBS and an ES is very thin. ES are KBS, but KBS are only ES if expert-level solutions are provided.

In this sense regarding building design framework and Architecture requirements, expert systems (ES) that store nomograms, rules of thumb and recommendations appear as a very feasible alternative for thermal assessment. The importance of a knowledge-base for a better project control was recommended by many researchers that suggest the opportunity of using results from parametric studies, rules of thumb and examples of existent cases in order to store them in a useful tool (Arain and Pheng 2006) (Gagne and Andersen 2012).

Accordingly, six tools considered as user-friendly are approached below.

1. *Energy Signature*

Balcomb introduced the concept of ‘energy signatures’ and gave the same name to the proposed method for aiding a designer in selecting and sizing passive solar elements of a building (Balcomb 1986). Figure 47 presents a nomogram representing the ‘energy signatures’ of direct gain, sunspace and Trombe wall choices in a room in which temperature are held almost constant. The following quotes of Balcomb allow for a better understanding of ‘energy signatures’:

An Energy Signature is an hourly profile of heat flux into or out of a space due to a particular component such a window, Trombe wall or sunspace.

Hourly heat flux profiles for each candidate design element are determined. These profiles are then matched to the hourly energy requirement of the space accounting for weather conditions, internal heat profiles of the space and the mass characteristics of the building. (Balcomb 1986)

Requirements and less treated elements: This method requires detailed simulation for results generation. The information from the literature showed that this method was in process of development. A longer range goal of the research was also to use the

method to help designers in determining other choices as orientation. No information was found regarding the method advance or application.

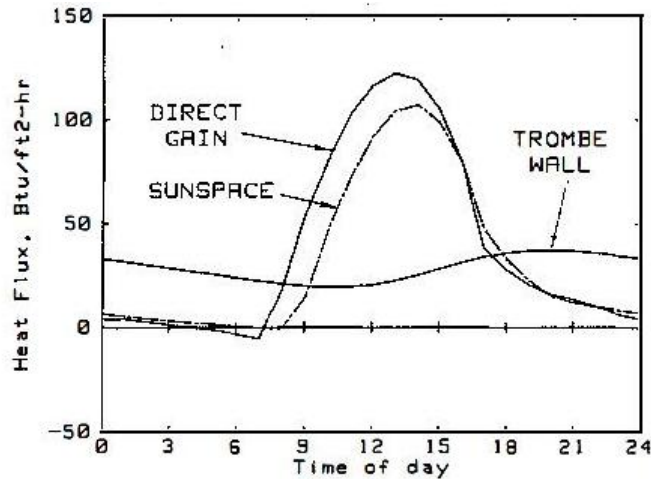


Figure 47 'Energy signatures' - direct gain, sunspace and trombe wall (Balcomb 1986)

2. LT Method

The LT Method has been developed by Baker and Steemers in the Martin Centre for Architectural and Urban studies, University of Cambridge. One of the first applications of the method occurred in the European Architecture Contest 'Working in the city' (O'Toole and Lewis 1990). At the time it represented a relevant advance in the comfort assessment of the architectural building design, namely by the different treatment of the passive zone and the non-passive zone of the building. The former LT method was a manual tool for the calculation of energy consumption in nonresidential buildings. Later on, studies have been developed for residential buildings.

The energy performance data in buildings is produced by a mathematical model, which attributes reference values for most parameters. Only a small number of parameters can be changed by the user, including the size and type of glazing surfaces and type of shading devices (Baker and Steemers 2000). Thermal curves for different climates are given by the method in order to help architects in choosing the glazing ratio. Outputs of heating, cooling and lighting loads are represented in the same graphic (Baker and Hoch 1988). More recently, Baker, Guedes and other researchers developed a LT method software for Portugal but it requires a sketch of the building (Baker, Guedes et al. 2013).

Requirements and less treated elements: The method focuses on glazing surfaces that constitute one of the most important elements for both the architectural language and

thermal comfort in buildings. It would be desirable to draw the LT curves also in function of the thermal inertia and of the thermal conductance.

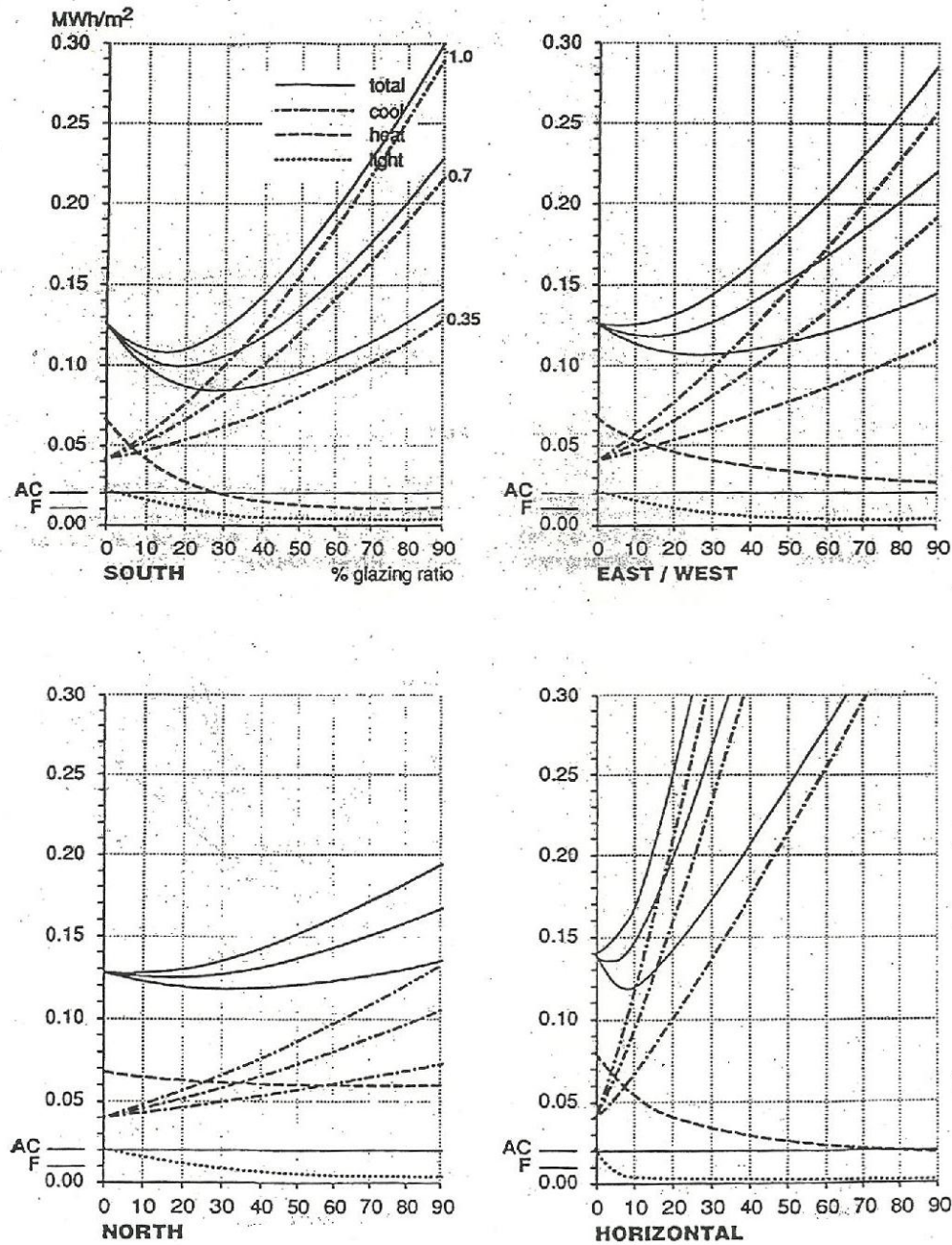


Figure 48 LT curves for residential buildings in South Europe (Baker and Steemers 1990)

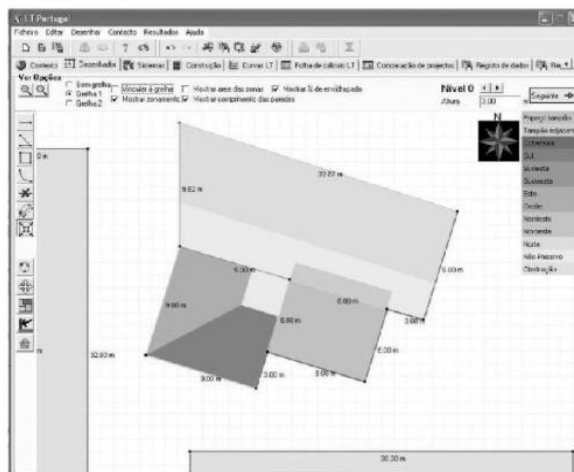


Figure 49 User interface of the LT software for Portugal (Baker, Guedes et al. 2013)

3. Expert system based on RCCTE 1990

This expert system that assesses the application and verification of RCCTE 1990 has been developed in 1999 by the architect Mariz Graça in the academic context. It has been written in Prolog and incorporates the algorithms of RCCTE method and a set of heuristic rules. The expert system also integrates a search mechanism that allows to find constructive solutions that complies with RCCTE, to a given geometry, materials and orientation of the building (Graça 1999). The inputs are the building occupation, the inertia, the geometry, the glazing ratio and orientation and the roof type and colour; and the outputs are the U-values and solutions for shading.

Requirements and less treated elements: The method is very restricted to the Regulation, because the aim is to ensure the satisfaction of its requirements. Explanations are not addressed during the assessment, i.e. the software asks the inertia of the space without giving any explanation of how to calculate it.

Orientação	Área da Parede	Área do Envidr.
Norte	48.75	26.25
Sul	56.25	18.75
Este	68.25	6.75
Oeste	66	9
Cobertura	Área Cobert.	Ár. Vid Hor.
Horizontal	132.8125	23.4375

Figure 50 User interface of the expert system developed by Graça (Graça 1999)

4. Climate Consultant

The method has been developed by the Architecture and Urban Design Department of Los Angeles (UCLA). The software stores an extensive list of weather data from different locations and different options of comfort models – California Energy Code Comfort Model 2008, ASHRAE Handbook of Fundamentals Comfort Model 2005, Adaptive Comfort Model ASHRAE 55-2004. The design of a building model is not needed. Climate choices and the comfort model generate graphics with data related to climate/comfort, namely psychometric charts and sun path diagrams. A list of design guidelines with graphical explanations for the building adaptation to a given climate is organized with an order or priority. It also presents an indication of the time percentage in which thermal comfort occurs (within the selected comfort mode).

Requirements and less treated elements: The method requires climatic data in EPW format and a familiarity of the user with psychometric charts and other several types of charts. Characteristics of opaque envelope are less treated.

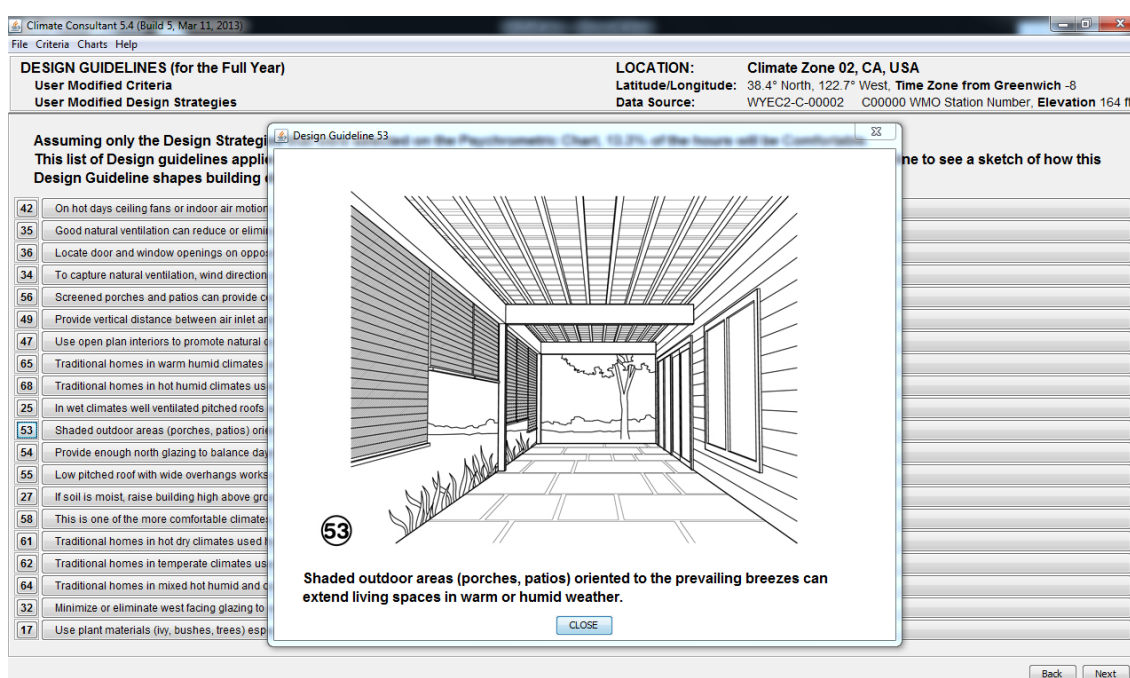


Figure 51 Climate consultant user interface – design guidelines

5. Archisun

Archisun has been developed by the Polytechnic University of Catalunya. It has been an outcome of the research of the Bioclimatic Design Manual, driven by Rafael Serra (Serra 1989). The software requires ability of abstraction for inputs introduction. The model is not represented by an exact geometry, being instead characterized by interior

parameters and skin parameters – for instance – compactness, porosity, mass and color. The language is user-friendly and the tool emphasizes the graphical approach not only in the data introduction but also in the result visualization (Ganem and Coch 2004) (Palme 2010).

Requirements and less treated elements: the software requires the introduction of too many parameters, without distinguishing those parameters that are determinant for the building thermal behavior and those that are less relevant.

6. MIT Design Advisor

The software is the result of a research project of Cambridge-MIT Institute. It provides a fast, simple tool for architects and building designers to assist in the decision making process during the first stages of design and to compare different alternative scenarios. The type of space is chosen by the user that has the following options: one zone confined to a single side of the building, four-sided building with well mixed air, or four-sided building with air unmixed between zones adjacent to each façade. Results are presented in graphics with the indication of energy consumption, thermal comfort, regulation compliance and daylighting design (Urban and Glicksman 2006).

Requirements and less treated elements: An order of priority is not considered neither explanations of the limits and the consequences of users' choices. Outputs are not easy to analyze.

3.4.3 Structure of ES oriented for assessment of architectural building design

Expert systems (ES) are a branch of applied artificial intelligence (AI) developed by the AI community in the mid-1960s (Liao 2005). ES are based on the extraction of experts' knowledge that later on is stored in a computerized system, in the form of rules, in order to make knowledge available to users. In this sense, we can expect a nearly expert-level performance by the user who follows the experts' advices and procedures which are stored in ES.

ES capture and deliver knowledge, not just information – 'Suggestions from past cases often help architects elaborate design problems, propose and refine solutions, critique and modify proposed designs and justify their choices' (Pearce, Corp. et al. 1992). In the case of building design, saving time in design decisions is another significant opportunity of ES (Lutton 1995). ES have been used in all scientific fields, but the ones that need the capture of problems that cannot be cast strictly in terms of numbers and

algorithms, such as Design, constitute fields that can more benefit from their application (Bédard 2003). Besides this, ES do not make decisions for users, but rather provides pertinent information in an easy-to-access format that allows users making well-informed final decisions (Arain and Pheng 2006).

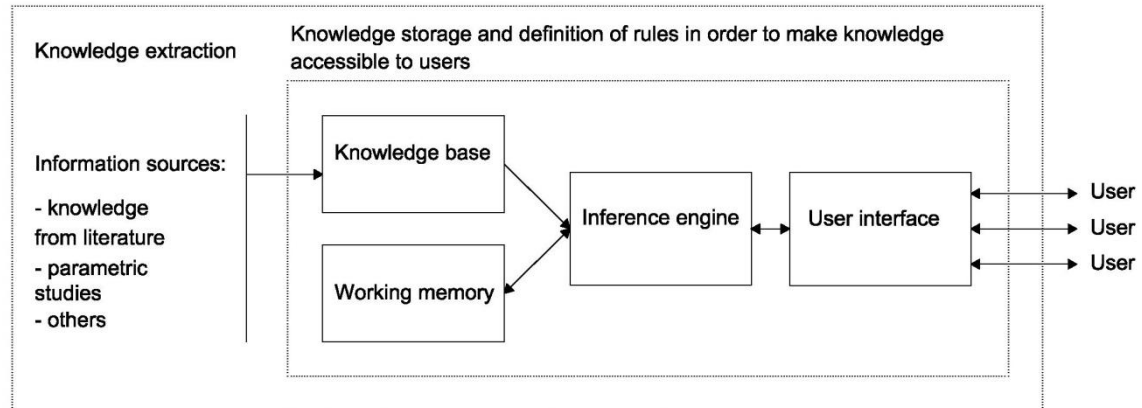


Figure 52 Structure of ES. Adapted from Arain and Pheng (2006)

Eleven ES for building design assessment have been found (Coyne, Rosenman et al. 1987) (Fazio and Gowri1988) (Peuportier and Sommereux 1991) (Pearce, Corp. et al. 1992) (Lutton 1995) (Shaviv, Yezioro et al. 1996) (Graça 1999) (Reffat and Harkness 2001) (Alibaba and Özdeniz 2004) (Arain and Pheng 2006) (Gagne and Andersen 2012).

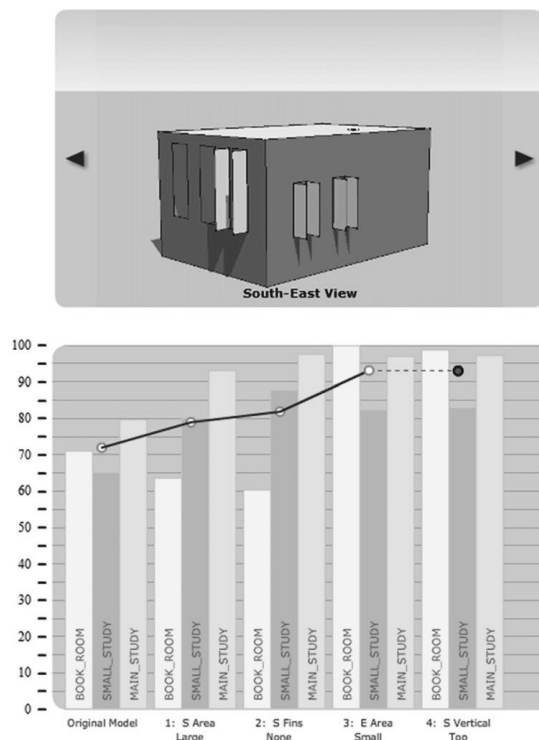


Figure 53 Lightsolve expert system user interface (Gagne and Andersen 2012)

Please enter a value between 1 - 100 for the importance of performance requirements of "EXTERNAL WALLS ". To eliminate a specific performance requirement enter a zero value.

Strength and stability	85
Raintightness	100
Airtightness	100
Fire resistance	70
Sound reduction	75
Sound absorption	50

Figure 54 User interface of an ES for the building elements selection (ES shell - 'Exsys Corvid') (Alibaba and Özdeniz 2004)

These ES belong to different scopes of building design. Interviews with experts and collection and filtration of data from simulation were the most frequent methods used for knowledge extraction. In some cases the developer of the ES is not an expert in computing and knowledge data must be introduced in the ES shell by a reasoning process. Both forward chaining and backward chaining are used. The number of rules differs, ranging from 100 to 629. Regarding this issue, a relevant consideration is made by Coyne *et al.* A system that has a large number of simple rules might be regarded as more innovative or creative than a system consisting of small number of rules which constitute large 'jumps' in reasoning (Coyne, Rosenman *et al.* 1987). Expert system shells used for application are diversified, but Exsys Corvid is the only shell that was found in more than one research.

KBS/ES which purpose is to assess building thermal performance in architectural building design were the ones developed by the following researchers: Peuportier and Sommereux (1991), Shaviv, Yezioro *et al* (1996) and Graça (1999).

1. Peuportier & Sommereux structured the analysis according to different physical values – thermal losses, solar aperture and thermal comfort. The building is divided into a set of zones, each one of them corresponding to a homogeneous thermal behavior. Regarding the structure of the software Comfie, a calculation tool is combined with a system of questions-answers and rules of the expert interface. Firstly, the needed inputs for calculating the building thermal balance are requested. Then the

thermal assessment is tackled according to different module indications. For instance for heat losses, the global UA value of the whole building is calculated as well as the UA value of each zone. The expert interface gives some advices according to results and can propose also to test other alternatives. For solar gains the concept effective UA is used. Effective UA is calculated according to the mean temperature difference (ΔT) over a heating season between the outside and the zone with south glazing (Peuportier and Sommereux 1991).

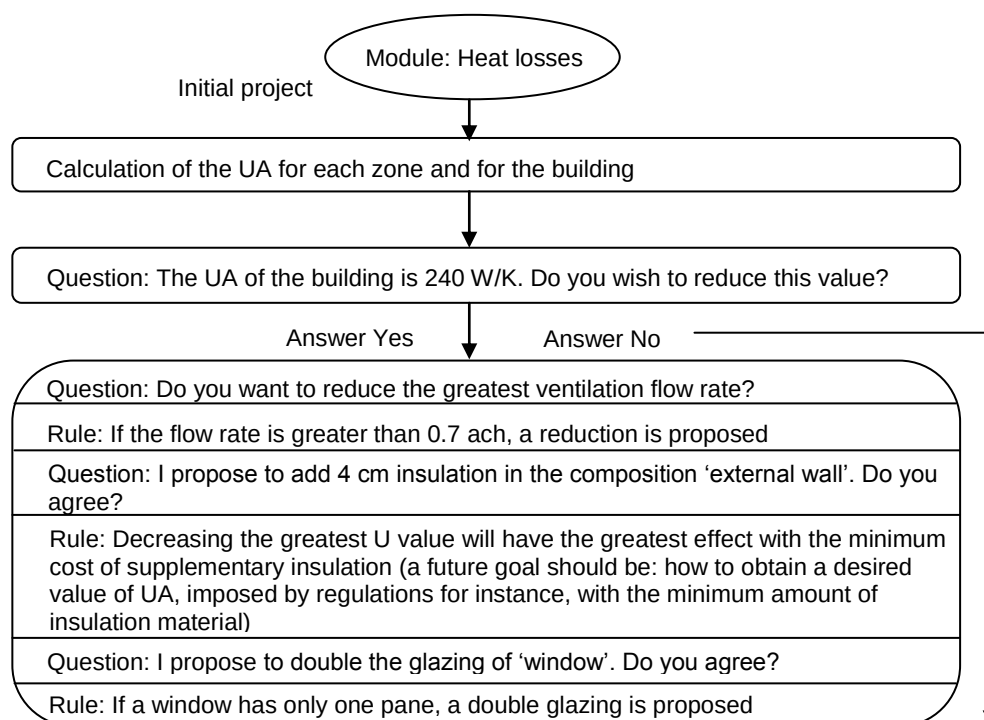


Figure 55 Comfie ES – heat losses module (Peuportier and Sommereux 1991)

2. Shaviv, Yezioro *et al* used simulation in order to find the influence of building design choices and how they interacted between them. Data related to building design parameters has been organized in three categories, being attributed an order of priority. According to these three categories, a KBS was developed and anchored on heuristics. For particular design situations in which heuristics and rules of thumb did not give satisfactory results, simulation could be performed by the system. Thus ENERGY software combines knowledge-based heuristic methods and procedural simulation in one integrated system aiming to guide the user during the building design process (Shaviv, Yezioro *et al*. 1996).

3. The expert system based on RCCTE was already approached in the last subchapter.

4 Methodology

The adopted methodological approach addresses the scope of this work, i.e., the identification of early critical inputs to support design that will satisfy the ultimate criteria – the comfort and health criteria – bearing in mind the climate under two perspectives – local and the respective impact on the design; and global and the energy pre-requisites to the design (Figure 2).

Figure 56 illustrates the whole context specifying from left to right:

- The design stages (base program, conceptual design, formal design and detailed design);
- The design parameters specifying a classification in four categories separating those who are absolutely critical for the design (A and B) from the complementary ones (C) and the consideration of those which represent unavoidable restrictions marked as site constraints (D);
- The physical values which quantification and arrangement leads to the values that express the health and comfort values (IAQ, thermal comfort, visual comfort and acoustic comfort), representing the final criteria (Figure 2). The final result will be a building that fulfils the purpose or function within all environmental conditions.

At the base program level, the site constraints are paramount on imposing eventual restrictions on the geometry, orientation of the façades, and access to the Sun, among others. Yet, at the level of the conceptual design there is a need to introduce the levels of thermal insulation and thermal inertia (both of category A) and the dimension of the openings as well as the presence and nature of the shading (both of category B).

Having in mind the scheme of Figure 56, the exercise will be to undertake in four steps a roadmap that can be identified and defined as follows:

1. To select the critical parameters;
2. To perform a thermal analysis that enables to characterize the performance of an architectural space and the influence of a critical input parameter regarding its interaction with the others;
3. To identify the relevant or critical aggregated parameters to assess or characterize relevant building thermal performance aspects and so to allow for some performance assessment;

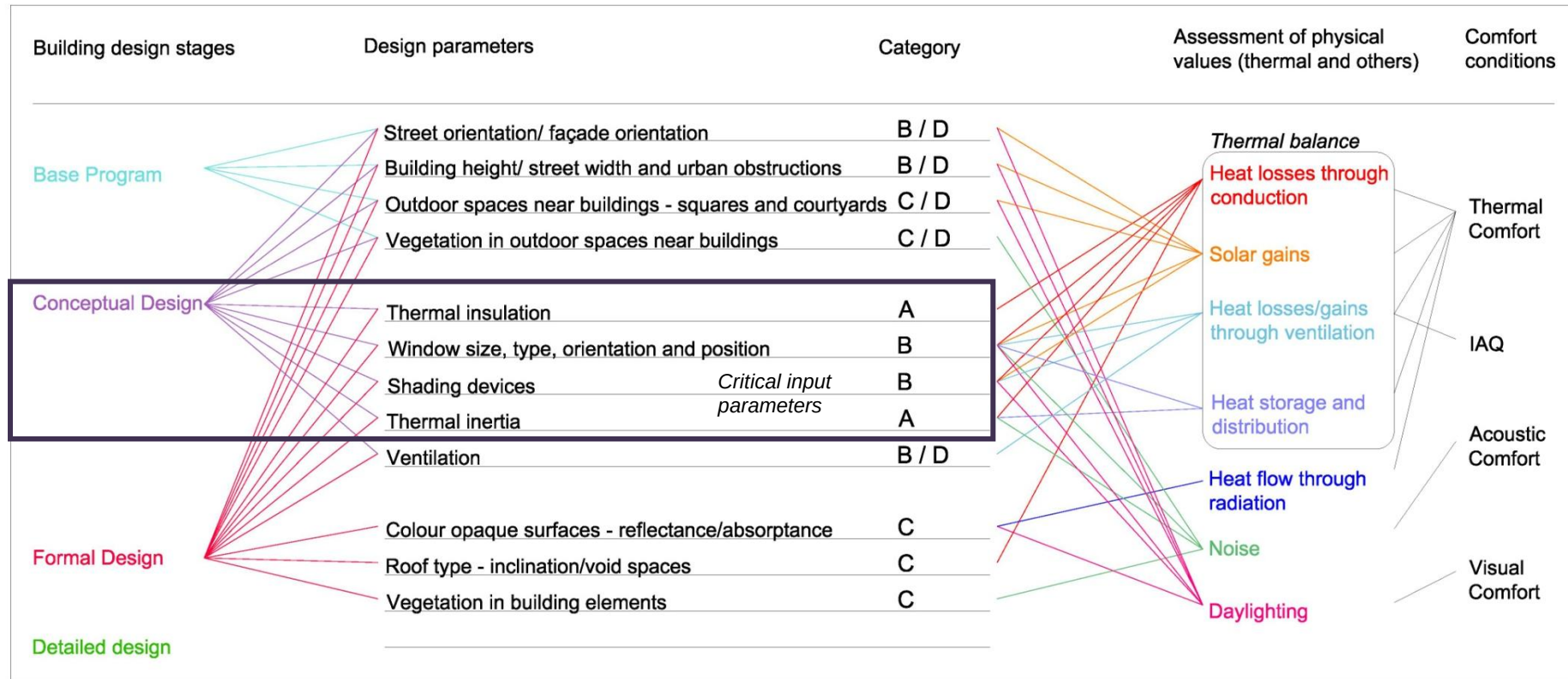
4. To elaborate a method and the respective accessible tool to be used in a very simple manner and at an earlier stage of the architecture design.

1. The selection of the critical parameters

From an exhaustive list of potential parameters that can be related to the thermal performance of a building, a selection of the relevant parameters is made and justified bearing in mind the balance equation and previous studies and results. The qualitative connection between the different architectural design stages and the relevant parameters for energy valorization is presented in Figure 56. During the architectural building design, architectural and construction choices are fine-tuned, being clear that correspondences are not univocal (Balcomb, Barley et al. 1980) (Achard, Baker et al. 1992).

The building design parameters can be identified with different categories taking into account the impact of their intervention in any building design. The relevance of design parameters depends also on the interaction between them. This is a relevant point leading to the need of setting a kind of order of priority of considering each parameter in the design phase meaning that an intervention in a parameter may reduce the impact of the intervention of another one. Shaviv and Peleg (1991) were pioneers in this approach. A sensitivity analysis was performed in order to establish relationships between design parameters, that end up with their categorization. This sensitivity study was performed in buildings in Jerusalem and in Tel Aviv which are two cities located along the Mediterranean Basin.

To summarize, the three categories of design parameters are: First, those for which default values can be specified by the knowledge base according to the specific climatic conditions and type of building. Only heuristic rules are used in this step (case-specific defaults). Second, those that have a significant influence on the energy consumption and are very sensitive to the other design parameters. These design parameters require a continuous guidance for their proper values. In this case heuristic rules are used with simulation analysis (combined case-specific defaults tested by simulation evaluation). And third, those that are free design parameters that can be arbitrarily specified, either by the system as defaults or by the designer (arbitrary design parameters). (Shaviv and Peleg 1991)



A – Reference values; B – Sensitive input parameters; C – Parameters of energy valorization; D – Site constraints

Figure 56 Categories of building design parameters and their connection with physical values

The categories considered in this study take into account the ones found by Shaviv and Peleg but add one more category considered here regarding the thermal assessment tool: the 'site constraints'. Thus, the building design parameters considered are distributed by four design categories which may be approached differently for each case in the practice of design.

A. Reference Values – Reference values should be assigned to parameters with a strong influence on the thermal performance of the building and which relevance is not dependent on other constructive choices. Two definite cases are the thermal insulation, essential for avoiding heat losses, and the thermal inertia, necessary for heat storage and diffusion. Advisable reference values are to be attributed according to climate requirements and building type.

B. Sensitive input parameters – In this category we have the windows parameters: orientation and position in the façades or in the roof, as well as the size and type. Besides windows, shading is also included in this category - shading devices and the flexibility regarding their use, namely allowing for being operable or not. Windows must be chosen and constantly fine-tuned according to the analysis of options regarding the inertia and thermal insulation. Moreover, even if it is considered that thermal inertia enters in category A, the distribution of interior mass must be regarded as a sensitive issue in direct gain systems. Good practices in buildings revealed the contribution of the interior massive elements for thermal storage and diffusion in compartments south oriented at the level of their influence on thermal comfort (Chapter 3 – Case studies of Architectural building design of residential buildings in Portugal).

C. Parameters of energy valorization – Color of opaque exterior components and vegetation in building elements and roof type can be chosen with entirely architectural freedom because they do not make a considerable difference in the building energy balance if proper reference values are attributed to thermal inertia and thermal insulation according to climate requirements and building type. However, they are relevant at the level of the microclimate and thermal comfort.

D. Site Constraints – Street orientation, the ratio building height to street width ratio, outdoor spaces and vegetation near buildings constitute almost always constraints of the site integration. Ventilation is not a site constraint, but it is highly

driven by site constraints and for that reason it is also considered within this category. Ventilation is highly dependent on the building location, i.e., on the circulation of the air outside the building, resulting not only from the wind direction, but also from obstacles of the surrounding urban forms. For being very often constraints and/or highly driven by site constraints these parameters constitute rigid components of the building design structure and the potential of their thermal assessment is quite reduced.

Building design choices must be focussed on the parameters from the categories A and B, excluding the ones that are driven by site constraints. These constitute the critical inputs for the building design. Additionally, the interaction between parameters from categories A and B can limit the extent of their relevance.

After the establishment of the different categories, physical values allows to link the main building design parameters with the actual most significant numbers that will be attached to them:

Table 7 Critical inputs – design parameters, physical values and indicators

Critical inputs		
Design parameters	Physical expressions	Indicators
Thermal insulation	Heat losses	Global thermal conductance per useful floor area $\Sigma UA/A_p$ [W/°C. m²]
Thermal inertia	Heat storage and distribution	Useful superficial mass per square meter [kg/m²]
Window size and window orientation	Solar gains	Glazing area to useful floor area [m²/m²] and orientation factor – useful solar gains
Shading devices	Solar gains control	Solar factor of windows [$g^\perp$]

On the right side of Figure 56 the physical values are listed, thermal or others, that will characterize the performance of architectural spaces. The overall scheme, read from right to left, illustrates how a ‘demand side approach’, expressed by requirements of thermal performance in terms of physical values can be tackled by relevant parameters.

2. The performance of the thermal analysis

The calculation tool used to perform the sensitivity study is based on the calculation method used by RCCTE 1990. As seen before, comparisons were established between results obtained through RCCTE and codes such as ESP-r (Leal, Ferreira et al. 2008) (Fernandes, Leal et al. 2009). Besides this, the RCCTE method has in fact two different versions (1990 and 2006). What can be said at this point is that the option for the RCCTE 1990 was, in the context of this thesis, to go back to the much genuine approach with the guaranty that results could, eventually in terms of more accuracy, be adjusted by using standard codes such as ESP-r. The targets here are the heating needs and cooling needs in case the passive conditions of the building can't assure the proper response regarding the indoor climate requirements. As inputs, different architectural and constructive alternatives are considered for the critical input parameters (A and B), while default values are attributed to parameters of energy valorization (C).

3. The identification of the critical aggregated parameters

Previous attempts such as 'Energy signatures' by D. Balcomb and 'LT curves' by N. Baker and K. Steemers performed the encapsulation of some design parameters and used them in graphics representing the influence of more than one relevant input design parameter.

Similar graphics will enable the study of the sensitivity of glazing surfaces, shaded or unshaded, taking into account a value of inertia and global thermal conductance that suit the climate of Portugal. The aggregation of all critical parameters, namely windows size, orientation, shading, global thermal conductance and thermal inertia will allow addressing three main issues:

- To know on what extent a specific constructive choice can influence a space thermal behavior both in the heating season and in the cooling season;
- To evaluate how the intervention in a critical parameter can influence other critical parameter;
- To take an informed and comparative decision regarding constructive and architectural choices without developing extensive thermal calculations.

4. The elaboration of a method and the respective accessible tool to be used at an earlier stage of the architecture design

It is strictly required to provide a user-friendly tool to users with no expertise in thermal issues. The tool thus intends that architects adopt their normal procedures, while having the possibility to consult a tool that provides an assessment both qualitative and quantitative: encompassing explanations regarding relevant issues, i.e. the relevance of thermal inertia; and a straightforward quantification of physical values, i.e. the thermal inertia category. The qualitative/quantitative aid will improve sensitivity and intuition of users during the process of decision making.

In order to use the results obtained in the thermal study of bullet 3, firstly decision trees are developed. The paths of decision trees determine possible options and desirable ways for more properly responses of buildings to improve thermal comfort conditions. The system appears to users as a sequence of questions, answers and indications of procedures. The sequence of questions will be driven by both constraints of site integration and of building physics. Decision trees are built in the form of questions - answers - recommendations (What-if-then) that will guide users in their design options.

Later on, these rules will be stored in the Exsys Corvid ES shell. In the Chapter 7 – ‘Guided methodology – decision trees used to build the Expert System’, the construction of rules embedded in Exsys for the construction of the expert system is explained. The thermal assessment tool performs indications of three types:

- qualitative, in the form of recommendations, taking as reference the findings from literature review;
- quantitative, in the form of graphics of thermal needs that encapsulate the critical parameters, taking as reference results from the parametric study;
- specific qualitative/quantitative assessment for thermal inertia, taking as reference a specific parametric study for spaces with different components mass.

An application case is performed in the subchapter 7.4.

5 Thermal analysis

A thermal analysis is performed in order to produce the agglomeration of critical inputs. Still, for critical inputs, choices that could clearly influence negatively the thermal behavior of architectural spaces in temperate climates are not considered, as weak thermal inertia, as well as glazing surfaces with more than 40% of ratio of glazing area to useful floor area.

The parametric thermal study should not be regarded as a precision model that produces accurate estimations for a given building thermal performance. It should be again underlined that accurate estimations are not useful during the conceptual phase of building design because a great distance remains between these estimations and the real building thermal performance. Rather, this type of thermal analysis aims at being used to evaluate the thermal performance of a number of alternatives and to establish comparisons, by creating a comparative framework.

The calculation method integrated in the RCCTE Regulation was used for the approach of sensitive climate buildings. The national regulation of 1990 is based on two index – the nominal heating needs (N_h) and the nominal cooling needs (N_c) of a building or independent zone of a building. These index represent the energy theoretically needed to provide heating and cooling, during a year, for a given building or part of a building, in order to compensate the heat losses (winter) or gains (summer), through its envelope, being it opaque or glazed, closed or with eventual or permanent openings on purpose or not. The criterion is to maintain a reference interior temperature of 15°C in the case of winter and 25°C in the case of summer. For winter, the setpoint of 15°C supposes that the internal heat gains due to the building occupancy provide 3°C.

Those temperature setpoints are the relevant thermal parameters for the evaluation of thermal comfort considered by the former RCCTE, more in line with the adaptive comfort model than later versions of the thermal regulation.

5.1 Climate zones

Despite being possible to consider the nine combinations of climate zones of winter and summer in Portugal, as it was previewed by the thermal regulation, this thermal study only analyzes design alternatives for four climate types represented by four cities:

- an extreme climate zone for winter in the north – Bragança;
- an extreme climate zone for summer in the south – Évora;
- a mild climate zone in the north – Porto;
- a mild climate zone in the south – Lisboa

5.2 Spaces geometry

Having in mind the desirable generalization of results, the space considered for the parametric study is a monozone architectural space with a glazing surface in only one of its exterior surfaces. Results of thermal performance of more abstract models seem more reliable for results extrapolation to buildings with different geometries. Thus, models of architectural spaces have a certain degree of abstraction and the geometry of spaces is defined by:

- alternative areas for exterior walls, roof and windows;
- reference values for useful floor area and floor to ceiling height

Table 8 Default values of spaces geometry

Dimensions	
Useful floor area	100 m ²
Floor to ceiling height	3 m

Figure 57 illustrates 16 architectural space types according to the level of contact of their envelope surfaces with the exterior. This leads to 16 types of architectural spaces. Regarding the proportions of architectural spaces, floor plans are considered to have the form of a square.

Alternative areas for exterior walls and roof are chosen taking into account different architectural types with the same useful floor area and floor to ceiling height. The calculated global thermal conductance values (ΣUA) takes into account that the ratio of the glazed area to the floor area is 10% and U-values attributed to walls and roofs are 0.6 and 0.4 W/m².°C respectively (Fig.57).

5.3 Alternatives for critical inputs parameters

5.3.1 Thermal conductance of opaque exterior components

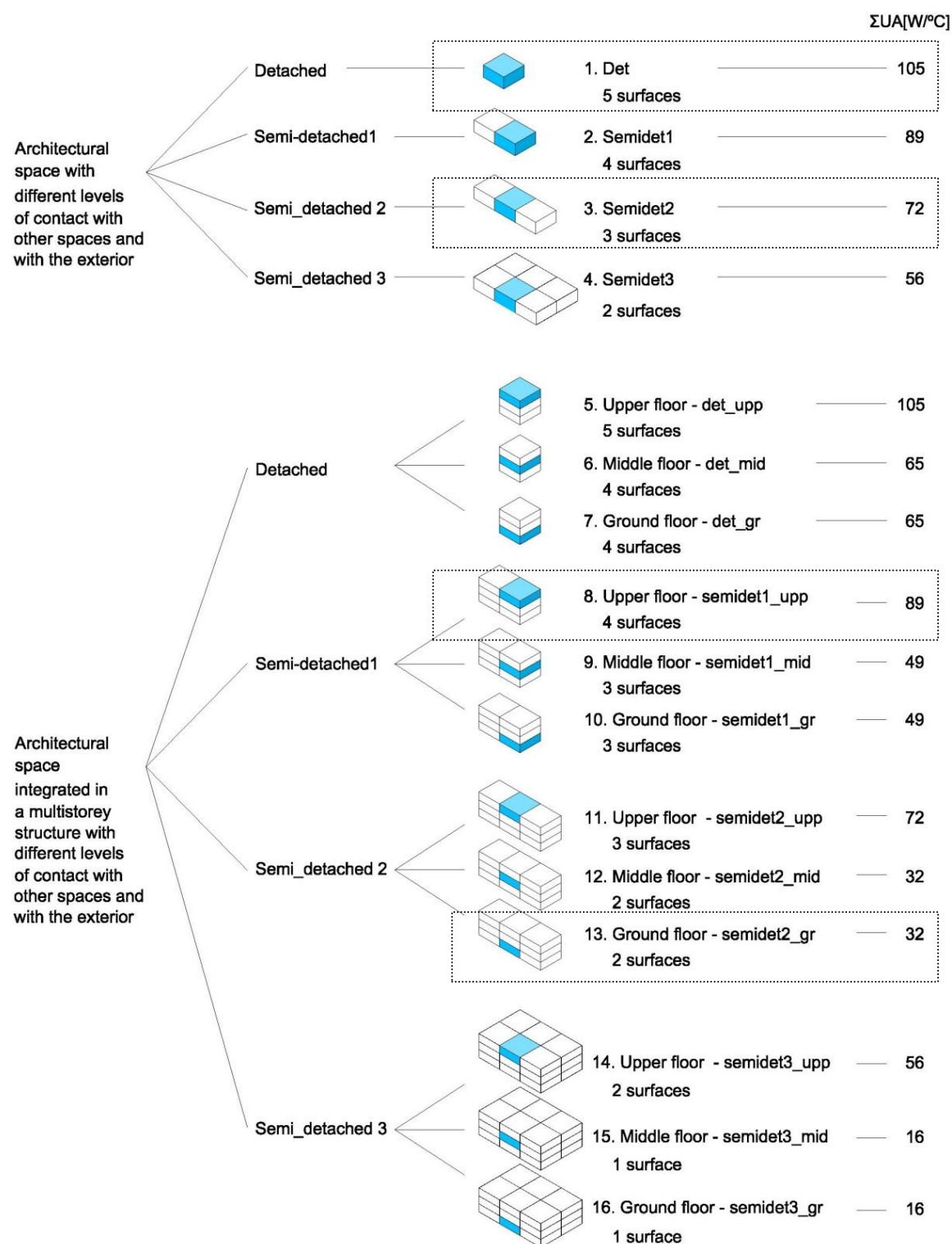


Figure 57 Types of architectural spaces according to the level of exposure of their components to the exterior

As it has been previously referred, areas of building components are aggregated with the values of thermal transmittance of exterior components. It is here considered that the most representative expression for heat losses of a given space is the sum of thermal conductance of their exterior components (ΣUA).

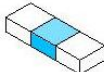
Alternative values for the parametric study were obtained through exploratory proceedings, which are summarized in Table 9. Firstly, areas for exterior components were set for each type of architectural space, presented in Figure 57. As it has already been referred, the useful floor area attributed to all types of spaces was 100m². Secondly, two alternative U-values were attributed to each exterior component – walls and roofs. Thirdly, the value of thermal conductance was established according to areas and U-values of exterior components.

Considered values for thermal conductivity of exterior building components encompassed two choices. The first envelope was constituted by walls with 0.3 W/m² °C and roofs with 0.2 W/m² °C and the second envelope with values of 0.6 W/m² °C for walls and 0.4 W/m² °C for roofs. Alternative U-values complies with reference U-values of Portuguese legislation. While the envelope with U-values of 0.6 walls/0.4 roof was conducted by reference values of the version of 2006 (RCCTE 2006), the envelope with U-values of 0.3 walls/0.2 roof was driven by the most recent version of the legislation, that presents stricter U-values (REH/RECS 2013). Reference U-values of 1990 were not considered as with posterior technological advances, the requirements for building exterior elements have become more demanding.

Values of thermal conductance for the thermal study couldn't encompass UA of all architectural space types not only because it would lead to a high number of alternatives, but also due to the proximity of some of the UA values for different types. Table 9 shows representative cases chosen for the parametric study. Calculated ΣUA values take into account that the ratio of the glazed area to the floor area is 0%.

It should be underlined that the aim of this study is not to compare space types, but rather use some space types, for having reference areas for exterior elements.

Table 9 Values attributed to the global thermal conductance of exterior elements

Architectural space type	Exterior components ²	A [m ²]	U-values [W/°C.m ²]	ΣUA^3 [W/°C]	$\Sigma UA/A_p^4$ [W/°C.m ²]
	Walls	120	0.6	112	1.12
	Roof	100	0.4		
	Walls	60	0.6	76	0.76
	Roof	100	0.4		
	Walls	90	0.3	47	0.47
	Roof	100	0.2		
	Walls	60	0.3	18	0.18

5.3.2 Thermal inertia

The RCCTE deals with thermal analysis over extended periods of time – the heating season and the cooling season. The method does not analyze the temperature fluctuations inside the building on an hourly or daily basis. However, as it has already been stated, in the conceptual phase of building design, accuracy of results is not a critical issue. This study considers reference values of the calculation method of RCCTE for thermal inertia. RCCTE defines three categories of inertia according to three range of values of useful superficial mass per square meter – I_t [kg/m²]. Heavy inertia is determined by I_t higher than 400 kg/m²; weak inertia is defined for values lower than 150 kg/m² and midterm values correspond to spaces with medium thermal inertia. Later on, in bullet 5.5.3., the influence of inertia in the calculation of useful solar gains will be described.

Given the relative high thermal amplitudes in temperate climates, weak thermal inertia cannot be a choice for buildings adaptation to these climates. Thus, only two levels of useful superficial mass per m² of useful floor area are considered for the parametric study, corresponding to heavy and medium inertia.

² Assumption no heat losses through the floor

³ Calculated ΣUA values take into account that the glazing ratio is 0%

⁴ A_p is considered as being 100m²

Table 10 Thermal inertia values

Thermal inertia	It [kg/m ²]
Heavy	>400
Medium	<150;>400

5.3.3 Glazing orientation

Glazing orientation has a great influence on building thermal needs both in winter and in summer. In the same building different spaces orientation can lead to significant different compartments thermal behavior. Thus, alternatives for orientation encompass all possibilities, with the exception of NE and NW, given that spaces oriented towards NE and NW have a similar thermal behavior to spaces oriented towards N. The sensitivity study only assumes one orientation per architectural space which is the most common situation in residential buildings.

Table 11 Architectural spaces orientation

Orientation
N
E
SE
S
SW
W

5.3.4 Glazing size

Building openings constitute one of the most relevant features for Architecture and expresses the level of contact of the building with the exterior. The maximum number of alternatives is studied in order to later better assess building design. Architectural spaces of residential buildings have relative small floor areas and the expression of glazing in façades is not as significant as in non-residential buildings. Thus, the considered glazing ratio is the glazing area to useful floor area.

Table 12 Glazing ratio (%)

Ratio of the glazed area to the floor area (%)
5
10
20
40

5.3.5 Shading devices

The indicator for shading is the solar factor or g-value that encompasses the type of window and type and position of shading in order to indicate the solar energy transmittance of glazing. For the parametric study, a default value for type of glazing is established, being double clear glazing. For shading type and position, two alternatives are considered – interior curtains and exterior shutters.

Regarding, solar factors for the heating season, curtains or blinds are considered opened, in order to increase solar gains. The solar factors for the cooling season were calculated according to the RCCTE. The method of calculation considers a sum of 30% of the g-value of the glazing and 70% of the g-value of the window with blinds closed.

Table 13 Solar factor

Solar factor	Winter - $g_{\perp}$	Summer - $g_{\perp}$
Double clear glazing with interior curtains	0.63	0.63
Double clear glazing without exterior protection in winter and with exterior movable devices in summer	0.63	0.07

5.4 Default values

As previous stated, default values are attributed for constrained parameters as well as to parameters of energy valorization. For the sensitivity study, selected reference values aim to meet the requirements for a low energy building.

Later on, the thermal assessment tool will drive design choices through recommendations settled according to design constraints. Ever possible, recommendations will meet reference values of the sensitivity analysis.

Ventilation

A reference value is attributed to ventilation as it has been shown that ventilation indoors is highly dependent of the air circulation around the building. The calculation method considers that mechanical ventilation is not used and that air renovation is assured at a rate of 0.6 RPH, with the assumption that frames are well sealed. Even if the value for RPH is 0.6, it is taken into account that windows can be opened during the night in summer in order to reduce the thermal load.

Type of glazing

Double glazing is the only choice considered as it is a pre-condition for acoustics. Besides this, technological advances have driven to the widespread application of double glazing. Obviously, the case of retrofit is an exception, as frequently older buildings have simple glazing. However, the case of simple glazing in buildings being retrofitted will be tackled later with the thermal assessment tool for Architecture with specific recommendations that aim to avoid thermal losses by conduction through glazing.

Roof color and type

Flat roofs of clear color are considered.

Thermal bridges

Constructive alternatives for walls and roofs consider thermal insulation applied by the exterior in simple walls and thermal insulation installed in the air cavity in double walls. Subsequently, the influence of thermal bridges is reduced.

5.5 Application of the calculation tool for the study of design alternatives

The tool used for the sensitivity analysis is based on the calculation method of RCCTE 1990 as previously stated. A calculation spreadsheet that integrates the climate data and relationships between design parameters and their interaction with the climate was used in order to study the 1536 alternatives described before.

Folha de Cálculo FCIV.1

Cálculo das Necessidades Nominais de Aquecimento do Edifício

	Necessidades Nominais Específicas de Aquecimento (W/°C)
Envolvente Opaca Exterior (FCIV.1a)	108,40
Envolvente Interior (FCIV.1b)	
Envidraçados (FCIV.1c)	14,25
Renovação de ar (FCIV.1d)	61,20

Total	183,85
--------------	--------

	184
	x
Graus dias de aquecimento (Quadro III.2 Anexo III).....	800
	x
	0,024
	=
Necessidades brutas de aquecimento (kWh/ano).....	3530
	-
Ganhos solares úteis da FCIV.1e (kWh/ano).....	1085
	=
Necessidades nominais de energia útil por estação de aquecimento, Na (kWh/ano).....	2445
Nic = Na/Ap.....	24,45

Folha de Cálculo FCIV.1a

Cálculo das Necessidades Nominais de Aquecimento devidas à envolvente opaca exterior

1. Perdas pelas paredes:

	A m ²	K W/m ² °C	fc	KA W/°C
Paredes	114,00	0,60	1	68,40
	114,00			68,40
				Total

2. Perdas pelas coberturas:

	A m ²	K W/m ² °C	fc	KA W/°C
Coberturas	100,00	0,40	1	40,00
	100,00			40,00
				Total

3. Perdas pelos pavimentos:

	A m ²	K W/m ² °C	fc	KA W/°C
Pavimentos				
				Total

Total da envolvente opaca exterior (W/°C).....	108,40
--	--------

Figure 58 Tool interface for the calculation of the nominal heating needs of a given space

5.5.1 Heating needs

The yearly energy needs for space heating of a given space are calculated as expressed by the following equation of the Thermal Regulation (RCCTE 1990). During the heating season, heating needs are obtained through the sum of the instantaneous losses during time being these losses offset by the sum of useful solar gains during the same period. In this equation the climate parameter is represented by heating degree days (HDD). HDD are obtained through the sum of the positive differences between a given interior base temperature and the exterior air temperature during the heating season. It should be underlined that even if reference conditions establish the base temperature of 18°C in interior spaces, the HDD specified in the thermal regulation take as basis the temperature of 15°C, being the difference of 3°C given by heat interior gains (people, lighting and equipment).

$$N_i = \frac{(\sum f_c U_w A_w + \sum f_c U_h A_h + \sum U_{glz} A_{glz} + 0.75 \sum f_c U_{int} A_{int}) + 0.34 A_p p_d RPH}{A_p} \cdot 0.024 HDD - \sum A_{glz} E S_v \Phi \eta f$$

Heat losses by conduction
Heat losses by ventilation
Useful solar gains

+ Heat storage and distribution

Where:

- f_c Factor of heat losses through thermal bridges
- U_w Coefficient of thermal transmittance of exterior walls (W/m² °C)
- A_w Area of exterior walls (m²)
- U_h Coefficient of thermal transmittance of exterior horizontal elements (W/m² °C)
- A_h Area of exterior horizontal elements (m²)
- U_{glz} Coefficient of thermal transmittance of glazing (W/m² °C)
- A_{glz} Area of exterior glazing (m²)
- A_{int} Area of interior elements in contact with non-heated spaces (m²)
- U_{int} Coefficient of thermal transmittance of interior elements in contact with non-heated spaces (W/m² °C)
- A_p Useful floor area (m²)
- P_d Floor to ceiling height (m)
- RPH Renovation of air per hour
- HDD Heating degree days per year
- E intensity of the solar radiation (solar irradiance) incident on glazing surfaces (W/m²)
- S_v Glazing solar factor winter - fraction of the incident energy on the glazing surface that is transmitted to the interior space
- Φ Obstruction factor – percentage of clear and not shaded glazing area that receives direct and incident solar radiation (the reference value for glazing not shaded by urban obstructions is 0.7)
- η Utilization factor of solar gains
- f Orientation factor

5.5.2 Cooling needs

The following equation of the Thermal Regulation expresses yearly energy needs for space cooling of a given space (RCCTE 1990). As it can be observed in the equation, the heat transfer through exterior opaque elements during summer is not a permanent process. Gains in summer are mostly dominated by the incident solar radiation in most exposed glazing surfaces.

Not all heat gains that enter in the building through walls and the roof represent thermal load. A part of them is stored in interior massive elements and diffused during the night. This fraction increases with the inertia of the building, thus factor I expresses the effect of the inertia in this process of heat storage and distribution.

$$N_v = \frac{(0.36) \sum_e f_c A_i U_i (\Delta T_e) e + \sum_g A_g G_g S}{A_p} \cdot I \cdot M$$

Heat gains by conduction
Solar gains through the glazing
Heat storage and distribution

Where:

- e Exterior elements
- f_c Factor of heat losses through thermal bridges
- A_e Area of each exterior element – wall or roof (m²)
- U_e Thermal transmittance of exterior elements – wall or roof (W/m² °C)
- ΔT_e Effective temperature difference through the wall or the roof; in the case of roofs the effective temperature difference is dependent on the roof type and color
- g Glazing element
- A_g Area of each exterior type of glazing according to orientation
- G_g Average monthly solar gains in periods of uncovered sunshine during the heating season for a solar factor of 100%
- S Glazing solar factor summer
- I Inertia factor of the architectural space
- M Average duration of insolation during the cooling season
- A_p Useful floor area

5.5.3 Useful solar gains calculation

Not all the solar energy that enters in the interior space is useful in terms of thermal comfort and not all the solar gains available are useful in offsetting auxiliary heating. In some cases solar gains can even result in the overheating of interior air. The expression used for the calculation of the utilization factor takes into account an inertia factor (K) and the ratio between gross solar gains and gross heating needs of a given architectural space. The utilization factor increases with the inertia of the construction and it is reduced with the increase of the ratio of gross solar gains/gross heating needs (RCCTE 1990). The calculation method of RCCTE 1990 only considers useful solar gains in south, southeast and southwest orientations as well as in horizontal surfaces, as it is expressed in the orientation factor (f) for these azimuths – 1 south; 0.7 southeast and southwest; 0.85 horizontal surfaces.

Inertia factor:

$$K = \begin{cases} 0.7 & \text{buildings with weak inertia} \\ 1 & \text{buildings with medium inertia} \\ 1.3 & \text{buildings with heavy inertia} \end{cases}$$

Gains-load ratio:

$$GLR = \frac{\text{Gross solar gains}}{\text{Gross heating needs}}$$

Utilization factor of solar gains:

$$\eta = 1 - \exp \left\{ -\frac{K}{GLR} \right\} \quad 0 < \eta < 1$$

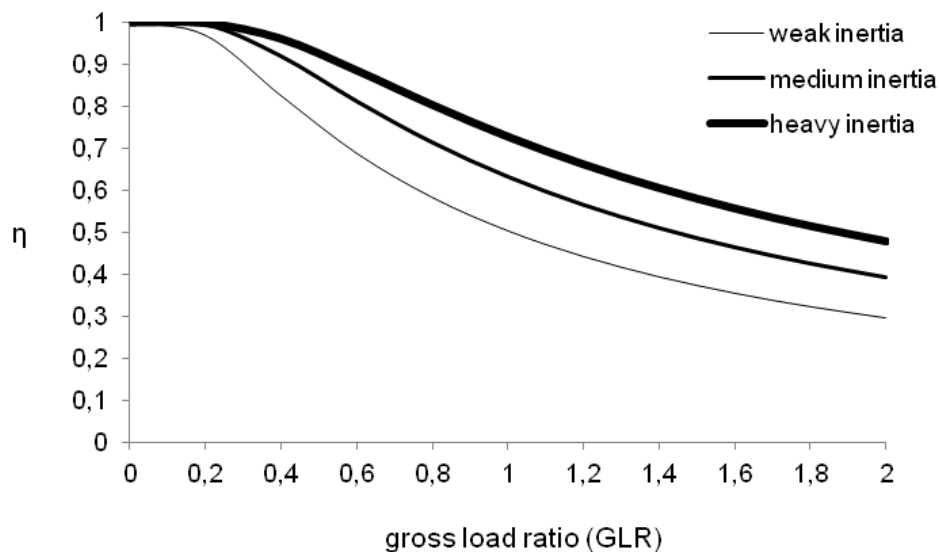


Figure 59 Relation between the utilization factor (η) and the ratio of the gross solar gains to gross heating needs (GLR) (RCCTE 1990)

5.5.4 Operative values

Both types of input parameters, default values and alternative values, are transposed to the calculation tool. Operative values are established below.

Table 14 Values attributed to the design parameters – operative values

ΣUA^5 [W/°C]	A_w [m ²]	U_w [W/°C.m ²]	A_h [m ²]	U_h [W/°C.m ²]	I (inertia factor)	A_{glz} [m ²]	Glazing orientation	Summer g-values
112	120	0.6	100	0.4	heavy – 0.9/ medium – 1.0	5/10/ 20/40	N/E/SE/ S/SW/W	0.63/0.07
76	60	0.6	100	0.4	heavy – 0.9/ medium – 1.0	5/10/ 20/40	N/E/SE/ S/SW/W	0.63/0.07
47	90	0.3	100	0.2	heavy – 0.9/ medium – 1.0	5/10/ 20/40	N/E/SE/ S/SW/W	0.63/0.07
18	60	0.3	-	-	heavy – 0.9/ medium – 1.0	5/10/ 20/40	N/E/SE/ S/SW/W	0.63/0.07

Operative values of the building construction that remain as default values:

Factor of heat losses through thermal bridges

f_c 1 – corresponding to thermal insulation applied by the exterior

Coefficient of thermal transmittance of glazing surfaces

U_{glz} 2 W/m² °C – double glazing

Useful floor area

A_p 100 m²

Floor to ceiling height

P_d 3 m

Renovation (of air) per hour

RPH 0.6

Glazing solar factor winter

S_v 0.63

Obstruction factor

Φ 0.7 – reference value for glazing not shaded by urban obstructions

Orientation factor

f south – 1; southeast – 0.7; southwest – 0.7

Roof type terrace

Roof color clear

⁵ Calculated ΣUA values take into account that the glazing ratio is 0%

6 Results. Analysis and discussion

6.1 Introduction

The relevant critical input parameters and corresponding physical values for the current exercise of presenting and discussing the results were summarized in Table 7 of Chapter 4. The different geometries (Section 5.3), alternative values (Tables 9-13), default values (Section 5.4) and calculations based on RCCTE algorithms (Section 5.5) are presented in Chapter 5.

In this chapter, the results are presented under the form of graphs for a number of cases considered as being sufficient to demonstrate the purpose of this thesis. Those graphs of thermal needs for heating and cooling a given building or, in this thesis, just one space in the respective season, illustrate the potential of exploring the building physics. Not just to reduce the energy needs but also to create conditions to reduce the 'add on' energy needs, if that is the case, so to make more positive the recently ambitious 'plus energy balance' for each building.

The results that will be presented and analysed, bear in mind the 'vademecum' suggested by Figure 56 and Table 7 of Chapter 4, in which the design parameters are organized in four categories. Those that are sensed to have a critical energy impact are precisely designated as critical input parameters:

- Envelope global thermal conductance per useful floor area ($\Sigma UA/A_p$)
- Thermal inertia
- Windows size and orientation
- Shading means and position

6.2 Results

In this phase, it is possible to identify the more relevant graphics, following the sequence of critical input parameters defined in Chapter 4 (Table 7). The results are outlined:

1. The energy needs for heating of a given space in the heating season of one typical year as a function of the heat losses through the envelope. These are expressed by the global conductance ΣUA calculated for the given geometry of one

single space, bearing in mind the following assumptions regarding its borders: a. no heat exchange through the floor, independently of the reason; b. consideration of the surface of the walls discounting the area corresponding to the area of windows. The adopted heat transfer coefficient is in some cases $0.6 \text{ W/m}^2 \text{ }^\circ\text{C}$ for the walls, $2 \text{ W/m}^2 \text{ }^\circ\text{C}$ for the windows and $0.4 \text{ W/m}^2 \text{ }^\circ\text{C}$ for roofs and in other cases $0.3 \text{ W/m}^2 \text{ }^\circ\text{C}$ for the walls, $2 \text{ W/m}^2 \text{ }^\circ\text{C}$ for the windows and $0.2 \text{ W/m}^2 \text{ }^\circ\text{C}$ for roofs. The values of ΣUA as well as those of the glazed areas are expressed per unit of floor area - glazing ratio; c. the windows orientation (south or other) and latitude (geography or location) impact is also taken into account; d. last but not the least, the thermal inertia is also an important independent variable which impact is to be studied.

2. The energy needs for cooling of the same space during the cooling season of one typical year as a function of the same parameters above plus, in particular, the shading applied either internally or externally.

3. The calculations are performed according to RCCTE equations for heating and cooling needs (Chapter 5) which includes a fixed value of 0.6 air changes per hour.

4. The total energy for comfort is also considered as an attempt to point out for criteria of optimization of the glazing surface.

To be noticed that RCCTE is an approximated method which use here was already justified before. Its results may not be always reflect the accuracy that is already possible since 1990 but bearing those limitations in mind it is to be recalled that the purpose of this procedure is to contribute for the early thermal aid.

So, a first analysis allows to assess the impact of the different critical parameters as shown firstly in Figures 60-63 where the heating and cooling needs are represented for Porto and Bragança as a function of the global thermal conductance (ΣUA) for three levels of inertia (weak, medium and heavy) and with windows oriented towards South with a glazing ratio of 10%, a quite traditional ratio in the Portuguese case.

The results are clearly showing that: a. high conductance of the envelope contributes to high heating and cooling needs, even if the variation is more evident during the heating season as the difference of temperatures through the envelope are higher in winter time (Figure 60); b. Figure 61 shows that the cooling needs for the case of Porto with windows oriented towards South and 10% of glazing ratio remain almost constant independently of the thermal inertia. In addition, the cooling load is almost independent of the conductance, which is an indicator that the temperature stated indoors is closer

to the mean temperature outdoors; c. the comparison of the results above with those for Bragança (Figures 62 and 63) shows that the cooling needs are similar to those for Porto, while the heating needs double. This illustrates how the temperatures in Bragança are lower than those of Porto in the heating season.

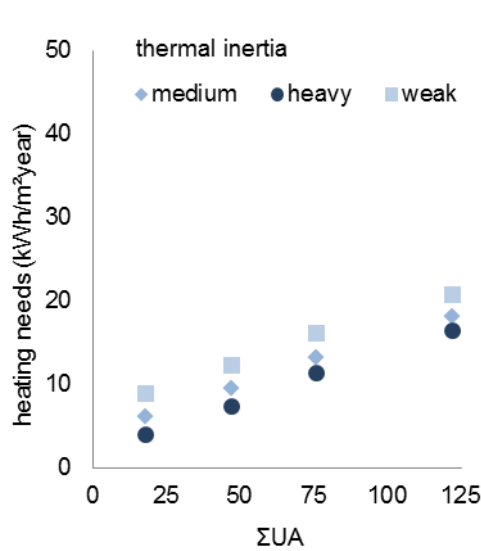


Figure 60 Influence of the ΣUA and inertia on the heating needs. Porto, S, 10% of glazing ratio

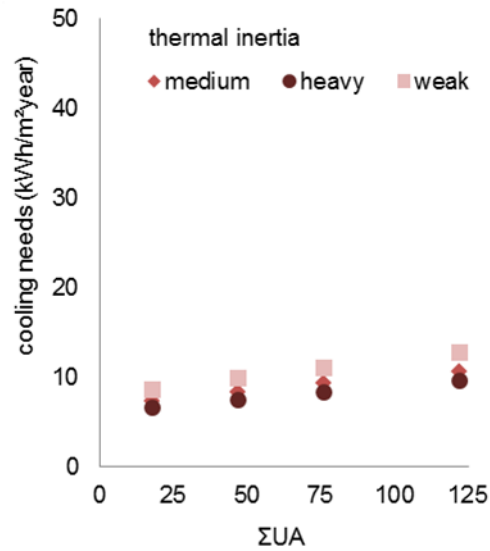


Figure 61 Influence of the ΣUA and inertia on the cooling needs. Porto, S, 10% of glazing ratio

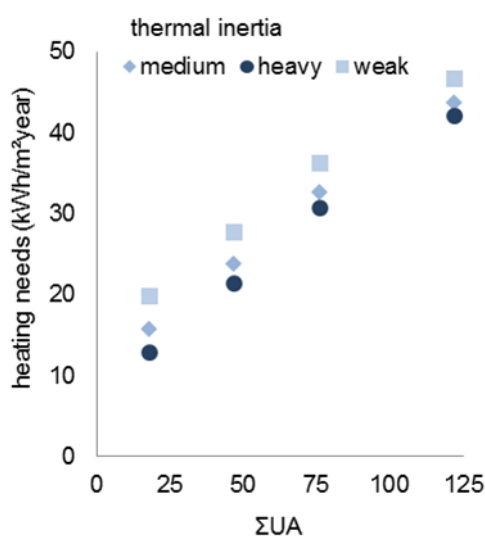


Figure 62 Influence of the ΣUA and inertia on the heating needs. Bragança, S, 10% of glazing ratio

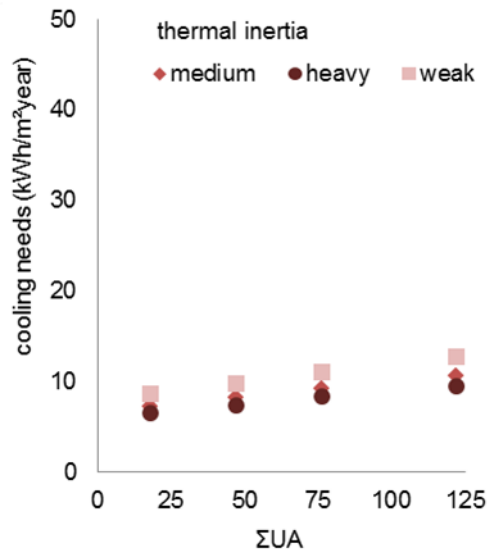


Figure 63 Influence of the ΣUA and inertia on the cooling needs. Bragança, S, 10% of glazing ratio

Those results show that the ‘add on’ energy needs for cooling in Porto (littoral city) and Bragança (easter mountain area) are rather similar and quite minimal to the point that

cooling may become unnecessary for an adequate building construction. The same does not happen for winter.

Pursuing with the first sensitivity analysis of the impact of some critical parameters, Figure 64 shows the strong negative impact of increasing the glazing ratio above around 15% in Porto on the overall yearly energy needs for comfort, mostly due to cooling needs.

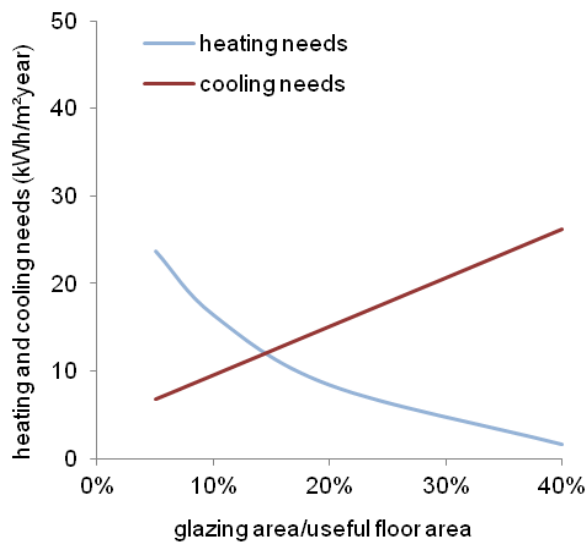


Figure 64 Influence of the glazing ratio on the heating and cooling needs. Porto, S, heavy inertia

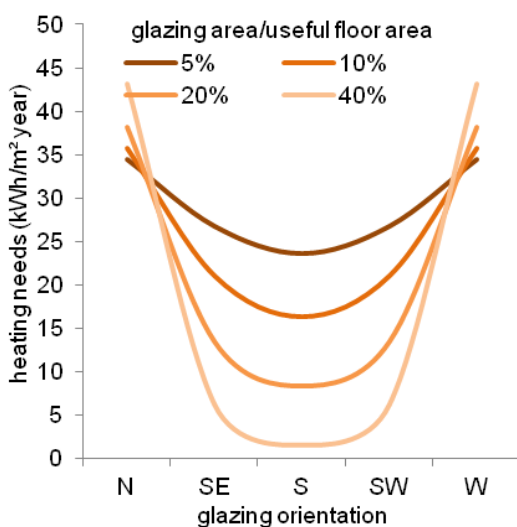


Figure 65 Influence of the orientation on the heating needs. Porto, S, heavy inertia

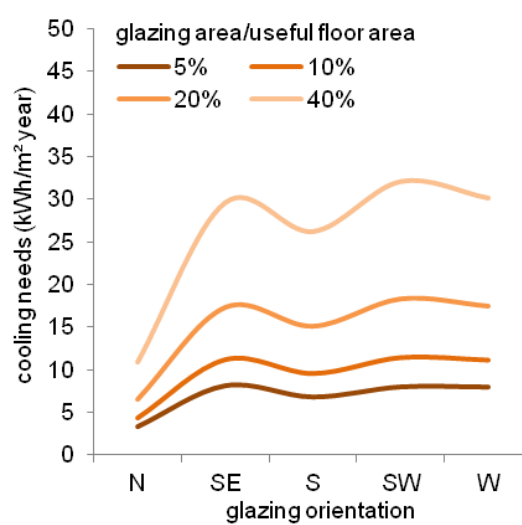


Figure 66 Influence of the orientation on the cooling needs. Porto, S, heavy inertia

Figures 65 and 66 show the sensitiveness of the heating and cooling needs for Porto respectively to the windows orientation and the glazing ratio. The results are obvious in what regards the heating needs and are more complex for the cooling needs due to the solar geometry.

Figure 67 presents a graphic that takes into account all parameters of interest, namely the critical ones and others. It creates a comparative framework to aid in the analysis, namely in the decision concerning the thermal insulation and inertia, the glazing ratio and the shading strategy and devices. The total thermal needs are less inspiring in what regards the design decisions as despite adding two forms of heat, these occur in different times and are of a very different energy value or exergy. To be noted the difference for the same kWh is that the one extracted from a room through a cooling process costs most probably up to three times the one added as heat. So, the sum of energies for heating and cooling start from the simplified assumption that those two kWh have the same price, and will allow for a rough optimization of the, namely, glazing ratio. In the following pages, thermal curves for other cases of inertia, orientations, shading devices as well as locations are presented.

Before undertaking the analysis of the new graphs, it is also pertinent to refer that overheating advices must be addressed. The fact is that some curves show only a slight increase in total thermal energy needs after the lowest point of the curve. However, the overheating risk will increase significantly with large glazing surfaces. Other comfort problems such as glare and 'cold radiation' may also occur with large glazing surfaces. Thus the method restricts the range of glazing to 40%. Additional information is given in order to avoid glazing ratios far away from the optimum point (the lowest point of the curve) in which global thermal energy needs are lower.

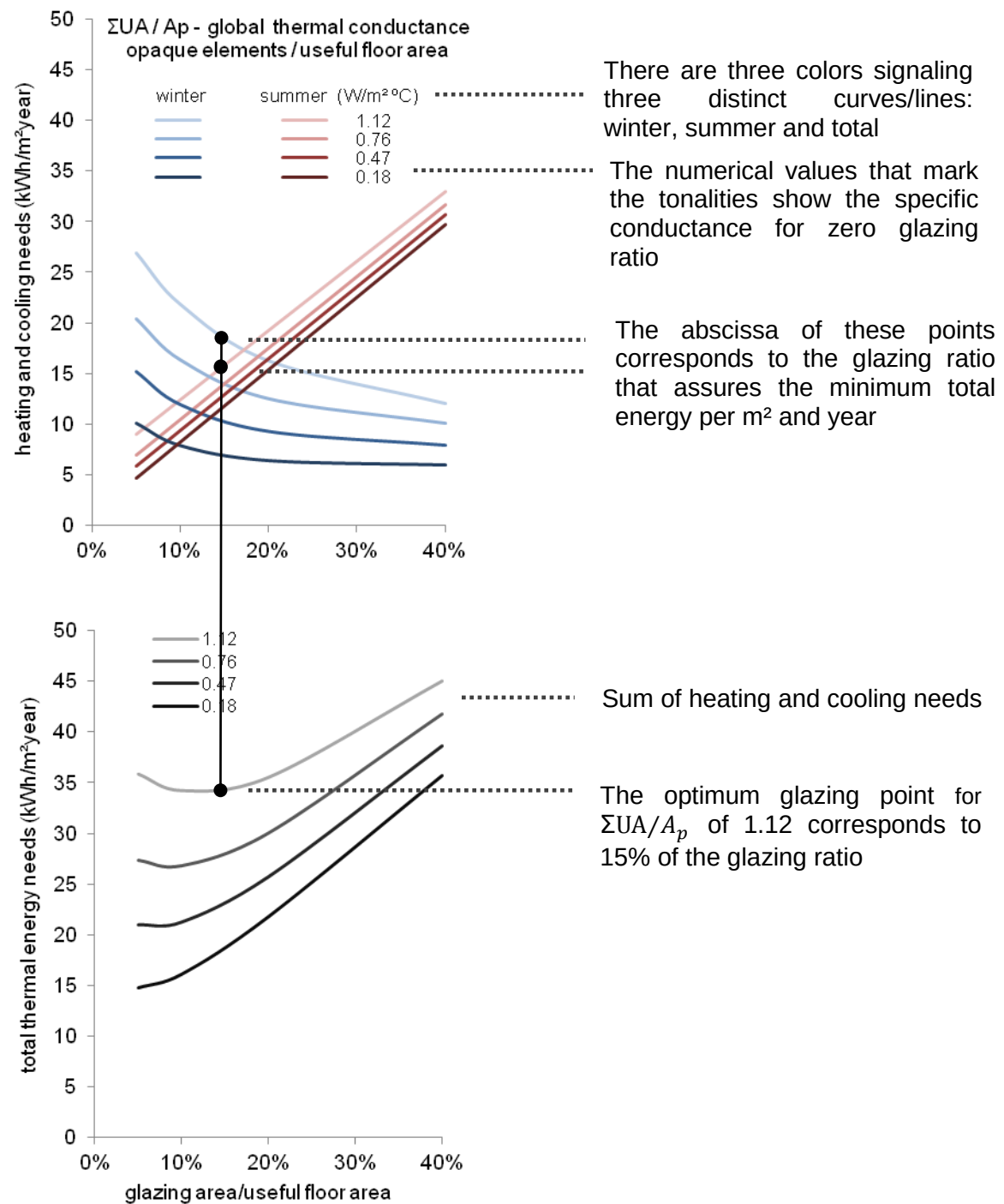


Figure 67 Heating, cooling and total thermal energy needs. Porto, SE, med. inertia, int. shading

A reduced number of cases was considered for analysis. Table 15 presents four cases that were considered for each one of the four locations taking into consideration Portugal from North to South: Bragança, Porto, Lisboa and Évora. The second and the third cities are located in the littoral and the other two are located in the interior.

South orientation was considered for spaces located in each one of those cities, either with heavy or medium inertia, as well as spaces oriented towards north and west with heavy inertia. Table 16 encompasses other complementary cases for a more complete analysis.

Table 15 Graphics of thermal needs 1 – number of the figure, space location, orientation, thermal inertia and shading

Location	Number of Figures	Orientation	Thermal inertia	Shading
Bragança	68	S	Medium	Interior
	69	S	Heavy	Interior
	70	N	Heavy	Interior
	71	W	Heavy	Interior
Porto	72	S	Medium	Interior
	73	S	Heavy	Interior
	74	N	Heavy	Interior
	75	W	Heavy	Interior
Lisboa	76	S	Medium	Interior
	77	S	Heavy	Interior
	78	N	Heavy	Interior
	79	W	Heavy	Interior
Évora	80	S	Medium	Interior
	81	S	Heavy	Interior
	82	N	Heavy	Interior
	83	W	Heavy	Interior

Table 16 Graphics of thermal needs 2 – number of the figure, space location, orientation, thermal inertia and shading

Location	Number of Figures	Orientation	Thermal inertia	Shading
Porto	84	S	Medium	Exterior
	85	S	Heavy	Exterior
	86	SE	Heavy	Interior
	87	SW	Heavy	Interior
	88	N	Heavy	Exterior
	89	E	Heavy	Exterior
	90	S	Weak	Interior
	91	W	Weak	Interior

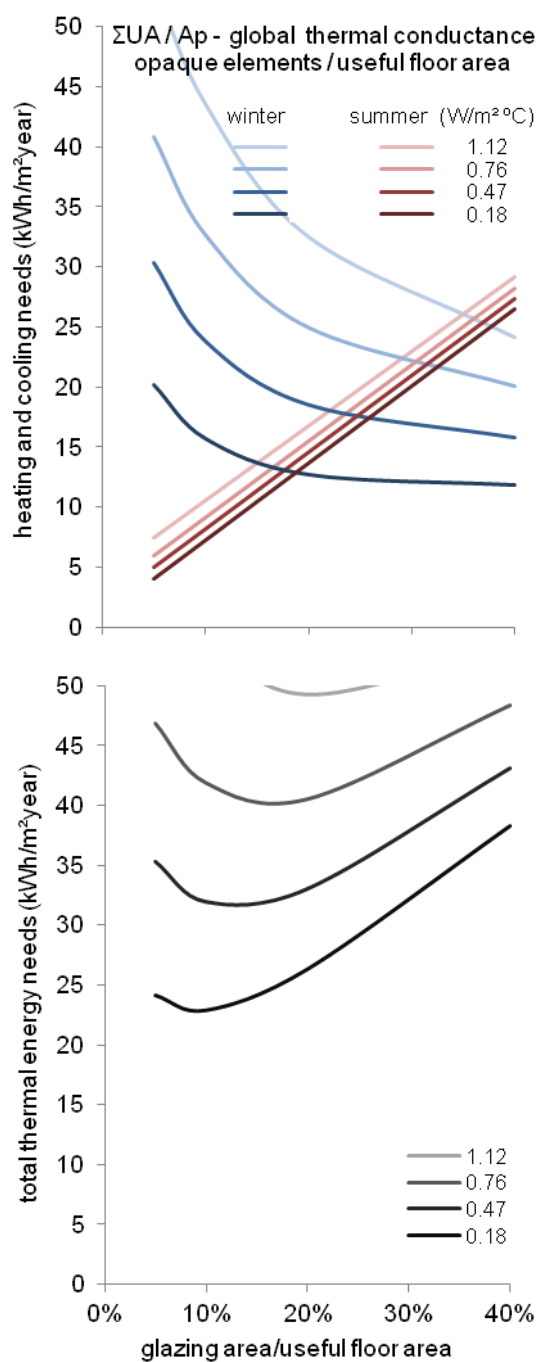


Figure 68 Heating, cooling and total thermal energy needs. Bragança, S, med. inertia, int. shading

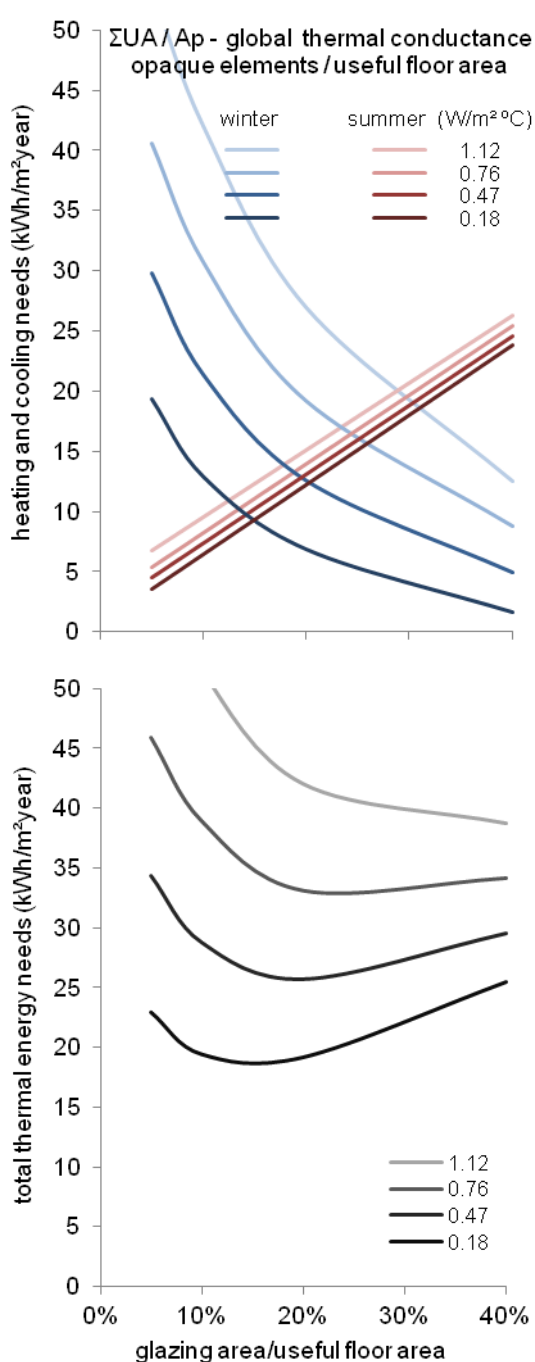


Figure 69 Heating, cooling and total thermal energy needs. Bragança, S, heavy inertia, int. shading

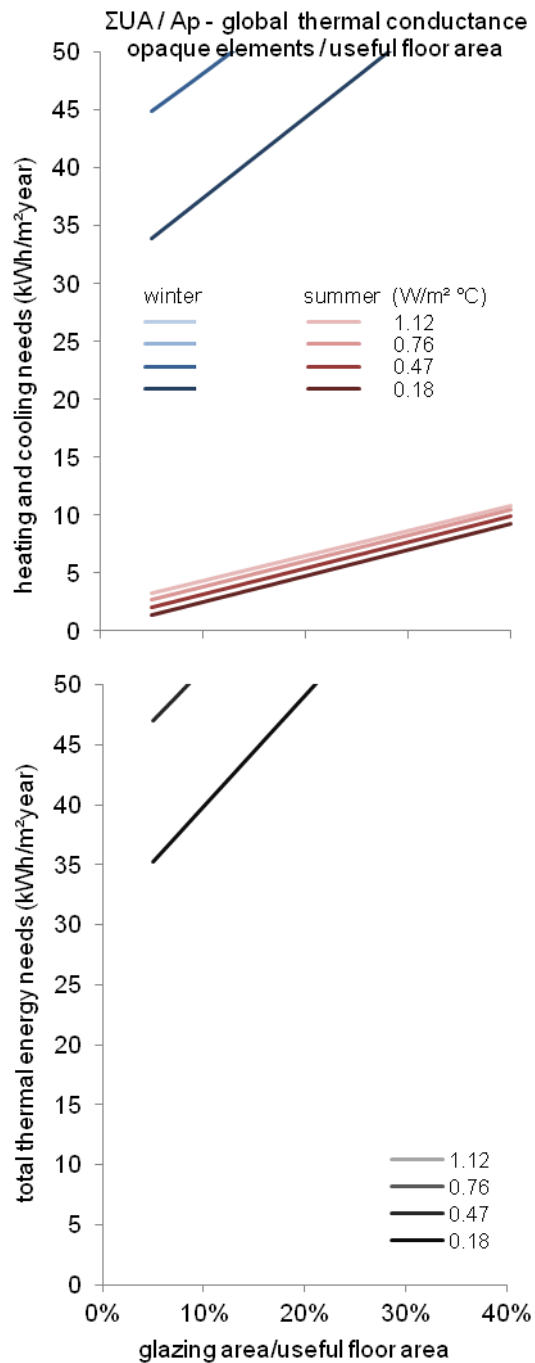


Figure 70 Heating, cooling and total thermal energy needs. Bragança, N, heavy inertia, int. shading

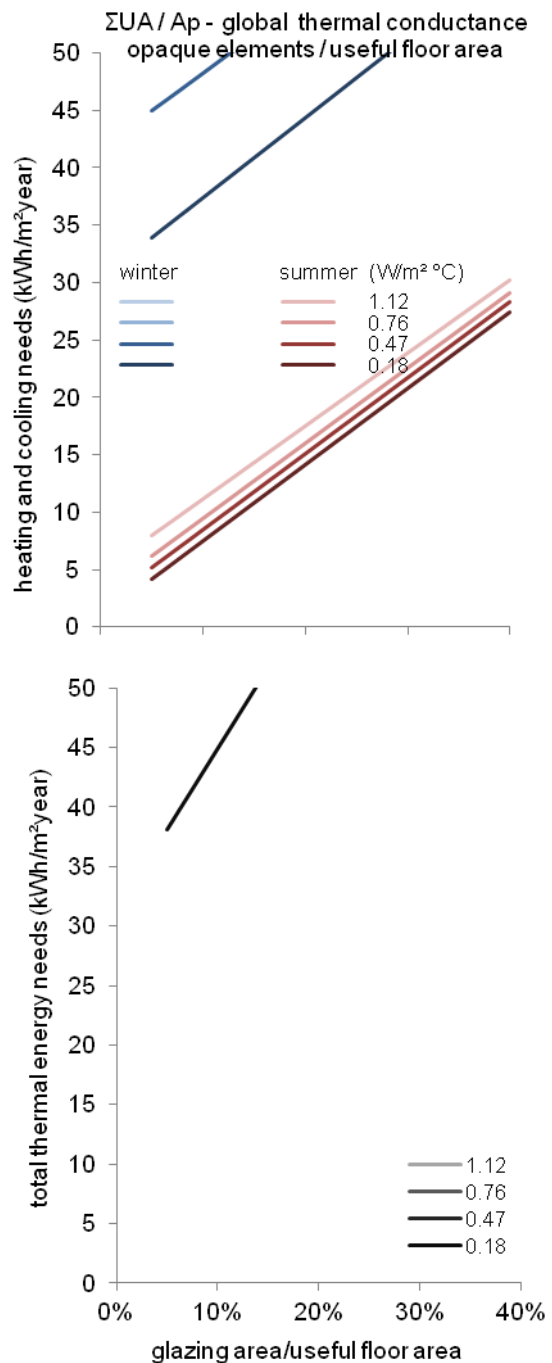


Figure 71 Heating, cooling and total thermal energy needs. Bragança, W, heavy inertia, int. shading

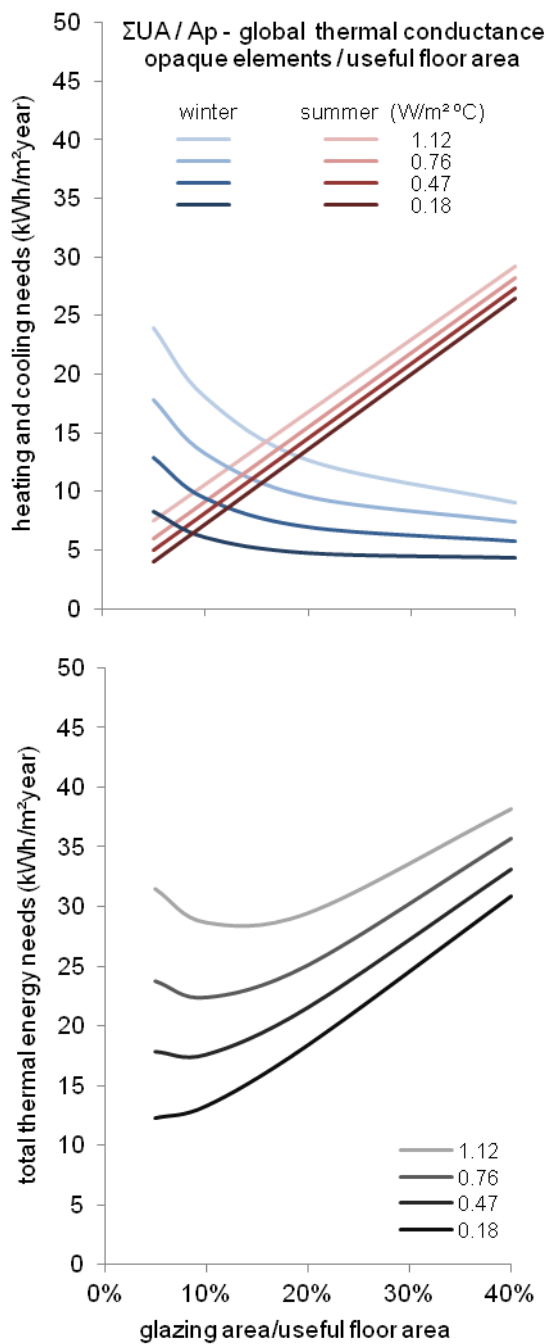


Figure 72 Heating, cooling and total thermal energy needs. Porto, S, med. inertia, int. shading

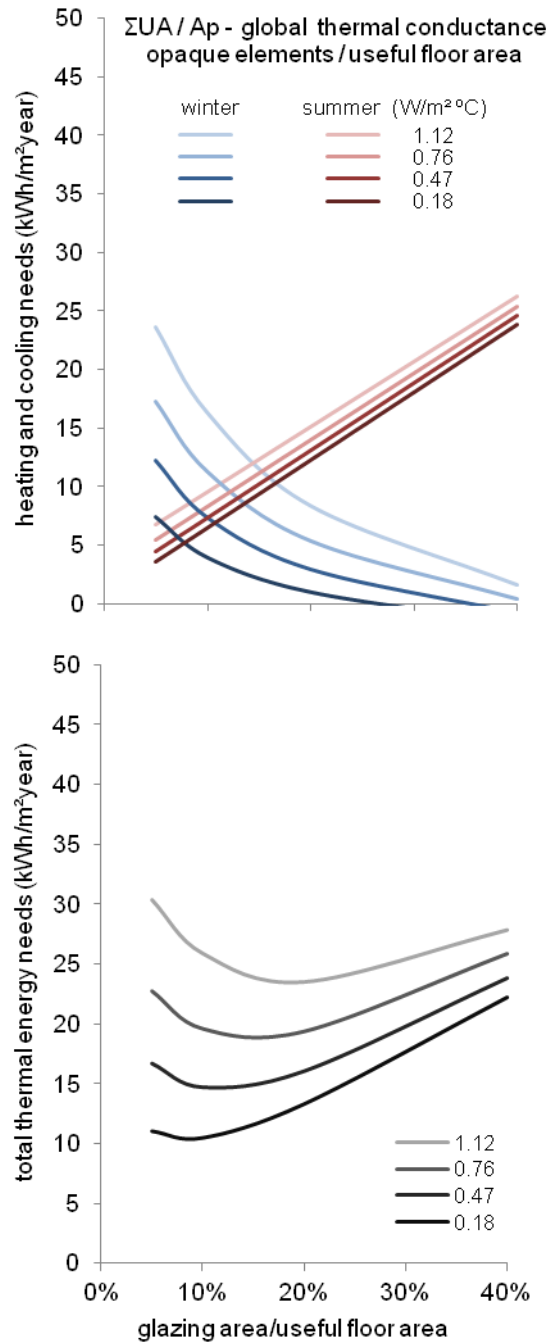


Figure 73 Heating, cooling and total thermal energy needs. Porto, S, heavy inertia, int. shading

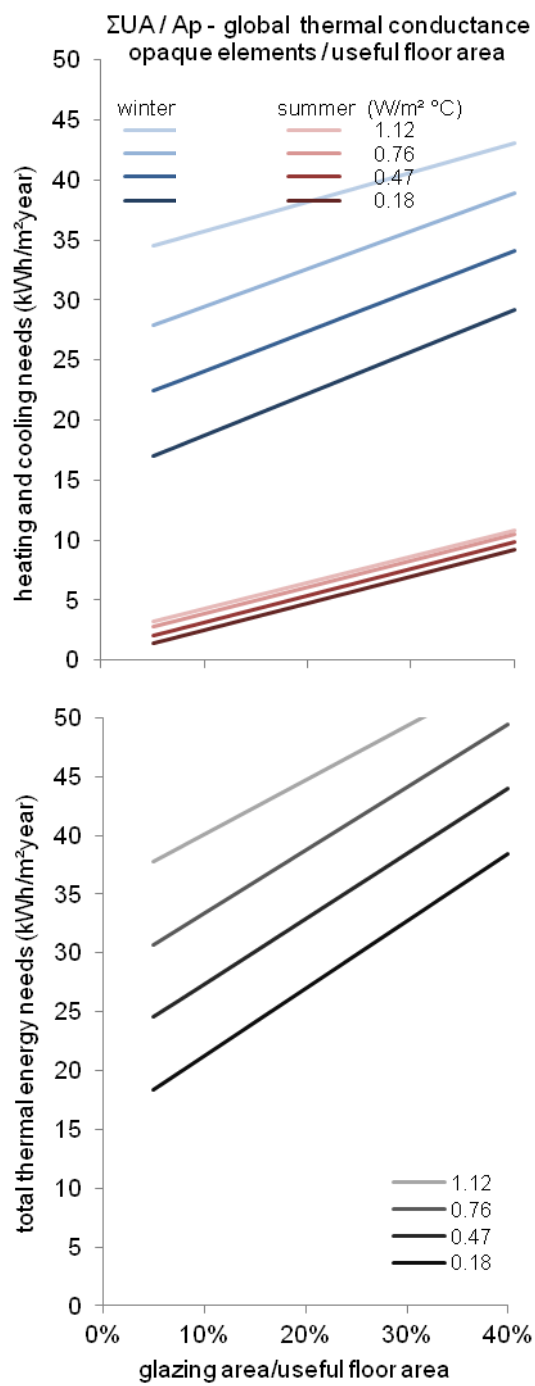


Figure 74 Heating, cooling and total thermal energy needs. Porto, N, heavy inertia, int. shading

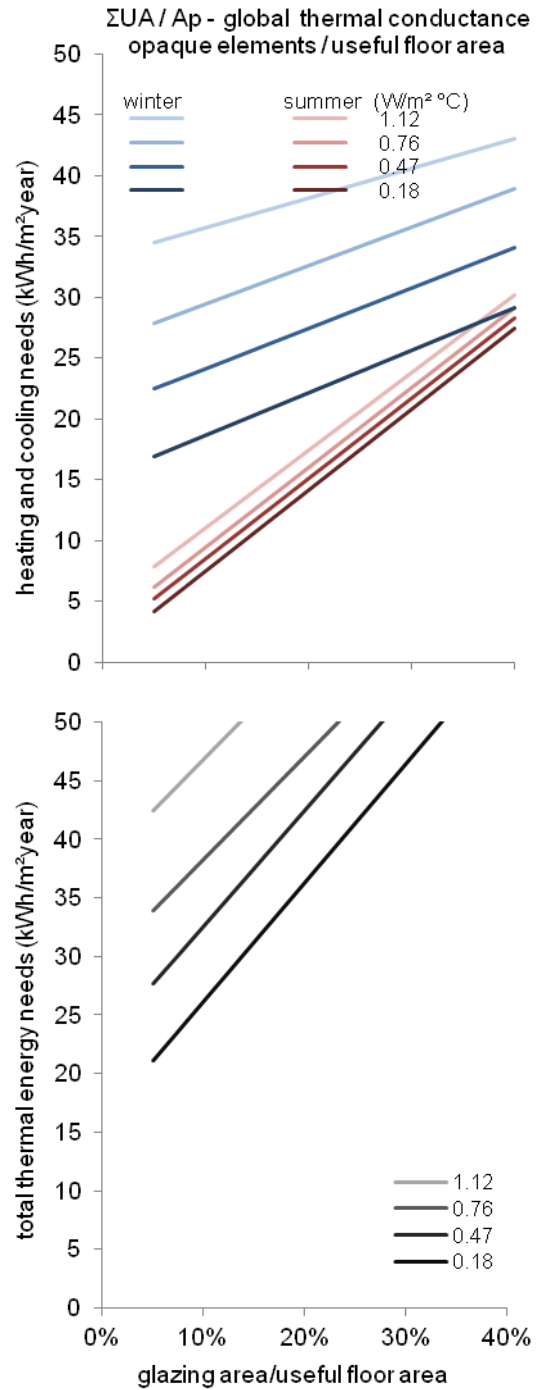


Figure 75 Heating, cooling and total thermal energy needs. Porto, W, heavy inertia, int. shading

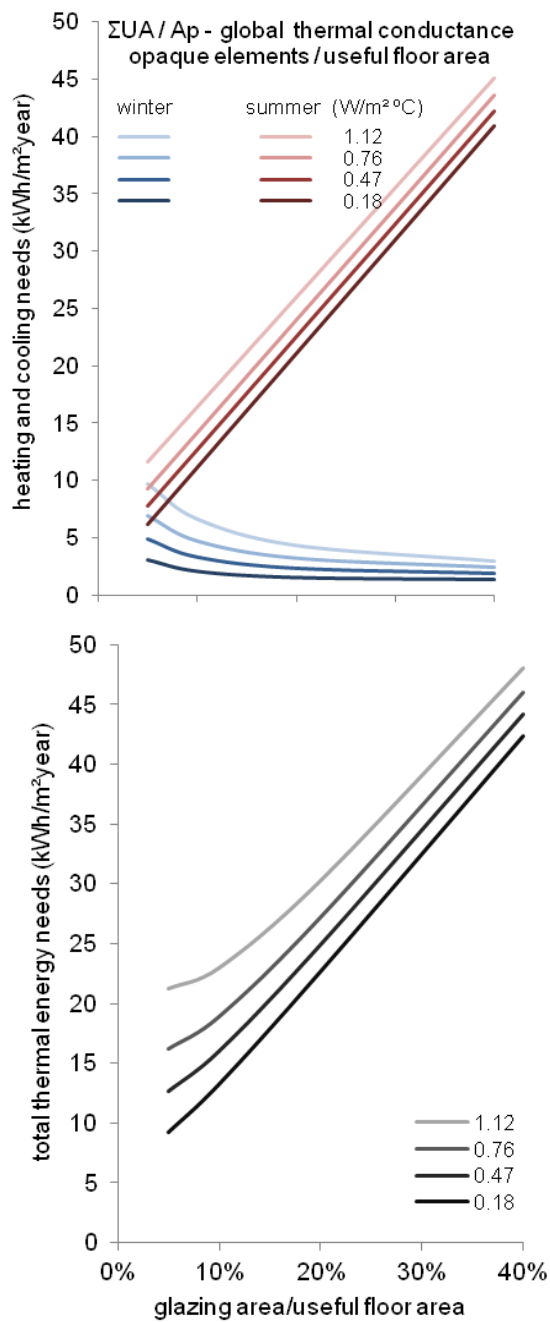


Figure 76 Heating, cooling and total thermal energy needs. Lisboa, S, med. inertia, int. shading

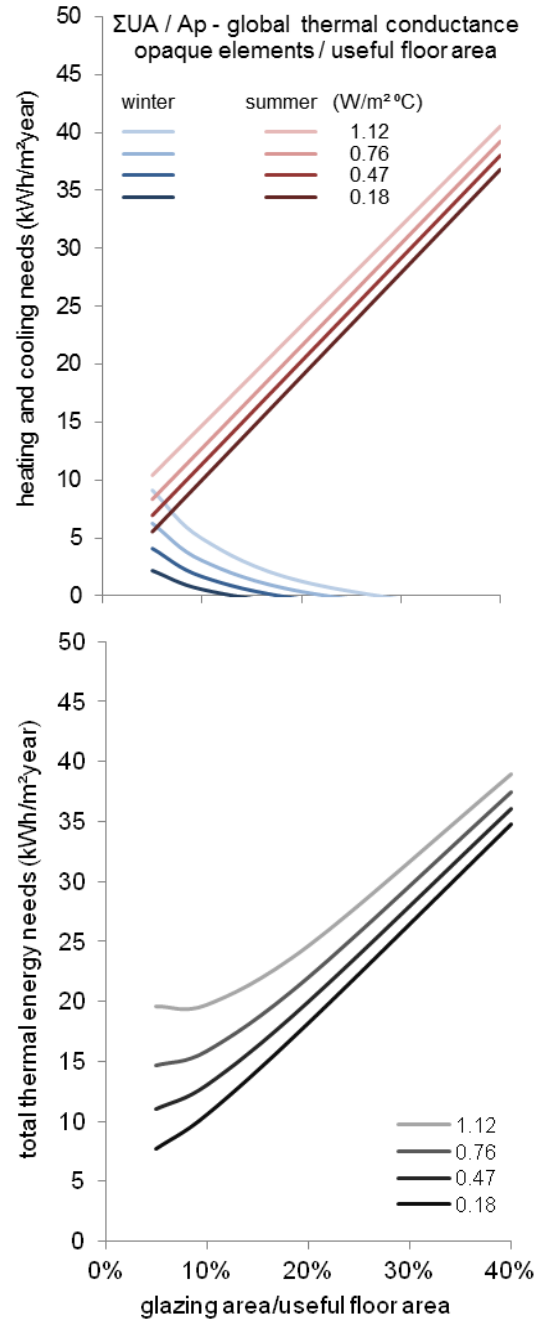


Figure 77 Heating, cooling and total thermal energy needs. Lisboa, S, heavy inertia, int. shading

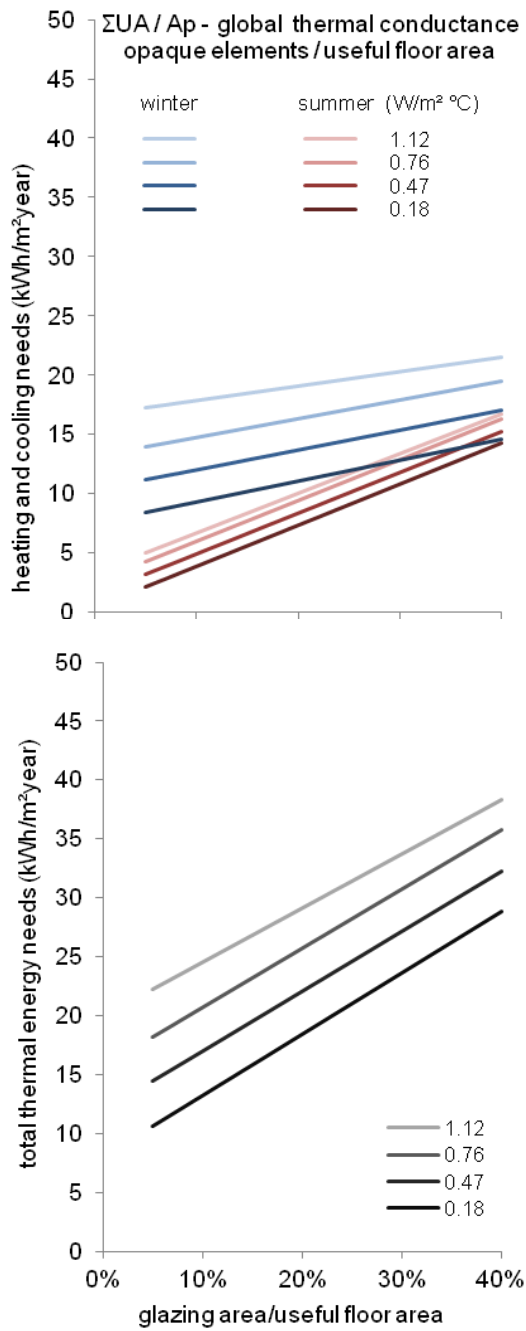


Figure 78 Heating, cooling and total thermal energy needs. Lisboa, N, heavy inertia, int. shading

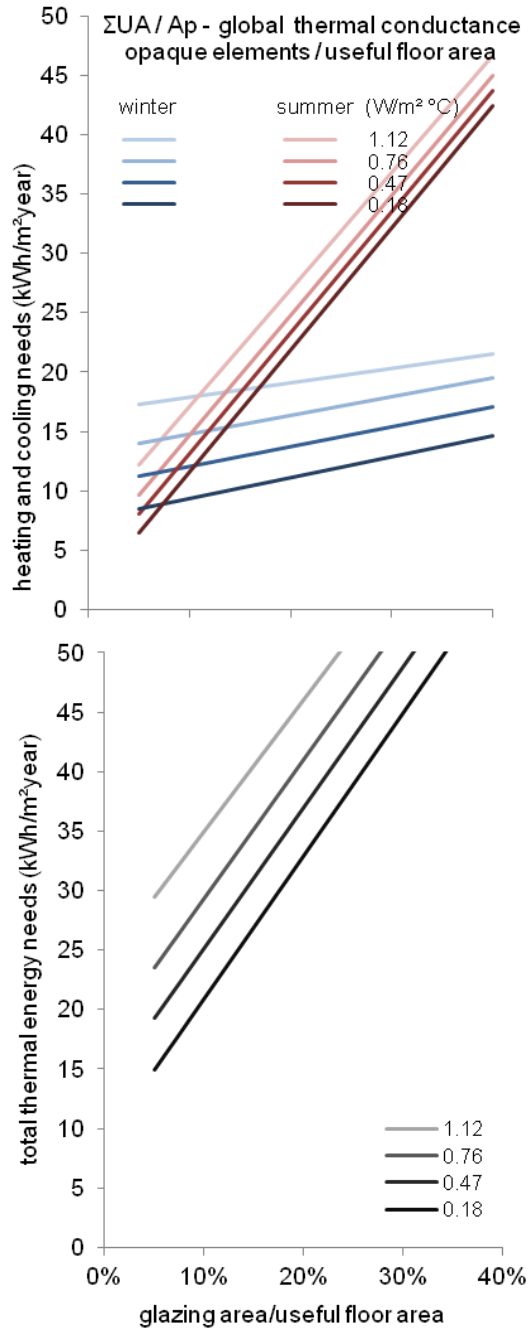


Figure 79 Heating, cooling and total thermal energy needs. Lisboa, W, heavy inertia, int. shading

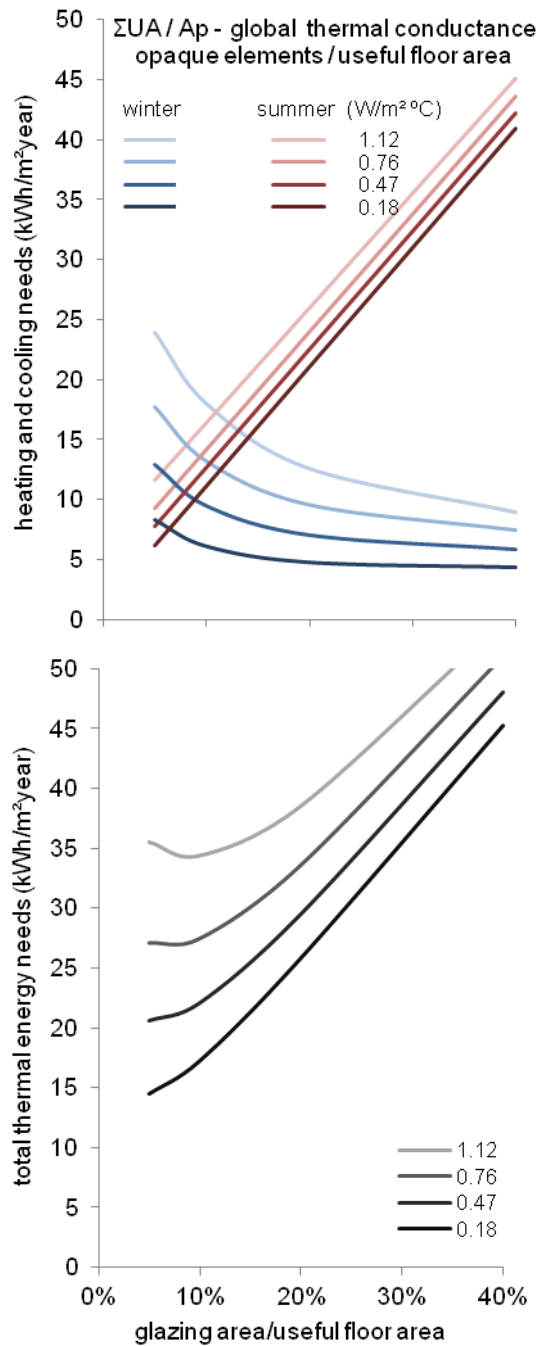


Figure 80 Heating, cooling and total thermal energy needs. Évora, S, med. inertia, int. shading

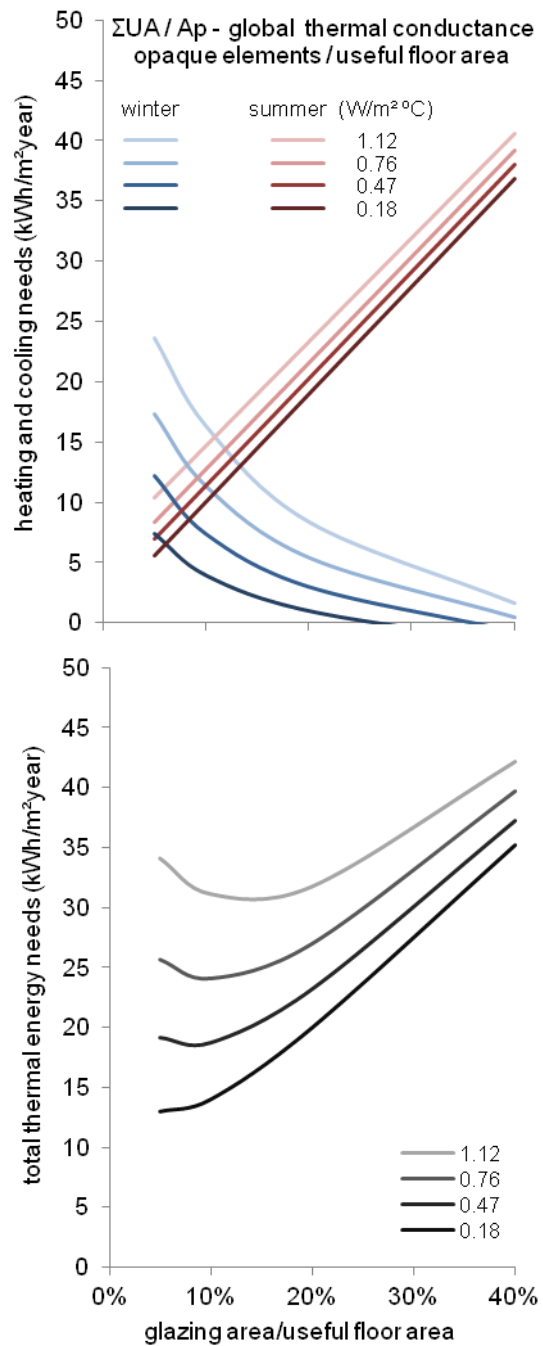


Figure 81 Heating, cooling and total thermal energy needs. Évora, S, heavy inertia, int. shading

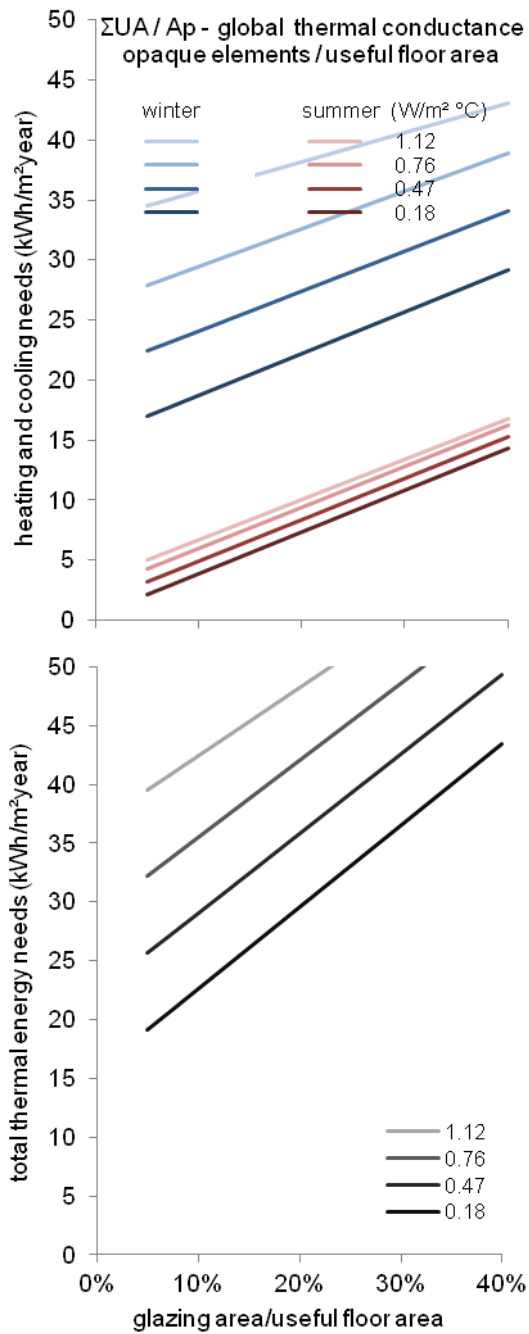


Figure 82 Heating, cooling and total thermal energy needs. Évora, N, heavy inertia, int. shading

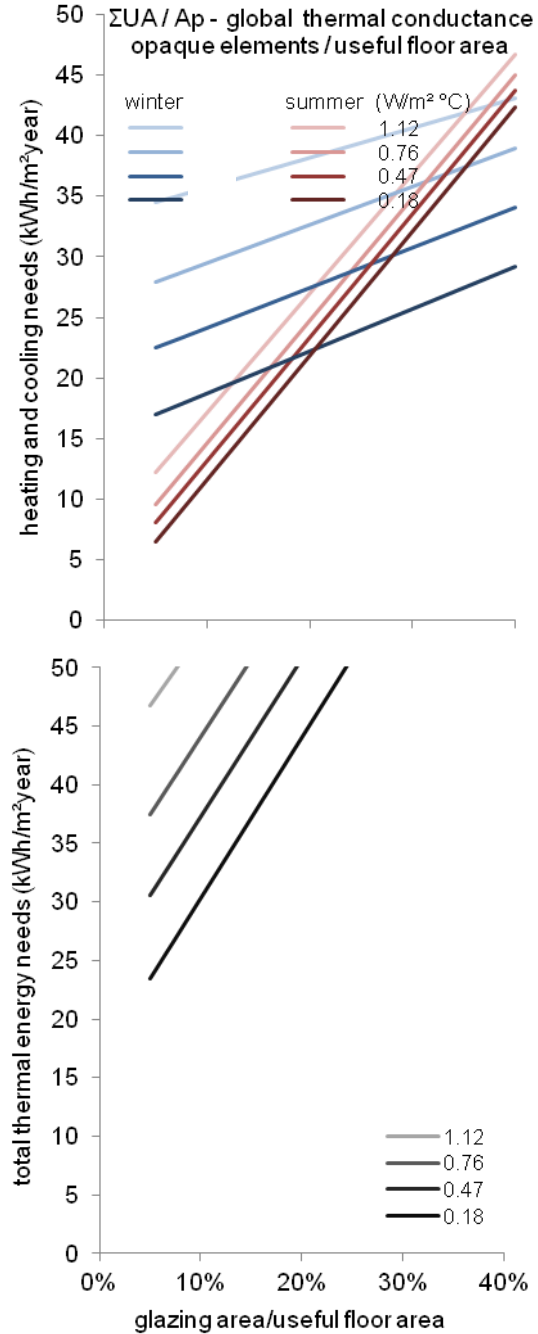


Figure 83 Heating, cooling and total thermal energy needs. Évora, W, heavy inertia, int. shading

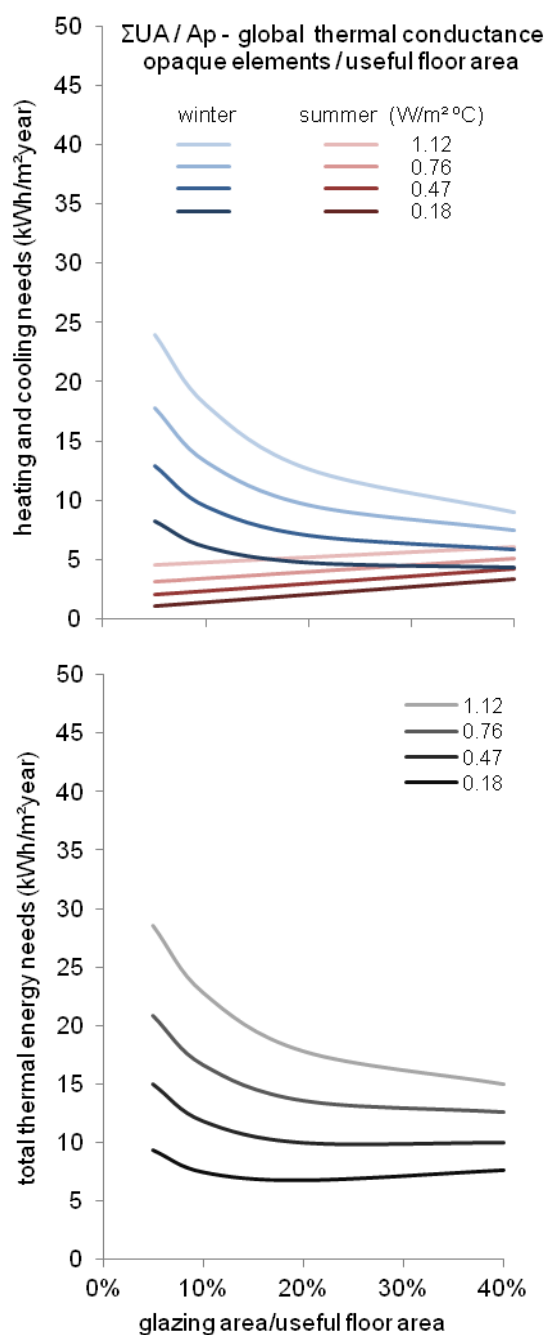


Figure 84 Heating, cooling and total thermal energy needs. Porto, S, med. inertia, ext. shading

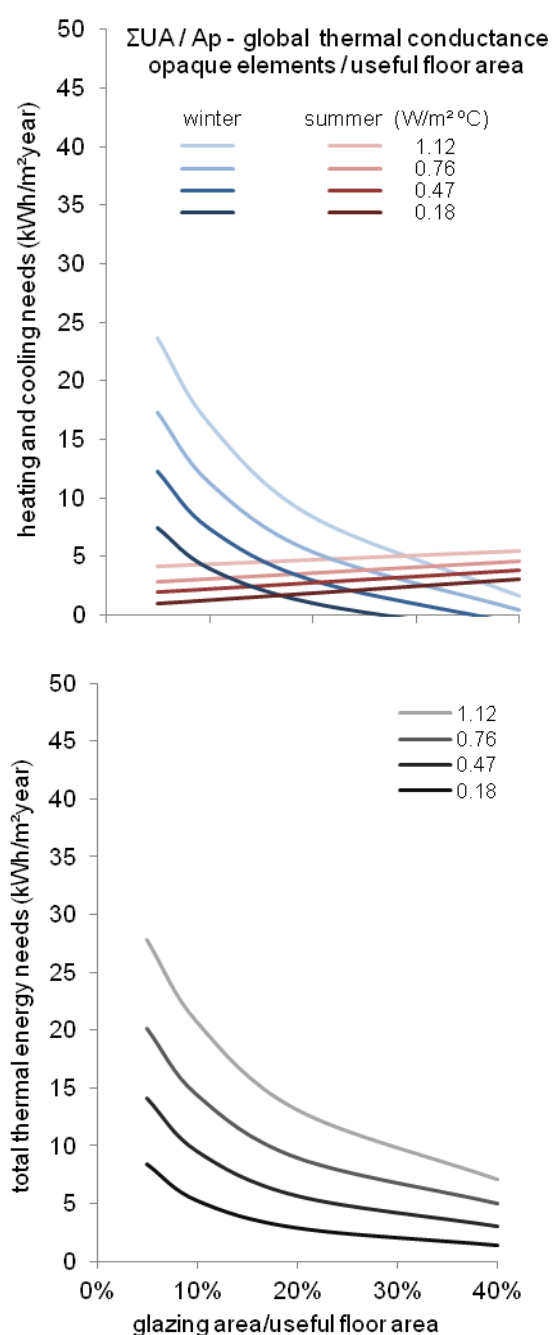


Figure 85 Heating, cooling and total thermal energy needs. Porto, S, heavy inertia, ext. shading

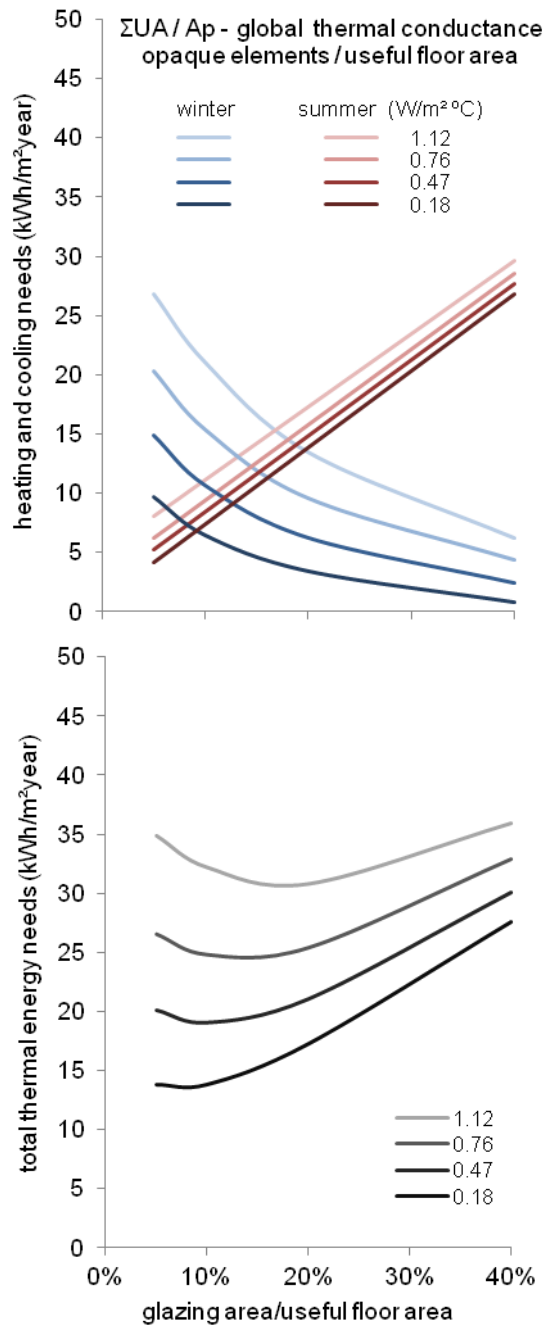


Figure 86 Heating, cooling and total thermal energy needs. Porto, SE, heavy inertia, int. shading

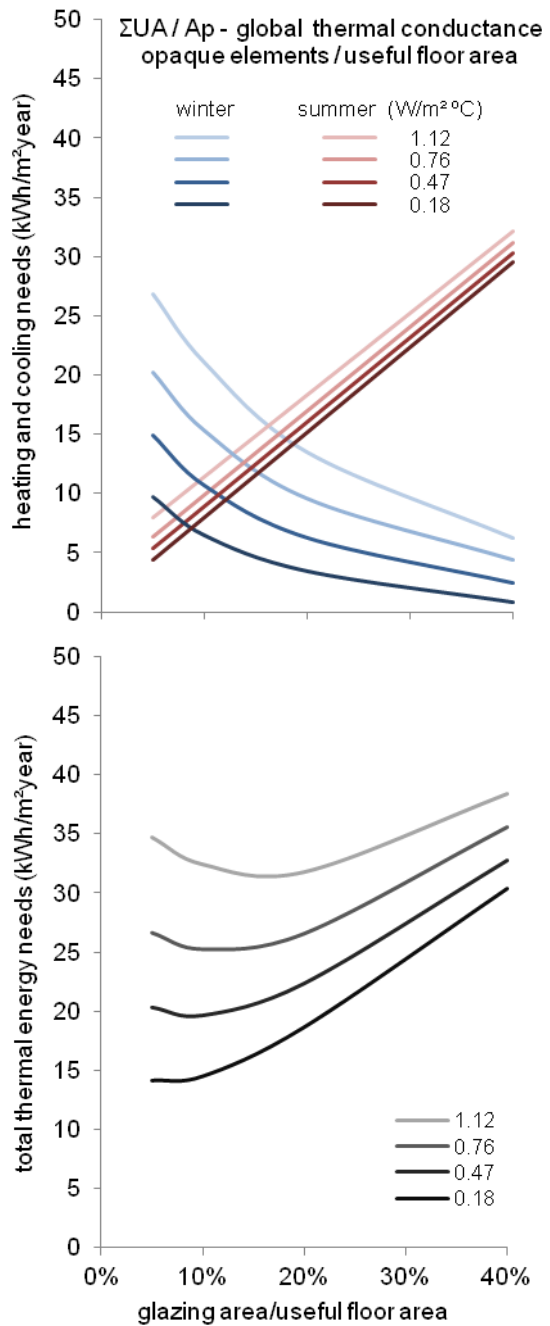


Figure 87 Heating, cooling and total thermal energy needs. Porto, SW, heavy inertia, int. shading

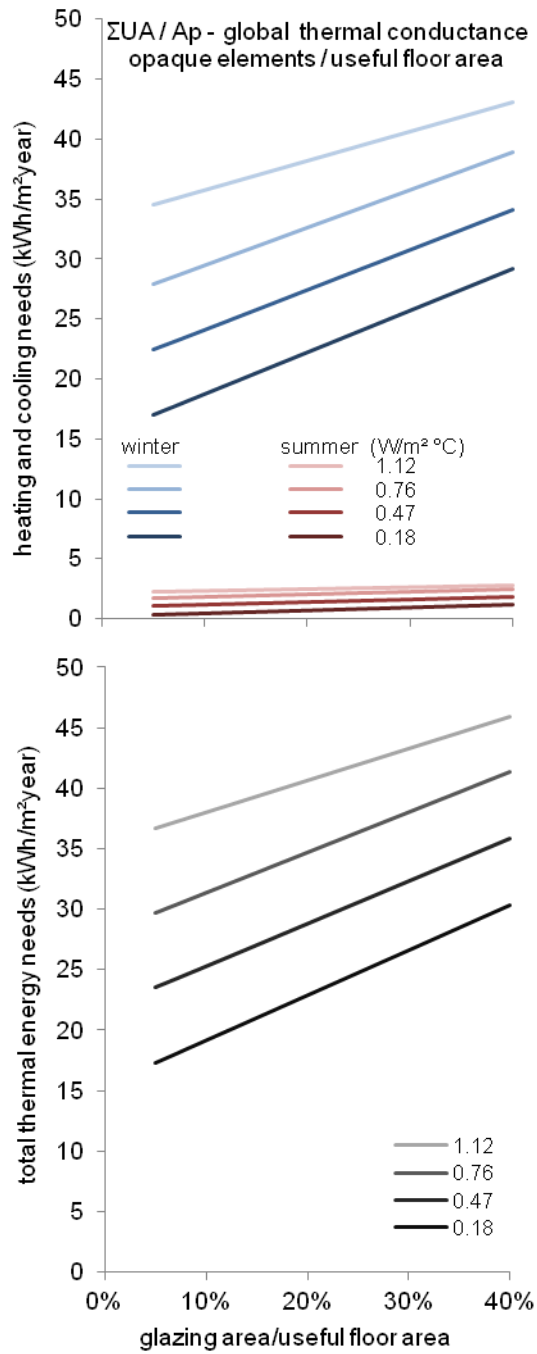


Figure 88 Heating, cooling and total thermal energy needs. Porto, N, heavy inertia, ext. shading

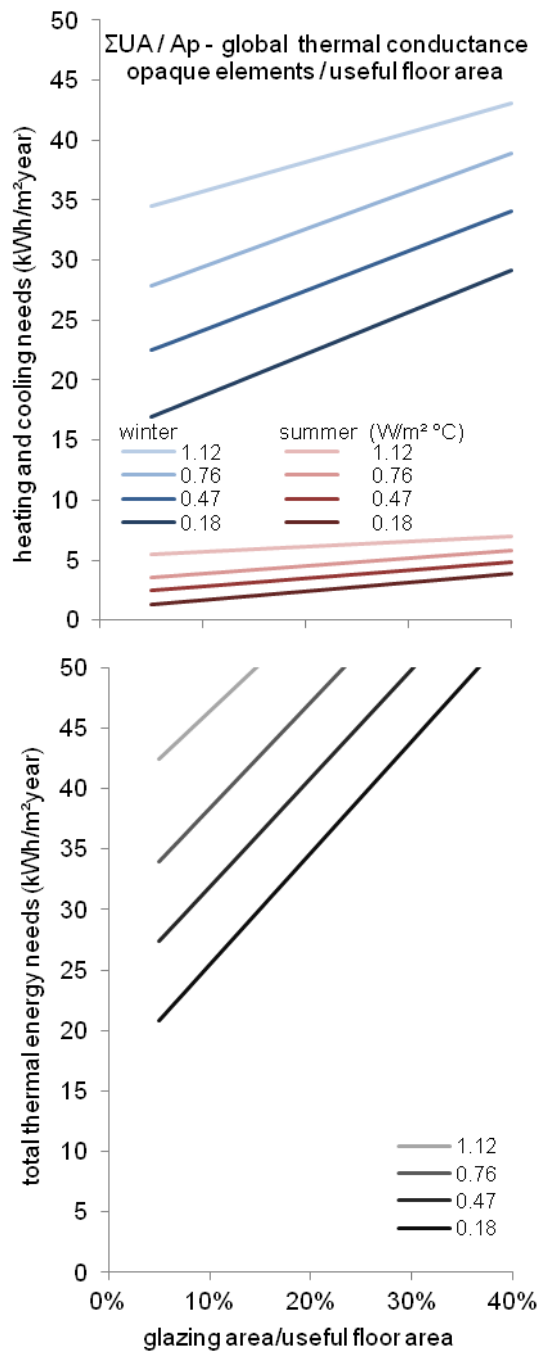


Figure 89 Heating, cooling and total thermal energy needs. Porto, E, heavy inertia, ext. shading

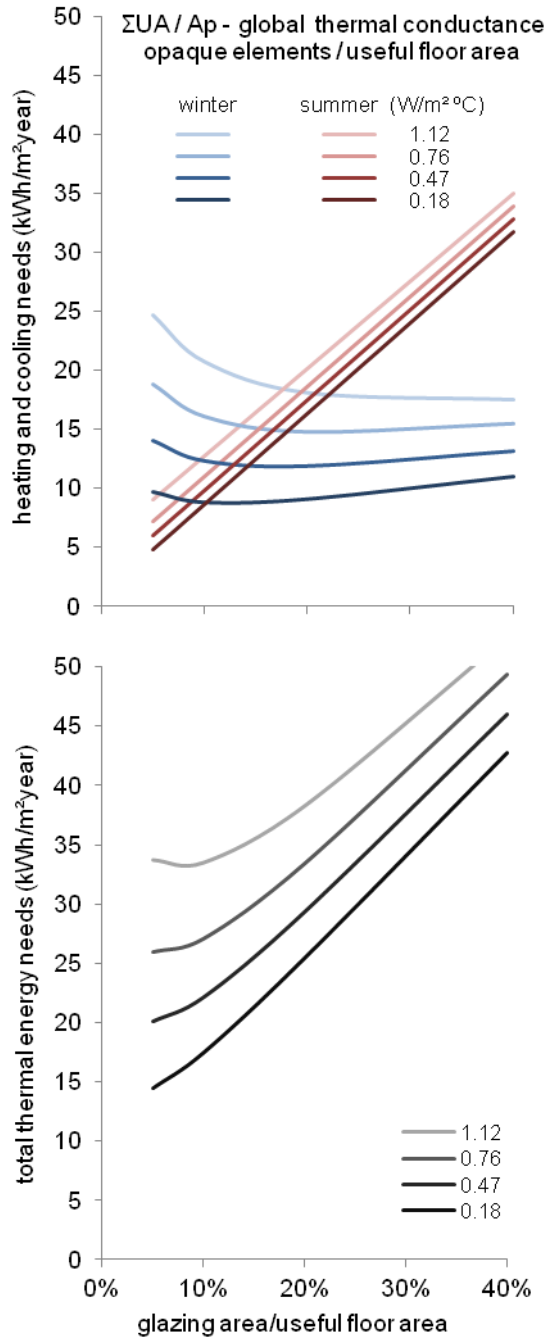


Figure 90 Heating, cooling and total thermal energy needs. Porto, S, weak inertia, int. shading

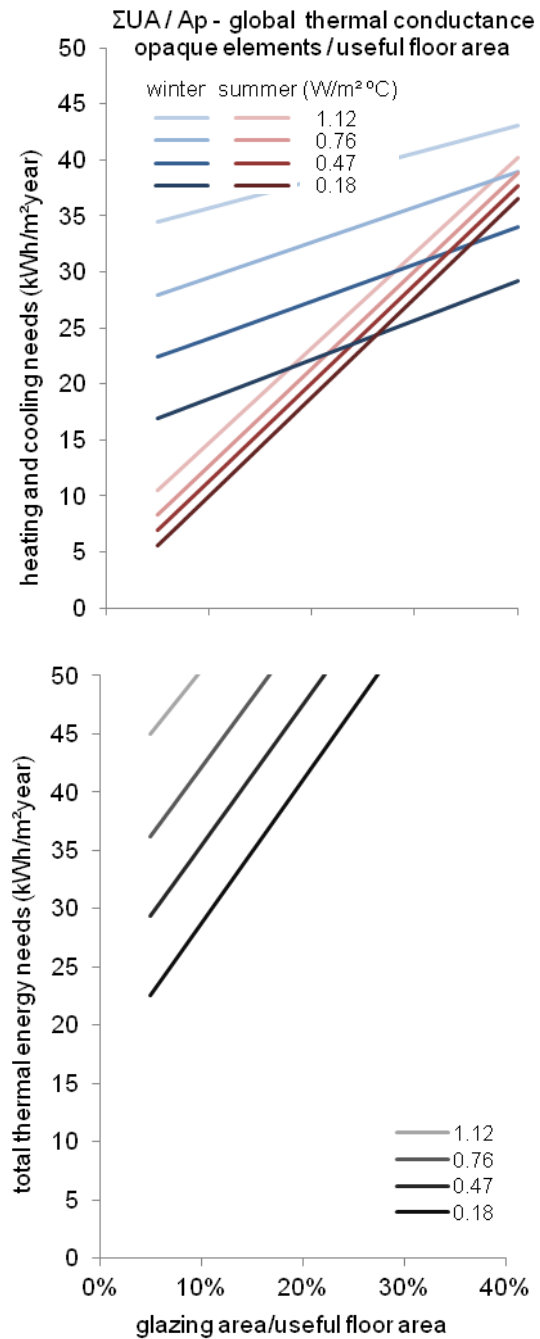


Figure 91 Heating, cooling and total thermal energy needs. Porto, W, weak inertia, int. shading

From the results on Tables 15 and 16, in general terms, it can be said that: a. heat losses in winter can be tackled with success using reasonable levels of insulation; b. the thermal inertia does not need to reach the 'heavy' levels, as results with 'medium' can be acceptable both for winter and for summer. Still, it is important to remember that rough categories of inertia are taken into account by the calculation method and some work would need to be done on the characterization of building components in order to somehow 'standardize' their thermal inertia; c. more attention must be paid to the orientation of openings and its relationship with the glazing ratio and shading strategies, wide windows bales oriented towards north and west are negative in winter, as they tend to reduce the envelope conductance and may be almost uncontrollable in summer if external shading is not provided.

As already discussed above when some comparisons were made between Porto and Bragança, the climate zones defined by RCCTE 1990 are not very determinant. The results for the two cities in the South, Lisboa and Évora, also meet this finding. Obviously, in terms of solar geometry, the difference is not noticeable, but those cities have higher temperatures in summer and so tend to have higher needs for cooling.

Yet, as the questions of the ventilation are not fully addressed in this thesis by option, the solutions will be likely to be very much focused on the dimension of the glazed areas, their orientation and the shading applications.

6.2.1 Thermal conductance of opaque exterior components

The study of exterior components with different global thermal conductance of opaque exterior components for the same space, with the same glazing ratio, showed that the relationship between the variation of thermal conductance of buildings exterior opaque components and their heating needs and cooling needs is linear (Figures 60-63), which means that reference values can be attributed to UA according to different climates.

6.2.2 Thermal inertia

By establishing a comparison between spaces with heavy and medium thermal inertia, it is possible to observe that while for summer comfort, heavy inertia plays always a relevant role, independently of the space orientation, for winter comfort heavy inertia

gives a more significant contribution for southern orientations and especially when glazing surfaces are larger (Figures 72, 73). The parametric study did not encompass weak thermal inertia for spaces under study. However, a few studies were driven for a south oriented space and for a west oriented space in Porto, in order to better evaluate the influence of the weak thermal inertia (Figures 90 and 91). It was observed that for the space oriented towards the south, heating needs are 50% higher for a space with weak inertia than for a space with heavy inertia. In the space oriented towards the west, with weak thermal inertia, the cooling needs are 40% higher than for a space with medium or heavy inertia.

Regarding total thermal energy needs for a space with global thermal conductance per useful floor area of 0.47 located in Porto (Figure 73), the choice of heavy thermal inertia in a south oriented space leads to an optimum point of 10% of glazing ratio (corresponding to 7 kWh/m² year of heating needs and 7 kWh/m² year of cooling needs), while the optimum point of glazing ratio for a space with weak thermal inertia is 50% less (corresponding to 14 kWh/m² year of heating needs and 6 kWh/m² year of cooling needs) (Figure 90).

6.2.3 Glazing orientation and size

Having in mind the presented graphics, it is relevant to underline that it is possible to carry on a space thermal assessment only with the parametric study of thermal needs for north, west (or east) and south. The others orientations can be inferred from these three. However, it is relevant to refer that spaces oriented towards east benefit from solar radiation from earlier hours of the day, while spaces west oriented are exposed to the intense solar radiation of later hours of the day and overheating is more likely to occur. Figure 92 below shows the three 'energy signatures' according orientations.

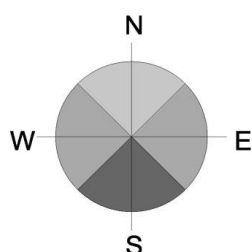


Figure 92 Different types of 'energy signatures' according to spaces orientation

Regarding the optimum point of the glazing ratio: for a given south oriented space with $1.12 \Sigma UA/A_p$ and heavy thermal inertia in Porto (Figure 73) and regarding total thermal energy needs, the optimum point is 20% of glazing ratio, corresponding to 8 of Nic and 15 of Nvc. The thermal curve also shows that increasing 1 kWh/m² year from this point leads to a large range of reasonable values for glazing surfaces, from 15% to 24% of glazing area to floor useful area.

The influence of the glazing ratio is significantly different in the heating and cooling needs for other locations. For the same space with heavy inertia oriented towards south in Lisboa (I2, V2) (Figure 77) the optimum point is 5% of glazing area to floor useful area, corresponding to 11 of Nic and 13 of Nvc, and increasing 1 kWh/m² year from this point leads to a range from 5% to 13% of glazing area to floor useful area. For Bragança (I3, V2) (Figure 69) the optimum point is 40% of glazing area to floor useful area, corresponding to 13 of Nic and 26 of Nvc, and increasing 1 kWh/m² year from this point leads to a range from 37% to 40% of glazing area to floor useful area. In the case of Évora (I2, V3) (Figure 81) the optimum point is 10% of glazing area to floor useful area, corresponding to 16 of Nic and 15 of Nvc, and increasing 1 kWh/m² year from this point leads to a range from 7% to 12% of glazing area to floor useful area.

6.2.4 Shading devices

During summer, exterior shading devices can reduce very significantly the cooling needs of a given space, independently from its orientation.

The comparison of Figures 73 and 85; Figures 72 and 84; and Figures 74 and 88 shows that the cooling needs of a space with exterior shading devices represent half, or even less, of the cooling needs of a space with interior curtains, depending on the glazing area to floor area. For a space oriented towards the south with interior curtains with heavy thermal inertia and $1.12 \Sigma UA/A_p$, the optimum point of the glazing ratio is 20%. The same space with exterior shading devices presents an optimum value of glazing ratio of 40%. The range of values for the choice of glazing ratio is also much higher for a building or space with exterior devices.

However and regarding the thermal assessment in building design, the graphic without exterior shading device is the best indicator for the choice of the glazing ratio, taking

into account that during summer, the exterior devices operation is highly dependent of occupants' behavior. The graphic without exterior shading should be used for assessing the choice of glazing ratio and the graphic with exterior shading should be used to inform about the influence of choosing exterior shading on the cooling needs, and subsequently, on the total thermal energy needs of a given space.

6.2.5 The climate type influence

There are no significant differences and these can be synthesized in the following points:

- For southern oriented spaces, the optimum point of glazing ratio is significantly different according to the location of the spaces. For the other space orientations (north, east and west), in which useful free solar gains are not considered, some locations have more heating needs than others, but, in any of the locations, the lowest glazing ratio should always be considered;
- The cooling needs of Lisboa (V2) and Évora (V3) are not significantly different. This is due to their location in the South. Thus both cities register high temperatures, closer to those of the Mediterranean climate and the summer climate zone category is not very relevant.
- In climate zones with more cold winters, as Bragança, it is desirable to choose solutions with lower total thermal conductance. However, if we ask: 'What are the most relevant solutions for each location?' The answer is that best fundamental constructive solutions match all locations – heavy inertia, south glazing, exterior shading, and global thermal conductance as low as possible. The most specific item to be optimized is the glazing ratio and the orientation towards the south.

6.2.6 Summary

Going back to Figure 56, Chapter 4, and bearing in mind the extrapolation of results of Chapter 6 for the building design, we can realize that for the starting phase of the architecture design a set of general rules must be followed:

1. To bear in mind the importance of the building location regarding, namely: a. the potential of the orientation of the more relevant façades; b. the potential for the use of vegetation as a design input to cope with a. and eventually for strategic shading and to refresh the incoming air in summer. That will cover the categories B and C of

the base program related to the 'site constraints' and could also lead to the study of the site potentialities.

2. Yet, at the earlier design stage it is crucial, as it was stated as a target for this thesis, to play with the critical inputs according to Table 7, corresponding mostly to parameters of category A and B, which were the ones tackled in thermal analysis in Chapter 5 and aggregated in this chapter.

Then, embracing the results presented, we can resume that:

Parameters from category A - The thermal insulation is a critical input that shall be selected with the appropriate thickness bearing in mind the climate references for the area but also the specific location and orientation of the building and shall be applied continuously for an external opaque envelope, without thermal bridges.

Parameters from category B - Double glazed windows shall also be used, as criteria of sympathy with the rest of the envelope, but also as a reference for acoustics.

- The windows size, i.e., the glazing ratio is particularly important for the case where solar radiation can be foreseen to have a great impact on the cooling energy needs. It is clear that wide window bales are good for solar gains but, a balance must be made.

- Shading devices must definitely be applied externally. That creates some difficulties to windows oriented towards west. When the Sun goes down to a height of zero and no geometry favors other shading, the total blockage of the view occurs through the west oriented windows.

6.2.7 Comparative analysis of thermal energy needs obtained through the RCCTE method and the LT method

At this point it is interesting to establish a comparative analysis between graphics produced in last chapter and graphics generated through the LT method for southern Europe. The LT graphics have already been presented in Literature Review – Subchapter 3.4.

In order to allow a comparison, LT graphics, for the climate of Porto, were generated by the RCCTE method, using the same inputs of LT (Baker and Steemers 1990) (Figure 93).

Firstly it is relevant to highlight that the calculation method integrated in LT departs from a different assumption of the RCCTE method as it considers different temperatures setpoints for thermal comfort. The setpoint for heating established by LT is 19°C and the one considered by RCCTE is 15°C with the addition of 3°C that are always supplied by internal gains, ending up to 18°C. The setpoint for cooling considered by LT is 24°C and 25°C by RCCTE. Secondly, the scope of assessment is also different. LT method considers not only thermal comfort but also daylighting assessment, being obviously by the LT graphics that lighting energy needs are low for residential buildings, resulting in a very modest contribution to total energy needs.

Both graphics, the one produced in this thesis and the LT graphics, intend to assess the decision of the glazing size choice in the architectural building design. However, and in what concerns the calculation method, indicators and reference inputs of LT for residential buildings and of RCCTE are slightly different. In order to make the comparison possible, LT graphics were generated by the RCCTE method, using the same indicators and inputs of LT, namely:

- The glazing indicator is the ratio of glazing area per façade area;
- Glazing areas encompass a large range of values as the former LT method was used for office buildings assessment;
- Attributed U-value for glazing is 2.85 W/m² °C;
- Attributed U-values for both roofs and walls are 0.6 W/m² °C;
- The rate of renovation of air per hour is 1.5;
- Three solar factors are considered for summer: 1, 0.7 and 0.35.

Graphics produced by the two methods are presented side by side in Figures 93 and 94. Two similarities and two divergences between the two methods are pointed out below.

One of the most remarkable similarities is that heating and cooling needs are similar in some orientations, namely for east and west, as well as for south, southeast and southwest. The grouping of energy needs by orientations can definitely lead to four 'energy signatures' resulting from building orientation/position of the glazing – south, east/west and horizontal surface.

The second similarity to highlight is that the optimum point recommended for the glazing ratio for spaces oriented towards south almost coincides, even if resulting in different heating and cooling needs. For a summer solar factor of 1, the best ratio of glazing is 20% for RCCTE and 15% for LT method, while for a summer solar factor of 0.35 the optimum glazing size is 40% for RCCTE and 35% for LT.

The first considerable difference between thermal energy needs is that cooling energy needs obtained through LT are substantially higher than the ones obtained through RCCTE. This divergence might be explained by the different cooling setpoints that are considered as a departing point. Another possible reason is that RCCTE underestimates cooling needs.

The second relevant divergence consists in heating needs for east/west and north orientations. RCCTE method considers that for these orientations, glazing areas should be as smaller as possible, because enlarging glazing surfaces increases both heating and cooling needs. This is due to the fact that the method takes into account that, for winter, none of these orientations receive useful solar gains. The LT graphics indicate that for north, east and west optimum glazing areas are 5% for these three cases with a solar factor of 1, and 25% with a solar factor of 0.35, given that the method considers that these orientations also receive some free solar gains in winter.

The sensitivity study didn't encompass horizontal surfaces, but the following graphics allow comparing results for skylights. As for other orientations, the differences are due to much higher cooling needs obtained through LT.

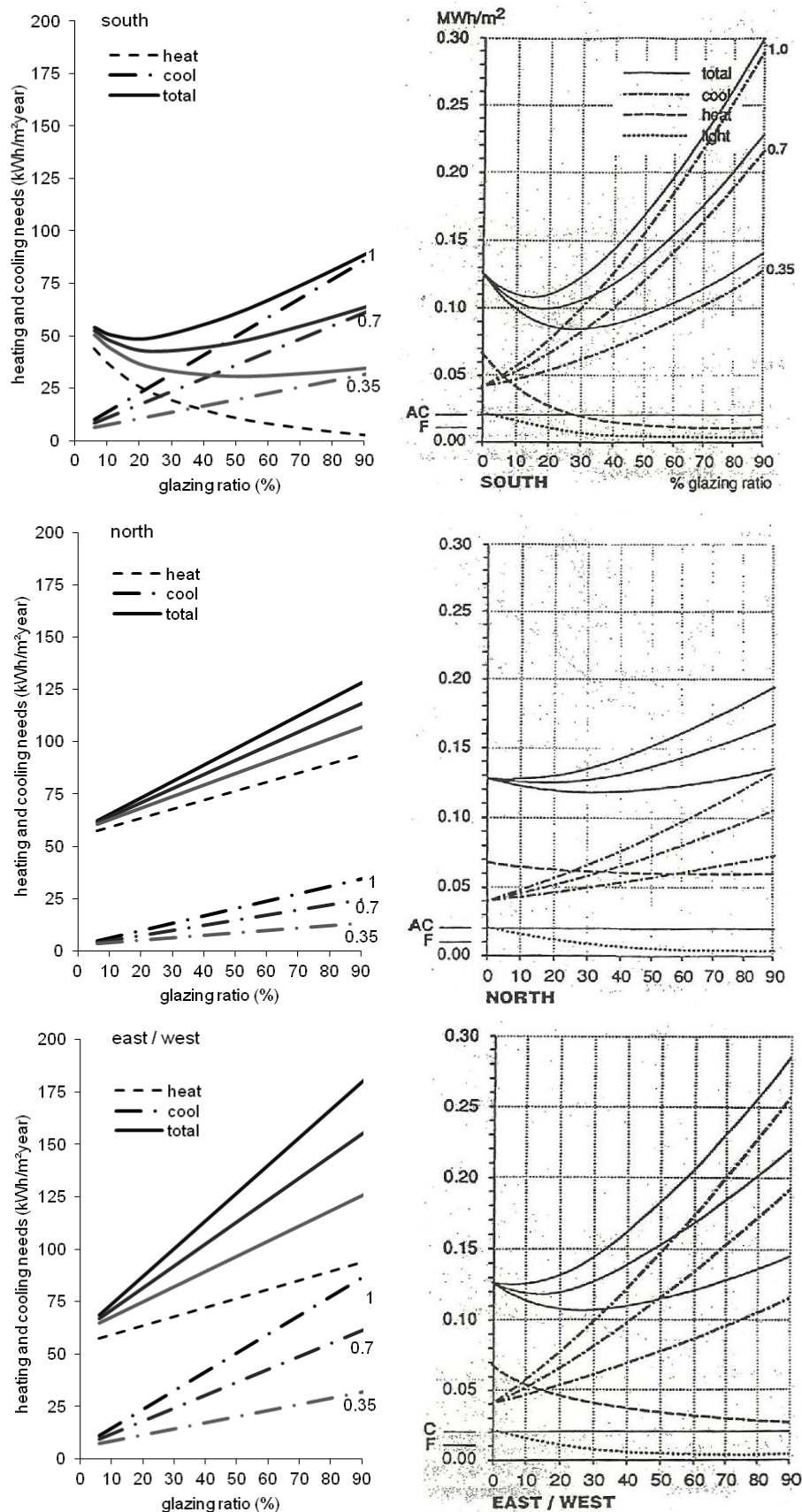


Figure 93 LT graphics (RCCTE method)/LT graphics (Baker and Steemers). S,N and E/W

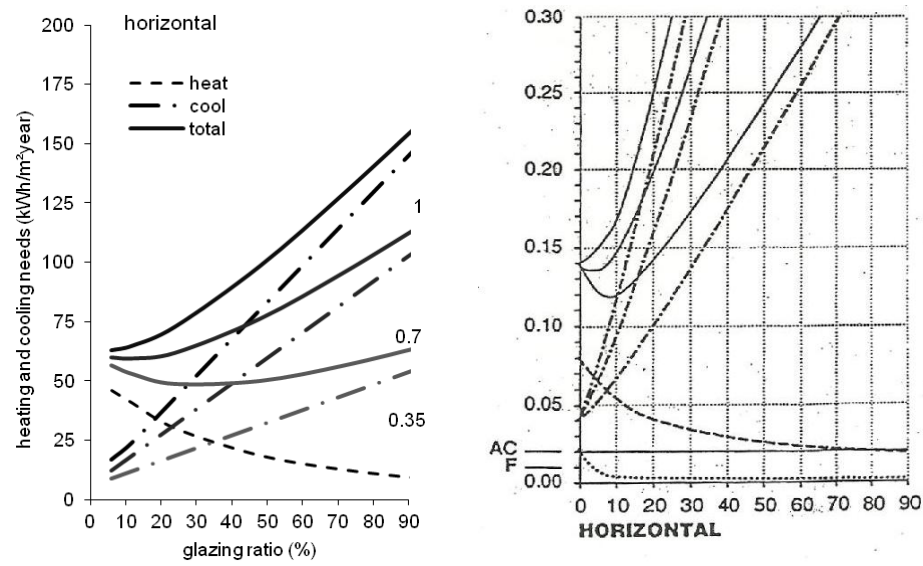


Figure 94 LT graphics (RCCTE method)/LT graphics (Baker and Steemers). Horizontal surfaces

7 Guided methodology – decision trees used to build the Expert System

7.1 Introduction

After the sensitivity study of Chapter 5 and the results of Chapter 6, it is possible to undertake an exploratory exercise on the integration of these graphics into a routine associated to an expert system to assist on the building design assessment. This will allow the architect to dispose of a timely quantification of the results of the options/decisions at an earlier phase of the building design, before all sophisticated simulations could have been undertaken.

As it has already been referred in Chapter 3, almost all assessment tools are black boxes and do not contribute to give users appropriate information regarding the adopted options. Thus, the roadmap to a practical and accessible methodology of thermal assessment is consistent with the development of a transparent method that follows the normal procedures of architects, being supported with recommendations and explanations, as well as a straightforward quantification of the constructive choices. This type of tool will improve the sensitivity and the intuition of users during the process of decision making of the Architectural building design.

The developed tool is an expert system built in Exsys Corvid with the data obtained through the sensitivity analysis and embedding qualitative data in the form of recommendations that guide users in their design options. In order to make the methodology practical and accessible, firstly decision trees are developed taking into account the possible paths of decision conducted by constraints of the building design. The paths of decision trees determine possible options and desirable ways for more properly responses of the architectural spaces to their adaptation to the climate, in order to improve thermal comfort conditions.

7.2 Decision trees and explanations of relevant information for the Expert System

Decision trees are structured by modules embedding rules that are expressed to users in the form of questions-answers-recommendations.

The assessment is made at the level of the architectural space, given that in the same building, different spaces orientation can lead to significant different thermal needs. However, at the level of the building as a whole, the orientation is also assessed in order to give recommendations to the best choices, at the building scale.

Decision trees begin with questions regarding the location of the architectural space and the type of intervention/scope of assessment – new/retrofit. In the case of retrofit, a higher number of constraints narrow the possibilities of the decisions, while for new construction the best choices can almost always be undertaken.

Subsequently, the questions of the modules that correspond to the critical input parameters – orientation, thermal insulation position and global thermal conductance, thermal inertia, and glazing ratio and orientation – guide the users' choices. The assessment is both quantitative and qualitative. The last modules are constituted by the ventilation and by the parameters for energy valorization and for these ones a qualitative assessment supports the users' choices, with graphical explanations of some of the most effective solutions.

The selected location, the choices related with the constructive elements, namely the area and the coefficient of thermal transmission, and the internal mass, as well as the glazing orientation, will lead to a specific 'energy signature' or graphic of thermal needs, which in the end is presented to the user. In order to allow the interpretation of the graphic and its application in specific cases, the user is previously informed of the $\Sigma UA/A_p$ of opaque exterior elements and of the thermal inertia category resulting from the selected constructive choices.

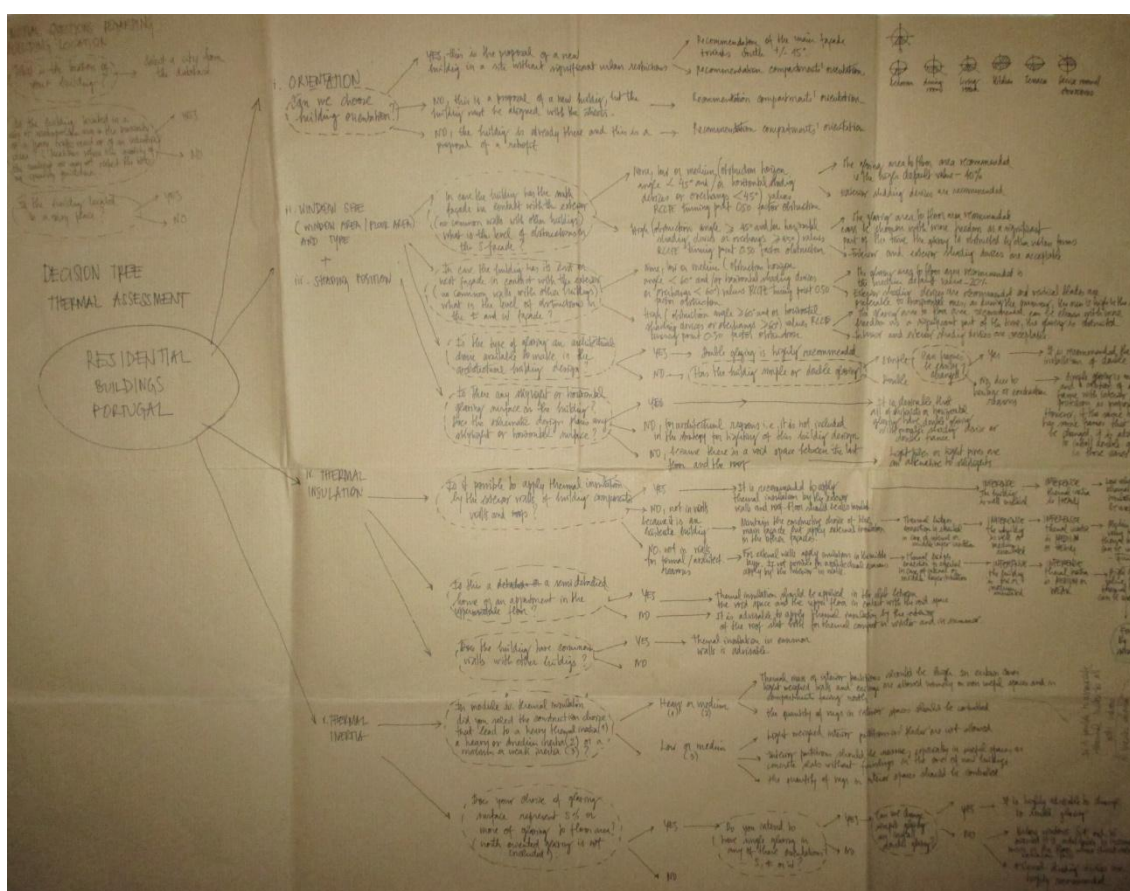


Figure 95 First sketch of the decision tree

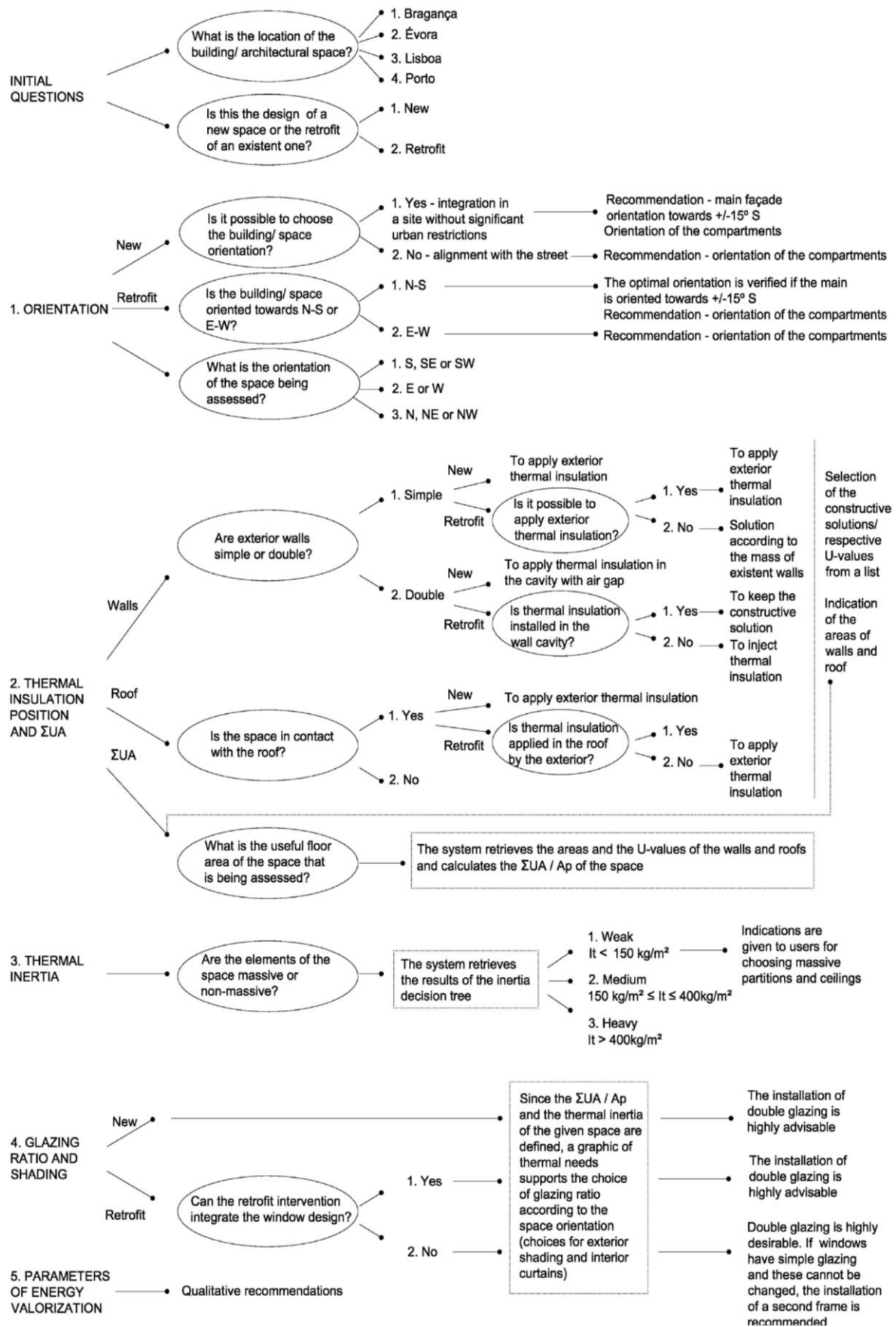


Figure 96 Decision tree for the thermal assessment of residential spaces in Portugal

1. Orientation

The thermal support encompasses both the building and its compartments according to their functions.

Table 17 Aid proceedings related with the building orientation

Scope of assessment	Main questions	Answers	Specific recommendations/indications
Orientation new	Is it possible to choose the building/ architectural space orientation?	Yes, this is the proposal for a building in a site without significant urban restrictions	Recommendation of the main façade orientation towards S or with an angle of $\pm 15^\circ$ deviation * Besides this, recommendations for the location and orientation of compartments should be followed **
		No, the building must be aligned with the street	The optimal orientation is verified if the main façade is oriented towards S or with an angle of $\pm 15^\circ$ deviation * Moreover, recommendations for the location and orientation of compartments should be followed **
Orientation retrofit	Is the building/ architectural space mainly oriented towards N-S or towards E-W?	N-S	The optimal orientation is verified if the main façade is oriented towards S or with an angle of $\pm 15^\circ$ deviation * Recommendations for the location and orientation of compartments should be followed **
		E-W	Recommendations for the location and orientation of compartments should be followed **

Additional information

Recommendation of location and orientation of compartments



Optimal orientation for compartments according to their functions

Bedrooms should be oriented mainly towards S, SE and E. Preferable orientation for living rooms and dining rooms is W, SW, S, SE, E. The kitchen should not be oriented towards NW. Service compartments, laundries, storerooms and pantries can be located in the orientations that are less insulated - N, NE, NW -, while terraces should have more insolation or benefit from morning sun - E, SE, S, SW, W (Atkinson 1912) (Olgay and Olgay 1963) (Montavon 2010).

2. Thermal insulation position and global thermal conductance

From this point on, the thermal assessment is performed for spaces.

The thermal insulation in exterior walls is one of the issues in which the level of thermal assessment more diverges regarding new spaces and spaces being retrofitted, while for roofs it is considered that the level of intervention is high for both cases. In fact, in the case of building retrofit, site regulations can limit the choices for exterior walls and very frequently, exterior thermal insulation may not be applied due to values linked to heritage conservation. In these cases, in order to choose the most adequate solution, it is relevant to know if existent walls are massive or non-massive.

Regarding the sequence in the assessment provided by the tool, firstly, the support is carried out at the level of the position of thermal insulation and the U-value of exterior components. After constructive solutions being chosen, the answers related to the areas of the elements of the space and to the useful floor area allow the calculation of the $\Sigma U A / A_p$, which is performed by the inference engine of the software Exsys Corvid.

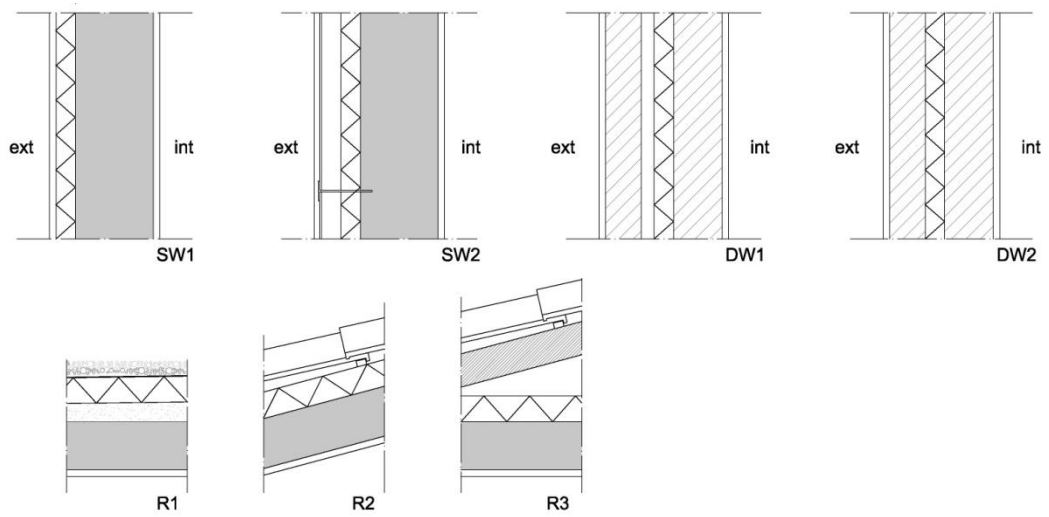
Table 18 Aid proceedings related with the thermal insulation position and global thermal conductance for new spaces

Scope of assessment: New		
Main questions	Answers	Specific recommendations/indications
Walls: Are exterior walls simple or double?	Simple	Exterior thermal insulation is highly advisable in order to reduce the heat losses during winter and it is a mainstream departing point for a low energy building.
	Double	It is recommended to apply thermal insulation in the air cavity with air gap.
Roof: Is the architectural space in contact with the roof?	Yes	Apply thermal insulation by the exterior of the roof slab both for thermal comfort of summer and to reduce heat losses in winter.
	No	—
U-values: What are the constructive solutions for walls and roofs?	The user indicates the requested values	Indications are given in function of the previous answers and in order that the user makes a conscious choice Choices given: List of constructive solutions and respective U-values based on the publication ITE-50 ***
$\Sigma U A / A_p$: What is the area of walls and roofs/ useful floor area of the space that is being assessed?	The user indicates the requested values	The systems performs the calculation according to users answers and gives the indication of the $\Sigma U A / A_p$ of the given space

Table 19 Aid proceedings related with the thermal insulation position and global thermal conductance for retrofitted spaces

Scope of assessment: Retrofit				
Main questions	Possible answers	Subsequent questions	Answers	Specific recommendations/indications
Walls: Are exterior walls simple or double?	Simple	Is it possible to install exterior thermal insulation?	Yes	Exterior thermal insulation is highly advisable in order to reduce the heat losses during winter and it is a mainstream departing point for a low energy building.
			No, only in some walls due to structural or heritage reasons linked to the site regulations where the building/ architectural space is integrated	Keep the constructive solution of the façades in which is not possible to apply exterior thermal insulation, but apply exterior thermal insulation in the other façades. In façades in which is not possible to apply exterior thermal insulation integrate a brick wall by the interior with air gap and thermal insulation in case existent walls are not massive. If these are massive, another combined solution, less strict, may be chosen.
			No, not in all exterior walls for constructive reasons or heritage reasons linked to the site regulations	Integrate a brick wall by the interior with air gap and thermal insulation in case existent walls are not massive. If these are massive, another combined solution, less strict, may be chosen.
			Independently of the constructive choice be aware: thermal bridges correction is essential in the cases of internal thermal insulation.	
	Double	Is thermal insulation installed in wall cavity?	Yes	Keep the constructive solution.
			No	Apply thermal insulation through an injection of foam in the cavity by strategic injection holes. This solution for walls has some limitations: the cavity can have a small thickness or be filled with mortar or debris, which in any case can be an obstacle to the homogeneous application of thermal insulation along the wall. So, the execution quality should be ensured by expert technicians.
			Independently of the constructive choice be aware: thermal bridges correction is essential in the cases of internal thermal insulation.	
Roof: Is the building/ space in contact with the roof?	Yes	Does the building have exterior thermal insulation?	Yes	Exterior thermal insulation is highly advisable in order to reduce the heat losses during winter and it is a mainstream departing point for a low energy building.
			No	Apply thermal insulation by the exterior of the roof slab both for thermal comfort of summer and to reduce heat losses in winter.
	No	-	-	-
U-values: What is the construct. solution for walls and roofs?	The user indicates the values	-	-	Indications are given in function of the previous answers and in order that the user makes a conscious choice Choices given: List of constructive solutions and respective U-values based on the publication ITE-50 ***
$\Sigma UA/A_p$: What is the area of walls and roofs/ useful floor area of the space?	The user indicates the values	-	-	The systems performs the calculation of $\Sigma UA/A_p$ according to users answers

Table 20 Aid proceedings related with the constructive solutions for exterior walls and roofs

Additional information
The following explanation is given to users for a better understanding of the meaning of the U-value: A U-value, or coefficient of thermal transmittance, is the physical property of a material to conduct heat. It measures the heat transfer through a building element such as an exterior wall and roof. The lower the U-value, less heat losses will be verified. Building elements with thermal insulation have relative low U-values.
List of constructive solutions and respective U-values based on the publication ITE-50
***  SW1 - Simple wall with exterior thermal insulation without air gap 6cm EPS, brick masonry (20-24cm) or lightweight concrete masonry (20-30cm) – 0.45 W/m² °C 6cm EPS, stone masonry (20-30cm) – 0.54 W/m² °C SW2 - Simple wall with exterior thermal insulation and air gap 6cm EPS, brick masonry (20-24cm) or lightweight concrete masonry (20-30cm) – 0.49 W/m² °C 6cm EPS, stone masonry (20-30cm) – 0.58 W/m² °C DW1 - Double wall with thermal insulation and air gap 6cm XPS, double brick masonry (11+15cm) - 0.37 W/ m² °C 6cm XPS, double lightweight concrete masonry (11+15cm) - 0.39 W/m² °C DW2 - Double wall with thermal insulation without air gap 6cm XPS, double brick masonry (11+15cm) - 0.40 W/m² °C 6cm XPS, double lightweight concrete masonry (11+15cm) - 0.42 W/m² °C R1 – Flat roof with exterior thermal insulation 8 cm EPS, massive concrete slab (10-20 cm) – 0.36 W/m² °C 8 cm EPS, lightweight concrete slab (13-15 cm) – 0.35 W/m² °C R2 – Sloped roof with exterior thermal insulation 10 cm XPS, massive concrete slab (10-20 cm) or lightweight concrete slab (13-15 cm) – 0.41 W/m² °C R3 - Sloped roof with attic and thermal insulation applied by the exterior of the attic slab 10 cm XPS, massive concrete slab (10-20 cm) or lightweight concrete slab (13-15 cm) – 0.3 W/m² °C

3. Thermal inertia

The choice of lightweight components is a tendency that is gaining momentum in current buildings, especially in partitions and ceilings. However, in temperate climates, in which thermal amplitudes are high, the consideration of heavy inertial masses of interior building components is an essential aid for the reduction of temperatures fluctuation indoors.

At the level of the thermal inertia, the support of the architectural building design, considers that a clearer support is needed in order to give explicit information about the following issues:

1. What are the massive and non-massive solutions for the different constructive elements? (Table 22).
2. What is the thermal inertia category (weak, medium, heavy) that may result from a given combination of elements? In order to do so, a parametric study is performed with several scenarios that will help in the construction of the thermal inertia decision tree paths (Figure 98).
3. What is the relationship between thermal inertia, glazing ratio and orientation that will result in a higher capacity of heat storage? This issue has already been established in the sensitivity study of the Chapter 5 and synthesized in the graphics of thermal needs produced in the Chapter 6.

The support in Exsys is structured as follows:

1. Regarding the first issue, the assessment tool presents the massive and non-massive elements to users (Table 22), asking them about the selected constructive solution for each element. This will allow knowing the combination of the elements' mass and, subsequently, to attribute the resulting thermal inertia category (Table 27 and Figure 98). By doing so, it is possible to provide a straightforward assessment to users, who will be able, without performing any calculation, to identify the inertia category of a space resulting from a given combination of elements. This will answer to the issue number two. The scenarios of the parametric study are not visible to the user, but are formalized through the result of the combination of the constructive elements that are selected. The interior mass of the exterior elements is taken into account. However, no questions are made, because in this phase of the assessment the user has already selected the constructive choices, determined during the support of the assessment of exterior opaque elements, in which indications were given about the

relevance of the thermal insulation applied by the exterior in order to conserve the inertia of the internal elements.

Table 21 Aid proceedings related with the thermal inertia

Scope of assessment: New and retrofit			
Indications are given to users regarding what are the constructive solutions that are massive and the ones that are non-massive. Subsequently, the user chooses the constructive solution for each element of the given space.			
Main questions	Questions assessment	Answers	Specific recommendations/indications
Are party walls, floors, ceilings and partitions massive with finishings with reduced resistance or rather non-massive elements with finishings with high resistance?	****	Massive	In the end, the system transmits to users the category of the thermal inertia of the considered space: - heavy: - medium or - weak In the case the space has weak thermal inertia, the constructive solutions must be changed as weak inertia is not an adequate choice for Portuguese buildings. A recommendation is given to users in order to go back and choose massive ceilings and partitions with finishings with reduced resistance
		Non-massive	

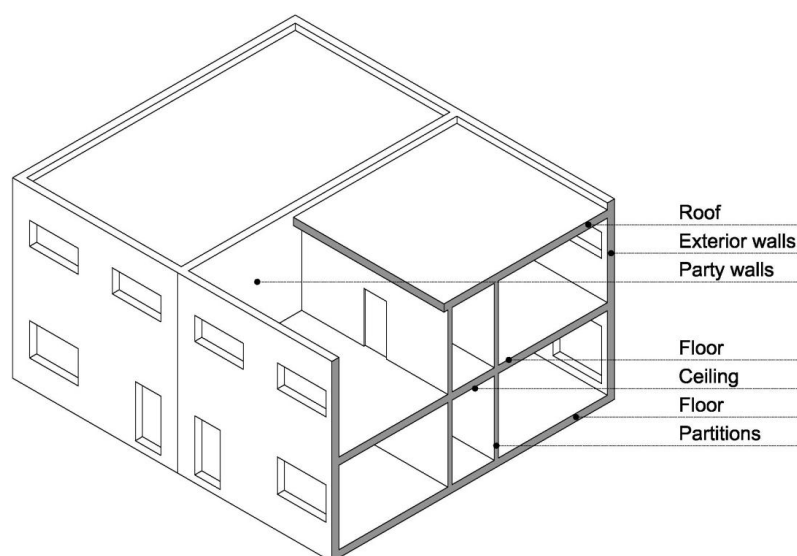
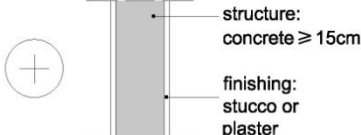
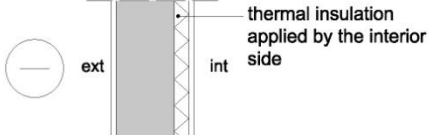
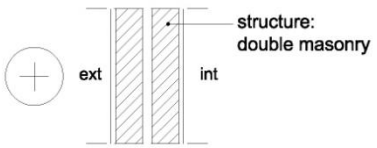
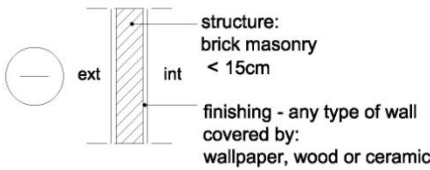
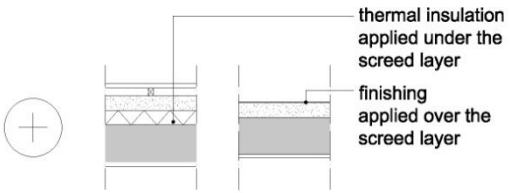
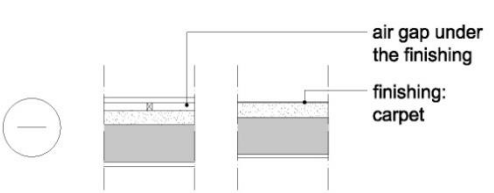
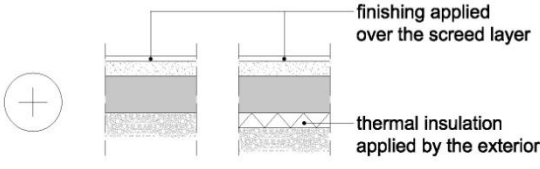
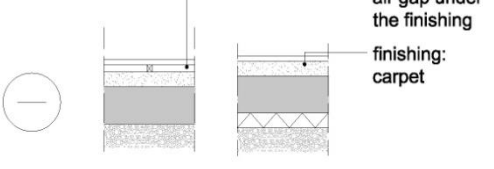
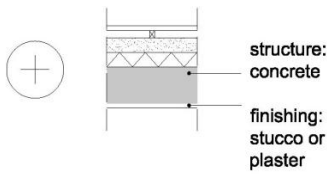
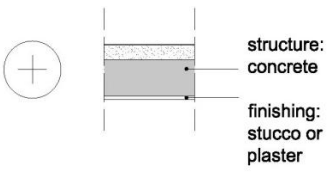
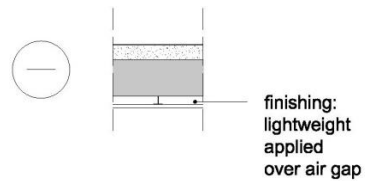
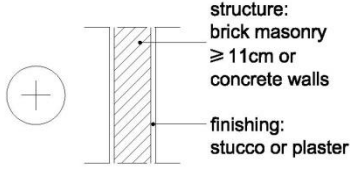
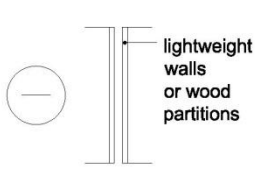
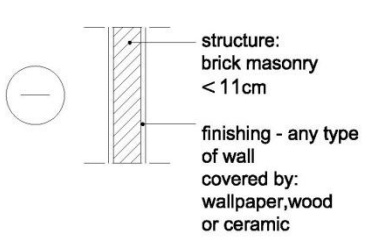


Figure 97 Identification of the elements of a given space

Table 22 Aid proceedings related with the massiveness of the building elements

Additional information	
List of massive and non-massive elements	
**** Party walls  structure: concrete $\geq 15\text{cm}$ finishing: stucco or plaster  thermal insulation applied by the interior side  structure: double masonry  structure: brick masonry < 15cm finishing - any type of wall covered by: wallpaper, wood or ceramic Floors in contact with the soil  thermal insulation applied under the screed layer finishing applied over the screed layer  air gap under the finishing finishing: carpet  finishing applied over the screed layer thermal insulation applied by the exterior  air gap under the finishing finishing: carpet Ceilings/floors between levels  structure: concrete finishing: stucco or plaster  structure: concrete finishing: stucco or plaster  finishing: lightweight applied over air gap Partitions  structure: brick masonry $\geq 11\text{cm}$ or concrete walls finishing: stucco or plaster  lightweight walls or wood partitions  structure: brick masonry < 11cm finishing - any type of wall covered by: wallpaper, wood or ceramic	

2. As it was referred before, a parametric study is performed in order to establish the category of inertia that corresponds to a given combination of elements.

The thermal inertia parametric study encompassed four different scenarios taken into account the mass of the different constructive elements. The scenarios were the following ones:

1. Combination of massive and non-massive elements, being exterior walls massive with exterior thermal insulation (1 constructive solution for exterior walls)
2. Combination of massive and non-massive elements, being exterior walls non-massive with interior thermal insulation (1 constructive solution for exterior walls)
3. Combination of massive and non-massive elements, being some of the exterior walls massive with exterior thermal insulation and, other exterior walls non-massive with interior thermal insulation (1 constructive solution for exterior walls based on the combination of elements)
4. Combination of massive and non-massive elements, being some of the exterior walls massive with exterior thermal insulation and, other exterior walls massive (3 constructive solutions for exterior walls based on the combination of elements)

The calculation method used for the mass calculation was the one used by the RCCTE, which considers three categories of inertia: weak: $I_t < 150 \text{ kg/m}^2$; medium: $150 \text{ kg/m}^2 \leq I_t \leq 400 \text{ kg/m}^2$ and heavy: $I_t > 400 \text{ kg/m}^2$. The thermal inertia categories are attributed by RCCTE, according to the sum of components mass and the degree of exposure of the space elements.

The useful superficial mass per square meter of floor (I_t) is calculated through the following equation (RCCTE 1990), being M_i the useful superficial mass of the element (Kg/m^2), S_i the surface of the element (m^2) and A_p the useful floor area (m^2):

$$I_t = \frac{\sum M_i S_i}{A_p} \quad (\text{Kg/m}^2)$$

The study of possible scenarios was applied to four types of spaces. These spaces were the same that were used for the sensitivity analysis (Chapter 5). This study ended up with the consideration of a total of 672 cases. The matching category corresponded in 86% of the cases.

A decision tree was built based on this parametric study (Figure 98). Most cases result in medium thermal inertia. The cases of heavy inertia require the massiveness and a reduced level of resistance of the finishing of too many elements of the space, while the cases of weak inertia require too many elements non-massive and with a high level of resistance of their finishing (Table 27). The parametric study for the thermal inertia quantification also showed the high contribution of the exterior walls for the thermal inertia of an architectural space.

In the end, it was established a comparison between this parametric study and the simplified method for quantification of inertia of the REH (REH/RECS 2013), being observed that the rules of simplification of the last method consider much more simultaneous conditions for heavy inertia and the same happens with weak inertia. For instance, the current parametric study showed that there are cases of architectural spaces with massive ceilings with plaster finishing that present weak thermal inertia, and the same occurs with interior partitions. However, the simplified method of REH states that if a space has all the following boundary components: lightweight ceiling, floor with wood finishing and lightweight partitions, its thermal inertia is weak.

The results from the parametric study can provide a more detailed assessment for the inertia quantification than the simplified method of REH, but it remains the need of translating the decision tree into an accessible method. This issue will be addressed in Exsys Corvid, through an inference method.

Table 23 Discretization of massive elements with finishings with reduced resistance
(used in scenarios 1-4)

Components	Layers	Mi (kg/m ²)	Total Mi (kg/m ²)	Mi RCCTE (kg/m ²)	ri
Floor 1 - between levels	Ceramic finishing (INT)	45	306	150	1
	Screed layer - Argamassa regularização 6cm	29			
	Concrete slab 20cm	220			
	Plaster 2cm (EXT)	12			
Floor 2 - contact soil	Ceramic finishing (INT)	45	294	150	1
	Screed layer - Argamassa regularização 6cm	29			
	Concrete slab 20cm (EXT)	220			
Walls	Plaster 2cm (INT)	12	282	150	1
	Concrete wall 20cm	270			
	Exterior thermal insulation 6cm	1,8			
	Plaster 2cm (EXT)	12			
Party walls	Plaster 2cm (INT)	12	294	147	1
	Concrete wall 20cm	270			
	Plaster 2cm (EXT)	12			
Ceiling	Plaster 2cm (INT)	12	306	150	1
	Concrete slab 20cm	220			
	Screed layer - Argamassa regularização 6cm	29			
	Ceramic finishing (EXT)	45			
Roof	Plaster 2cm (INT)	5	254	150	1
	Concrete slab 20cm	220			
	Screed layer - Argamassa regularização 6cm	29			
	Exterior thermal insulation 6cm	1,8			
	Cobble (EXT)	12			
Partitions	Plaster 2cm (INT)	12	144	144	1
	Brick masonry 11cm	120			
	Plaster 2cm (EXT)	12			

Table 24 Discretization of non-massive elements and/or with finishings with high resistance (used in scenarios 1-4)

Components	Layers	Mi (kg/m ²)	Total Mi (kg/m ²)	Mi RCCTE	ri
Floor 1-between levels	Wood finishing (INT)	20	20	10	0,75
	Air gap				
	Screed layer	29			
	Lightweighed concrete slab 12cm	160			
	Air gap				
	Lightweighed ceiling plasterboard 8cm (EXT)	12			
Floor 2 - contact soil	Wood finishing (INT)	20	20	20	0,75
	Air gap				
	Screed layer - Argamassa regularização 6cm	29			
	Lightweighed concrete slab 12cm (EXT)	160			
Walls	Plaster 2cm (INT)	12	12	12	1
	Interior thermal insulation EPS 6cm	1,8			
	Lightweight concrete wall 20cm	190			
	Plaster 2cm (EXT)	12			
Party walls	Plaster 2cm (INT)	12	12	12	1
	Thermal insulation EPS 6cm	1,8			
	Concrete wall 20cm	270			
	Plaster 2cm (EXT)	12			
Ceiling	Lightweighed ceiling plasterboard 8cm (INT)	12	12	6	0,5
	Air gap				
	Lightweighed concrete slab 12cm	160			
	Screed layer	29			
	Air gap				
	Wood finishing (EXT)	20			
Roof	Plaster 2cm (INT)	5	5	5	1
	Interior thermal insulation EPS 6cm	1,8			
	Concrete slab 20cm	220			
	Screed layer - Argamassa regularização 6cm	29			
	Cobble (EXT)	12			
Partitions	Lightweighed walls with 7cm plasterboard and 10cm total thickness	29	29	29	0,5

Table 25 Discretization of combined solutions for exterior walls (used in scenario 3)

Components	Layers	Mi (kg/m ²)	Total Mi (kg/m ²)	Mi RCCTE (kg/m ²)	ri
Walls_int insulation	Plaster 2cm	12	12	12	1
	Interior thermal insulation 6cm	1,8			
	Concrete wall 20cm	270			
	Plaster 2cm	12			
Walls_ext insulation	Plaster 2cm	12	295,8	150	1
	Concrete wall 20cm	270			
	Exterior thermal insulation 6cm	1,8			
	Plaster 2cm	12			
Average				81	1

Table 26 Discretization of combined solutions for exterior walls (used in scenario 4)

Components	Layers	Mi (kg/m ²)	Total Mi (kg/m ²)	Mi RCCTE (kg/m ²)	ri
Walls	Plaster 2cm (INT)	12	133,8	133,8	1
	Brick masonry 11cm	120			
	Exterior thermal insulation 6cm	1,8			
	Air gap				
Walls_ext insulation	Stone 20cm (EXT)	300	295,8	150	1
	Plaster 2cm (INT)	12			
	Concrete wall 20cm	270			
	Exterior thermal insulation 6cm	1,8			
Average	Plaster 2cm (EXT)	12		141,9	1

Components	Layers	Mi (kg/m ²)	Total Mi (kg/m ²)	Mi RCCTE (kg/m ²)	ri
Walls	Stone 100cm	300	300	150	1
Walls_ext insulation	Plaster 2cm (INT)	12	295,8	150	1
	Concrete wall 20cm	270			
	Exterior thermal insulation 6cm	1,8			
	Plaster 2cm (EXT)	12			
Average				150	1

Components	Layers	Mi (kg/m ²)	Total Mi (kg/m ²)	Mi RCCTE (kg/m ²)	ri
Walls	Plaster 2cm (INT)	12	133,8	133,8	1
	Brick masonry 11cm	120			
	Exterior thermal insulation 6cm	1,8			
	Air gap				
Walls	Brick 11cm	120	133,8	133,8	1
	Plaster (EXT)	12			
	Plaster 2cm (INT)	12			
	Brick masonry 11cm	120			
Walls	Exterior thermal insulation 6cm	1,8	133,8	133,8	1
	Air gap				
	Brick 11cm	120			
	Plaster (EXT)	12			
Average		133,8		133,8	1

Table 27 Combination of elements of a given space and resulting thermal inertia

Scenario 1 - Combination of massive elements and non-massive elements for spaces with massive exterior walls with exterior thermal insulation

Exterior walls	[Pattern of brown and white squares]																													
Roof	[Pattern of brown and white squares]																													
Party walls	[Pattern of brown and white squares]																													
Floors	[Pattern of brown and white squares]																													
Ceiling	[Pattern of brown and white squares]																													
Partitions	[Pattern of brown and white squares]																													
	H										M															W				

Scenario 2 - Combination of massive elements and non-massive elements for spaces with non-massive exterior walls with interior thermal insulation

	M															W														
Exterior walls																														
Roof																														
Party walls																														
Floors																														
Ceiling																														
Partitions																														

Scenario 3 - Combination of massive elements and non-massive elements for spaces with some massive exterior walls with exterior thermal insulation and other non-massive exterior walls with interior thermal insulation

[illegible]

Scenario 4 - Combination of massive elements and non-massive elements for spaces with some massive exterior walls with exterior thermal insulation and other massive exterior walls

Exterior walls																																								
Roof																																								
Party walls																																								
Floors																																								
Ceiling																																								
Partitions																																								
	H										M																				W									

Legend

- | | |
|---|--|
|  | Massive elements with reduced level of resistance |
|  | Non massive elements elements with high level of resistance |
|  | Combined solutions for exterior walls - massive and non massive exterior walls |
|  | Combined solutions for exterior walls - massive exterior walls |
|  | Interior spaces with heavy thermal inertia |
|  | Interior spaces with medium thermal inertia |
|  | Interior spaces with weak thermal inertia |

4. Glazing and shading

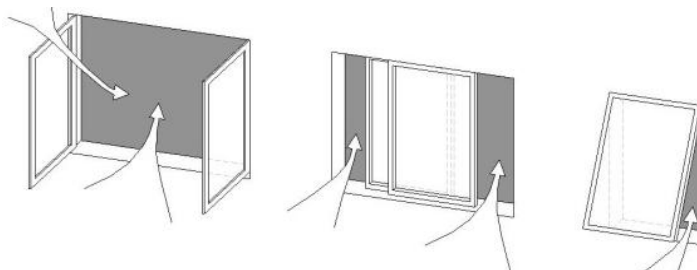
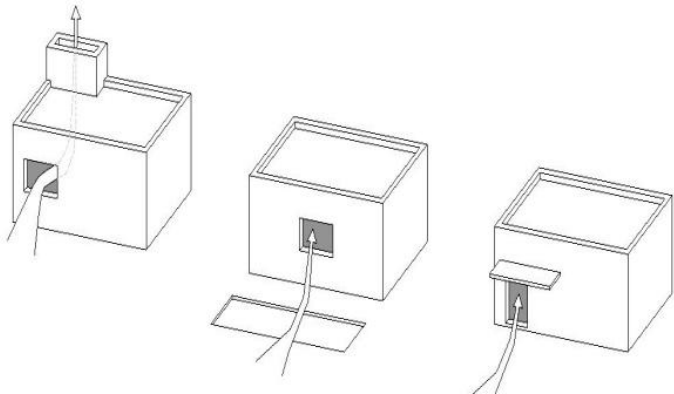
The family of graphics of aggregated parameters produced in Chapter 6 is stored in Exsys and the system retrieves the graphic for each specific case of glazing orientation, $\Sigma UA/A_p$ of the opaque elements and thermal inertia. The optimal glazing ratio is advised, taking into account the aggregated parameters.

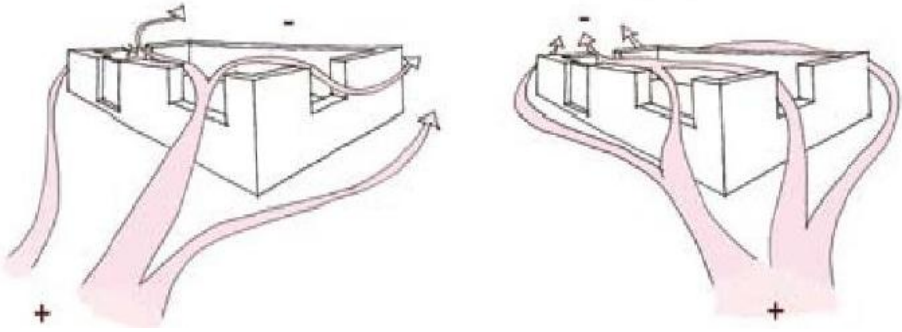
Table 28 Aid proceedings related with the glazing and shading

Scope of assessment: New		
Since the glazing orientation, the $\Sigma UA/A_p$ of the opaque exterior elements and the thermal inertia of the given architectural space are defined, the following graphic supports the choice of the glazing ratio, being the glazing double. The graphic allows finding the optimal or nearing optimal glazing ratio. Check the thermal needs for the different glazing choices. The installation of double glazing is advisable as a reference for both acoustic comfort and thermal comfort. Besides this, reducing the amount of air leakage in buildings through seal air barrier to frame is also desirable.		
Scope of assessment: Retrofit		
Main questions	Answers	Specific recommendations/indications
Is it possible to change the glazing type and design?	Yes	The installation of double glazing is advisable as a reference for both acoustic comfort and thermal comfort. If windows have simple glazing and these cannot be changed, install a second frame. Besides this, reducing the amount of air leakage in buildings through seal air barrier to frame is also desirable.
		Since the glazing orientation, the $\Sigma UA/A_p$ of the opaque exterior elements and the thermal inertia of the given architectural space are defined, the following graphic supports the choice of the glazing ratio, being the glazing double. The graphic allows finding the optimal or nearing optimal glazing ratio. Check the thermal needs for the different glazing choices.
	No	The installation of double glazing is advisable as a reference for both acoustic comfort and thermal comfort. If windows have simple glazing and these cannot be changed, install a second frame. Besides this, reducing the amount of air leakage in buildings through seal air barrier to frame is also desirable.
		Since the glazing orientation, the $\Sigma UA/A_p$ of the opaque exterior elements and the thermal inertia of the given architectural space are defined, the following graphic supports the choice of the glazing ratio, being the glazing double. The graphic allows finding the optimal or nearing optimal glazing ratio. Check the thermal needs for the different glazing choices.
Additional information		
Glazing ratio: Presentation of graphics of thermal needs		
Shading: Windows should be provided with more than one unique solution for shading – for instance, a combination of interior curtains with exterior shutters. Exterior shading is recommended for south, east and west. For east and west, vertical blades are preferable to horizontal ones, as during the summer the sun is higher in the sky.		

5. Other parameters of energy valorization

Table 29 Aid proceedings related with the parameters of energy valorization

Scope of assessment: New and retrofit	
Ventilation	Ventilation is needed both for IAQ and thermal comfort during summer. Openings design is an opportunity to enhance air renovation indoors. Some strategies for ventilation openings are pointed out: 1. Shape of the opening - horizontal formats are more efficient in stimulating air velocities 2. Openable area - the type of the opening can bring more benefits to natural ventilation according to the area of the openable area  - Slide hung – 100% openable; sash can redirect air low; good sealing - Horizontal sliding sash – adjustment of the opening area is possible to direct air flow to a specific area; opening limited to 50% of the window area; the vertical open area does not favor the speed of air flow - Top or bottom hung – reduced open area 3. Ventilation by stack effect is always recommended for kitchens 4. Fresh air should be uptaken from shaded zones, where the air is fresher. Open or screened porches allow capturing fresh air  5. Evaporative cooling is associated to fountains in patios or water tanks near the buildings 6. Opening placement - Vents strategically located in window heads or in other upper level of the room and self-regulated by occupants is advisable

	 7. In case the direction of winds is known – positive pressures and negative pressures caused by the wind direction should be taken into account
Color of exterior opaque surfaces	Light colours of coating materials reflect a considerable amount of solar radiation and help to minimize solar gains through the opaque components of the building envelope. Light colour choices are especially relevant for the roof as it is the part of the building that receives more solar radiation.
Vegetation	Trees and shrubs strategically planted next to buildings can attenuate temperatures indoors during the summer season. In case of not deciduous trees, and taking into account the winter season, a reasonable distance between the not deciduous tree and the building façade should be considered.
Buffer spaces	Intermediate or buffer spaces between the interior and the exterior, as courtyards, pergolas and shaded terraces can originate favourable microclimates. Their occupation can also depend on the season and on the hour of the day.

7.3 Variables and rules integrated in Exsys Corvid

7.3.1 Building a system in Exsys Corvid

As it has already been referred in Chapter 3, expert systems are computer programs that emulate the interaction that a person would have by being advised by a human expert. Procedural steps and logic rules used by experts are collected and are subsequently stored in a system in the form of rules that are easy to build, read and maintain by non-programmers. Expert system building tools allow some flexibility in building these rules. Thus, advices and recommendations can be delivered to users and not exclusively quantitative data or information. This is one of the main advantages of using an ES in the building design knowledge field, as in building design the knowledge is both qualitative and quantitative and needs a holistic approach. Another very relevant advantage is the user-friendly interface, providing a very easy interaction

of the user with the system. The flexibility of integrating graphical information is another advantage, because architects are very visual oriented.

Exsys Corvid is an expert system building tool or 'shell'. Expert system shells allow a non-expert in programming to build an expert system in an easy way. 'The 'shells' are also expert systems that have been emptied of their rules so that the knowledge engineer concentrates on entering the knowledge base without having to build everything, including the inference engine and user interface.' (Alibaba and Özdeniz 2004).

Advantages of using the Exsys Corvid shell include: the great flexibility for including graphical data, the possibility of using it through internet, the user-friendly interface and the easiness of building and using rules. Exsys Corvid system differs from standard procedural programming in the way it uses rules. The order of rules that is embedded in the system is not relevant. The ES inference engine will find the ones it needs and when it needs them.

'Rules are processed by the inference engine which automatically determines the relationship between rules. If one rule needs the value of X, and some other rules anywhere else in the system can set the value of X, the inference engine will automatically recognize that the needed value can be derived from the other rules. It will automatically use the rules to set X and then return to the original rule.' (Exsys 2011).

At this point, it is needed to make it clear how does Exsys work and how a system can be built in Exsys. As it has already been referred, an ES can be built by a non expert in programming. However the construction of the ES requires a very clear knowledge about the decision steps. In fact, 'a large part of building a Corvid system is identifying the individual decision steps and converting them into a form that a computer can use.' (Exsys 2014) The definition of the decision steps is especially relevant as 'In Exsys Corvid, rules are very similar to the form that you would use to explain to another person how decisions are made.' (Exsys 2014).

Building a system with Corvid is largely based on creating individual decision steps, or simple rules that describe the logic of a decision making process. The rules are 'Heuristics' - IF/THEN rules of thumb that are the individual steps that determine the

overall decision. The THEN statements assign a value to a variable. The rules are introduced in the ES shell and processed by the Corvid Inference Engine, which combines and uses them to drive and assess the users' choices and to produce results. (Exsys 2011).

Rules in Exsys are built through a given combination of variables. In fact in order to understand how Exsys work, it is needed to stress its key elements: variables, rules ('logic and action blocks') and 'command blocks'. 'Building a Corvid system requires describing the system logic either in Logic Blocks or Action Blocks. There are special windows for building each of these. In either case, the system logic will be described using Variables. The overall procedural control of the system will come from a Command Block, which is often just a few commands, but can be more complex when needed. The system is run using the Corvid Runtime program.' (Exsys 2014).

These three elements are addressed bellow:

1. Variables

The variables are items that have associated names, values and prompts. The name is used to identify the meaning of the variable. The values constitute the decision choices and can be asked to the end user, as far as needed. The variables' values are also used to build rules in a Corvid system. Prompts are used to ask the user for a value of a given variable. In the case variables are not asked to the user, the prompt is used for advices, recommendations or just for giving information to users in results and reports.

2. Rules – logic blocks/action blocks

All Exsys Corvid systems use the rules that are built in logic and action blocks.

In logic blocks, Corvid variables are used for building rules, through IF/THEN expressions. Each one of these rules provides an individual 'heuristic' and constitutes a single step to use in the overall decision-making. The logic blocks can contain one rule or a set of rules. What is important is that a single logic block is built in order to contain all the rules relevant for a specific 'part' of the decision. What makes up a 'part' depends on how the developer wants to structure the decision-making task. The organization of the rules is flexible but it should be always structured and organized to match the way the problem is approached.

In the end, Corvid Inference Engine processes all the rules in a system, combining them into a logical flow, in order to use them in the most effective way to give a specific required answer.

The action blocks use a procedural approach, with forward chaining, by asking a set of questions, in order to give answers to a specific problem. The answers to a question may allow skipping some other questions, or may require asking additional questions (Exsys 2014).

3. Command blocks

The following statement by Exsys Inc. gives a straightforward explanation of the function of command blocks: 'Logic Block rules tell the system how to do things. Command Blocks tell the system what to do'(Exsys 2011). Command Blocks control how a system operates, what actions to take, especially what logic blocks should be used, and in what order actions should be performed. Besides this, in command blocks the question formatting and the user interface design are determined, as well as, the display of results and possible recommendations.

This description of variables, rules and command blocks refers to how the system is built.

The way the ES system is presented to the end user is now addressed:

Any expert system built with Exsys is presented to users through a sequence of questions and list of possible answers. The system asks questions to users, in a logical flow, skipping irrelevant or not needed questions, but asking for more details when these are needed. The user selects the answers from a list, which allows the system to use these inputs. The users' answers constitute the data that the system needs to determine which rules are true and what advices should be given. The program will continue asking questions until all the information is gathered in order to make possible to achieve to a result, which is displayed in the end of the session. The specific advices tailored to specific answers given by users can also be displayed.

Systems can be delivered via web browsers, run standalone or embedded with other programs (Exsys 2014).

7.3.2 The proposed system for thermal assessment built in Exsys Corvid

The expert system proposed by this thesis is called 'ARCH2SUN'.

It is a design assessment tool to aid architects in the decision making of the critical inputs during the early phases of the Architectural building design of residential spaces.

The following paragraphs will describe how graphics of thermal needs (Chapter 6) and decision trees (Subchapter 7.2.) are integrated in the expert system shell, having in mind that the way the design knowledge is structured is essential for the construction of any expert system. Gero (1990) explored knowledge representation schemas as a form of structuring the design process:

Design requires a representation framework that has sufficient expressive power to capture the nature of the concepts that support design processes. The use of a knowledge representation schema such as design prototypes provides such a framework. It separates the knowledge from the computational processes that operate on it. The use of this representation effectively provides a translator between structure, which can be seen as the syntax of a design, and function, which can be treated as the semantics of a design. Such an articulation is useful not only in the production of designs but also in their analysis and evaluation. For example, traditional computer-aided design systems produce a design description in their databases that maps onto the syntax of a design. For these databases to be useful for other than purposes of graphic representation, a translation to the semantics of the design is needed.

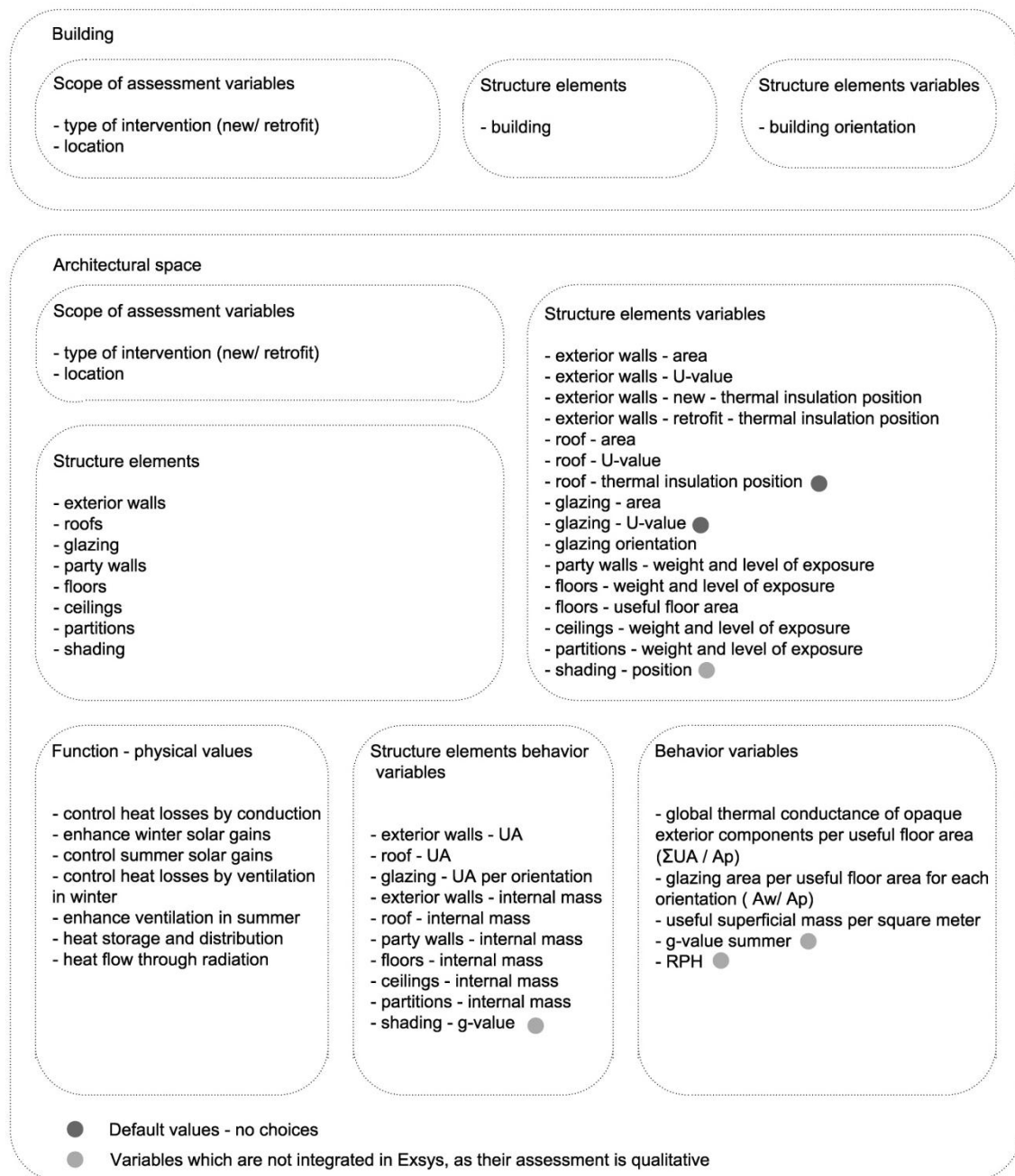
(Gero 1990)

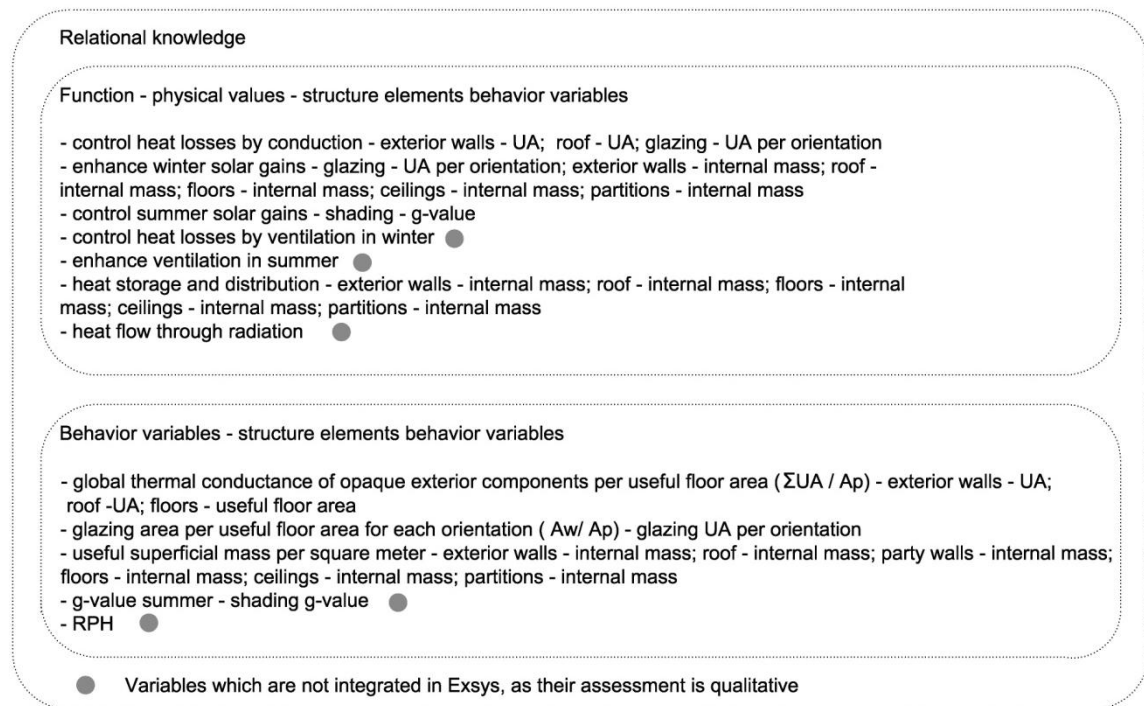
The following table (Table 30) is based on the ‘design prototype’ concept explored by Gero and other researchers. It allows a quick understanding of how the information of the decision trees in this thesis was represented in the Exsys Corvid system. This representation ends up as a ‘bridge’ between the decision trees contents and the proposed Exsys system. The departing point are the ‘structure elements’, which constitute the components of the building under study (e.g. exterior walls, roofs). The ‘structure elements variables’, the ‘scope of assessment variables’ and ‘the behavior variables’ correspond to the variables created in the Exsys Corvid (e.g. exterior walls – area). The ‘structure elements variables’ and the ‘scope of assessment variables’ are the elements used for the creation of rules in Exsys Corvid, from which the ‘behavior variables’ will be inferred. The relational knowledge shows the relevance of the use of each ‘structure elements variables’ for a determined function (e.g. control heat losses by conduction) and for a given ‘behavior variable’ (e.g. global thermal conductance of opaque exterior components per useful floor area).

This table presents two different scopes of thermal assessment – the building and the space of the building. As it has already been referred the thermal aid will be made for

architectural spaces, but a single question will be oriented for the building itself in order that the system gives recommendations to the orientation, both of the building and of its compartments. Thus, a single variable called ‘building orientation’ was integrated in the system.

Table 30 Schematic representation of the function, behavior and structure components of the building/architectural space design as well as their variables and most relevant relationships





The variables, logic blocks and command blocks of the proposed system are described below.

1. Variables

The variables of the system are constituted by the variables from the following groups of the Table 30:

- The 'scope of assessment variables';
- The 'structure elements variables';
- The 'behavior variables'

A 'prompt' and 'values' are attributed to each one of the variables. The prompt text describes what the variable represents. An example is given below:

e.g. Variable 'glazing orientation'

Prompt – 'what is the orientation of the architectural space/compartment to be assessed? Note that recommendations are only given for spaces with glazing surfaces in one of its exterior walls.'

Values – 'South, Southeast or Southwest'; 'East or West'; 'North, Northeast or Northwest'

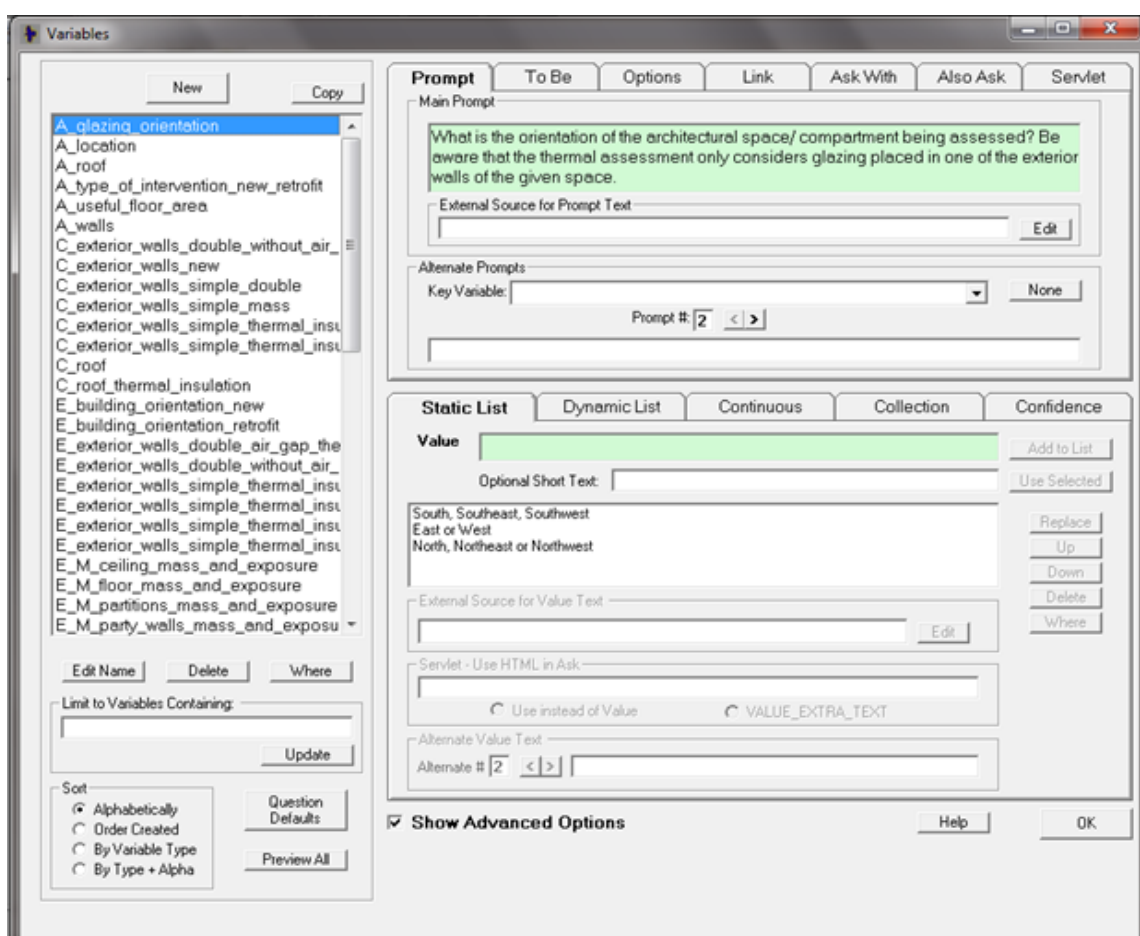


Figure 99 Exsys Corvid. List of variables

2. Rules – action blocks and logic blocks

Two types of set of rules are built: action and logic blocks.

The action block built in Exsys is called 'Thermal procedures' and guides the users choices according to a sequence previously set, that correspond to the sequence defined in the decision tree in Subchapter 7.1. (Figure 96). It is structured as a questionnaire. A sequence of questions (prompts of variables) is ordered in order to give users the possible decisions (values of variables) and recommendations from best practices. All the questions that are set in the users interface are built in this action block.

Five logic blocks are built in the Exsys Corvid:

- 'Thermal inertia logic block' – a set of rules allows to infer the thermal inertia that result from a certain combination of building elements. The questions about the internal mass and level of exposure of each building element in the 'Thermal procedures' action block allow informing about the decisions of the user. The rules of

the ‘Thermal inertia logic block’ embed the inertia decision tree built in the last subchapter (Figure 96);

- ‘Global thermal conductance per useful floor area’ – the expression that allows calculating the global thermal conductance per useful floor area is used. The values that were attributed by the user during the thermal assessment of exterior walls and roofs are retrieved;
- ‘Graphics of assessment of the glazing ratio’ – A set of rules allows inferring the specific graphic to display in function of the $\Sigma U A / A_p$, the glazing orientation, thermal mass and location of the architectural space.
- ‘Glazing type’ – A set of rules aims to give alternatives to users in case the glazing surface of the space has simple glazing and if this cannot be changed.
- ‘Weak inertia’ - A rule aims to give indication to users in order to choose another interior constructive solutions, as weak inertia is not a choice of spaces in temperate climates.

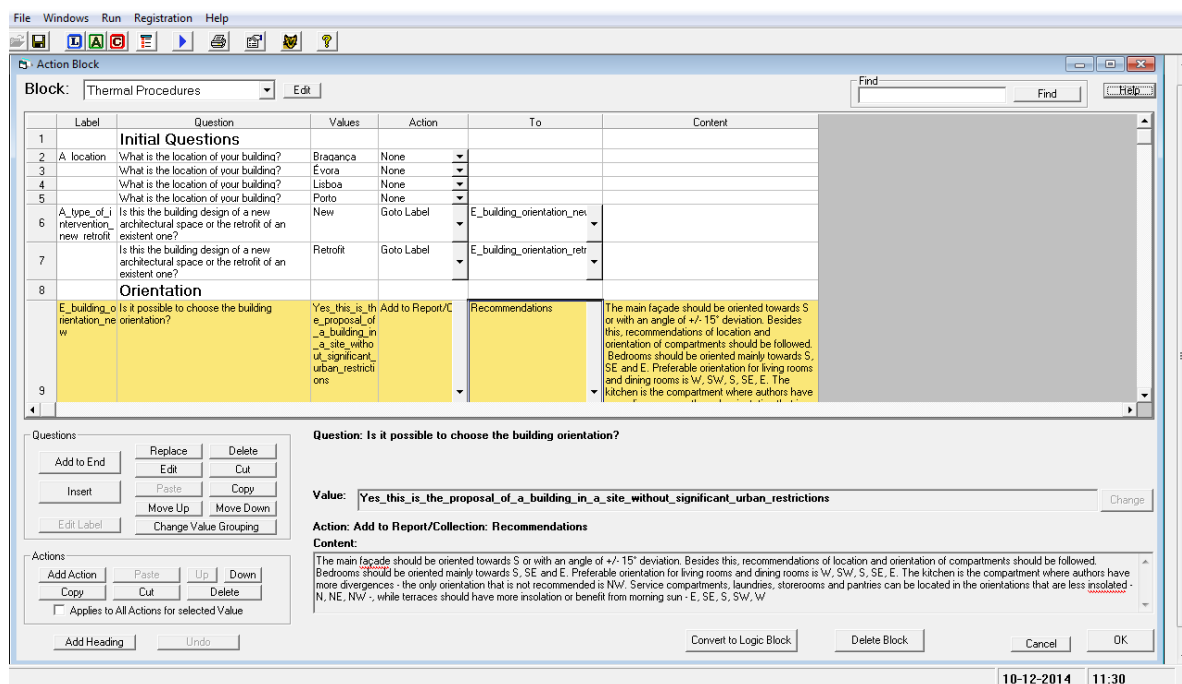


Figure 100 Exsys Corvid. Action block ‘Thermal procedures’

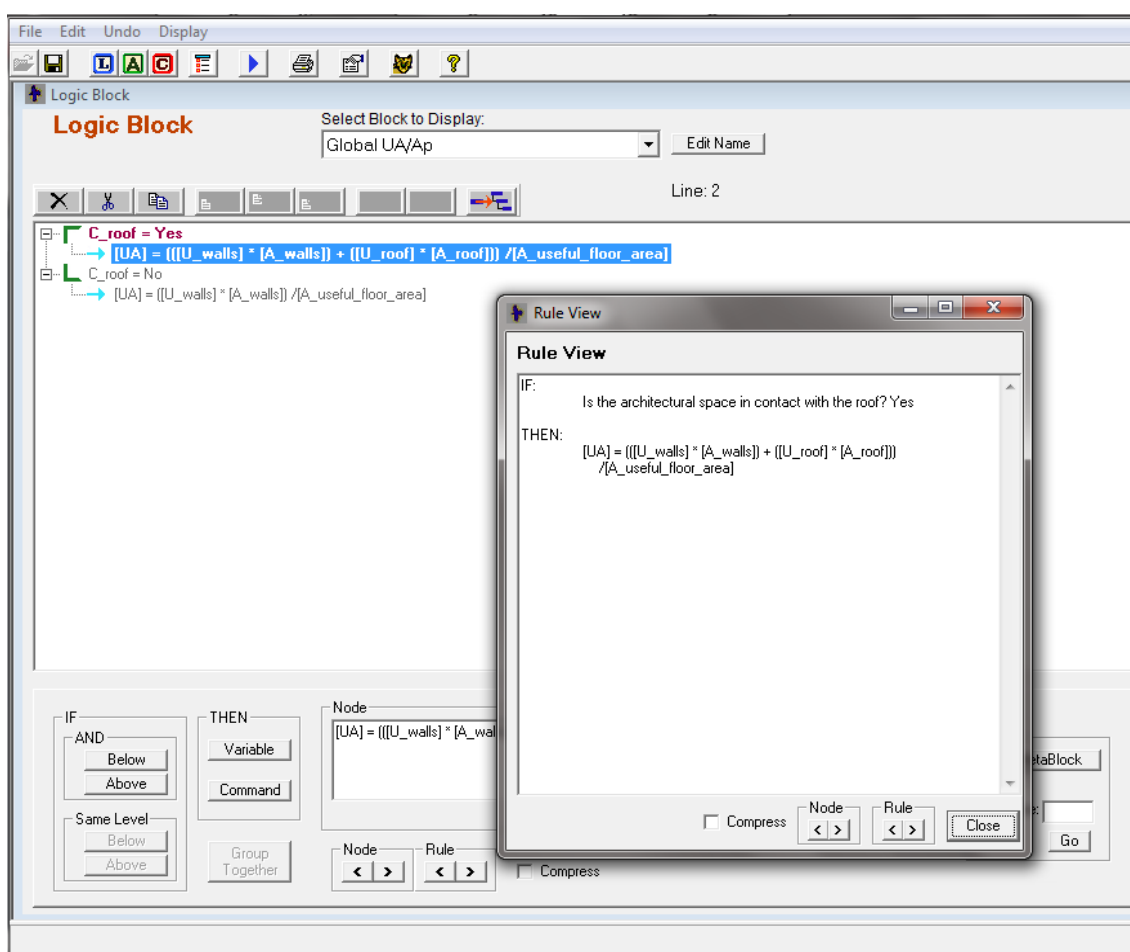


Figure 101 Exsys Corvid. Logic Block 'Global thermal conductance per useful floor area'

Logic blocks allow inferring the 'behavior variables' accordingly to the choices of 'structure elements variables' and 'scope of assessment variables'. Rules are integrated in the system in order to inform the system of what should be inferred. The combination of all the rules of the system provides a complete understanding of the overall decision-making.

3. Command blocks

A single command block is used. It gives to the system the indications of using all the logic blocks and the action block. The questions formatting, the user interface, as well as, the indications of how to display results is also defined in the command block.

The next subchapter presents an application case and the different user interfaces of the expert system.

7.4 Application case

The design of a space integrated in a new building, which orientation can be chosen, with a useful floor area of 12m², area of exterior walls of 12m² and area of roof of 12m² was assessed through the system built in Exsys Corvid. It should be underlined that questions displayed in the user interface can be different for other cases, as the questionnaire is driven by the paths that users choose.

- The first user interface presents the thermal assessment tool and gives indications to users of how to proceed. It also stresses that the thermal assessment undertaken is for an architectural space, being the initial questions related to the building itself;
- The second user interface asks the user about the location of the building;
- The third user interface asks the user about the scope of assessment – new or retrofit;
- The fourth user interface aims to know if it is possible to choose the building orientation;
- The fifth user interface asks the user if the exterior walls are simple or double;
- The sixth user interface assesses the U-value and thermal insulation position in exterior walls. It also asks what is the U-value and the area of exterior walls;
- The seventh user interface asks the user if the space is in contact with the roof;
- The eighth user interface assesses the U-value and thermal insulation position in roofs. It also asks what are the U-value and the area of the roof;
- The ninth user interface asks what the useful floor area is;
- The tenth user interface presents the building elements and addresses the relevance of the thermal inertia;
- The eleventh user interface asks if party walls are massive and with a high level of exposure or non-massive and with a reduced level of exposure. Party walls with both solutions are presented in order to aid the users' choices;
- The twelfth user interface asks if floors are massive and with a high level of exposure or non-massive and with a reduced level of exposure. Floors with both solutions are presented in order to aid the users' choices;
- The thirtieth user interface asks if ceilings are massive and with a high level of exposure or non-massive and with a reduced level of exposure. Ceilings with both solutions are presented in order to aid the users' choices;

- The fourteenth user interface asks if partitions are massive and with a high level of exposure or non-massive and with a reduced level of exposure. Partitions with both solutions are presented in order to aid the users' choices;
- The fifteenth user interface asks the user about the orientation of the glazing of the specific space being assessed;
- The sixteenth user interface displays the results. In the beginning, recommendations are given for the building and its compartments orientation;
- From the seventeenth to the twenty one user interface the results are displayed. Information about the global thermal conductance per useful floor area and the thermal inertia of the space are given to users, as well the respective graphic of thermal needs. Qualitative recommendations are also addressed.

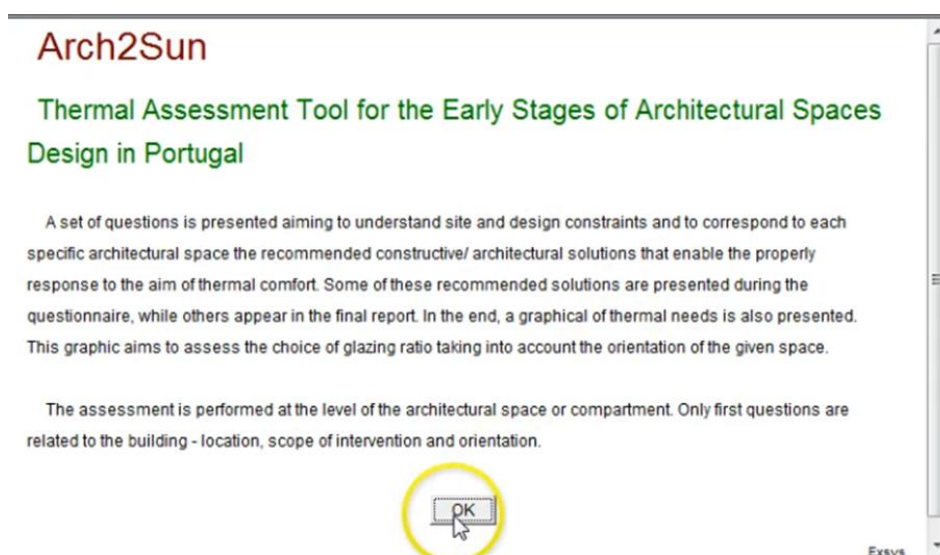


Figure 102 Exsys Corvid. User interface 1 – presentation of the design tool

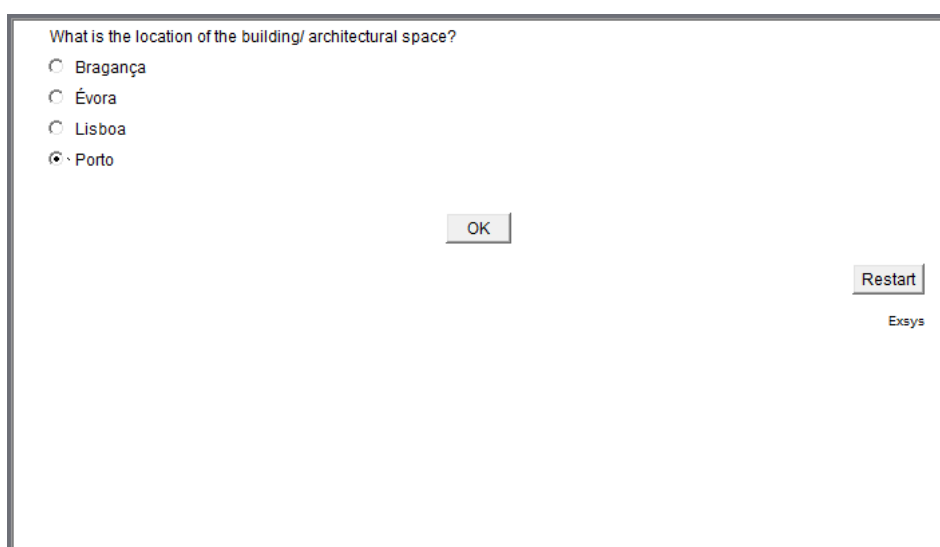


Figure 103 Exsys Corvid. User interface 2 – location of the architectural space

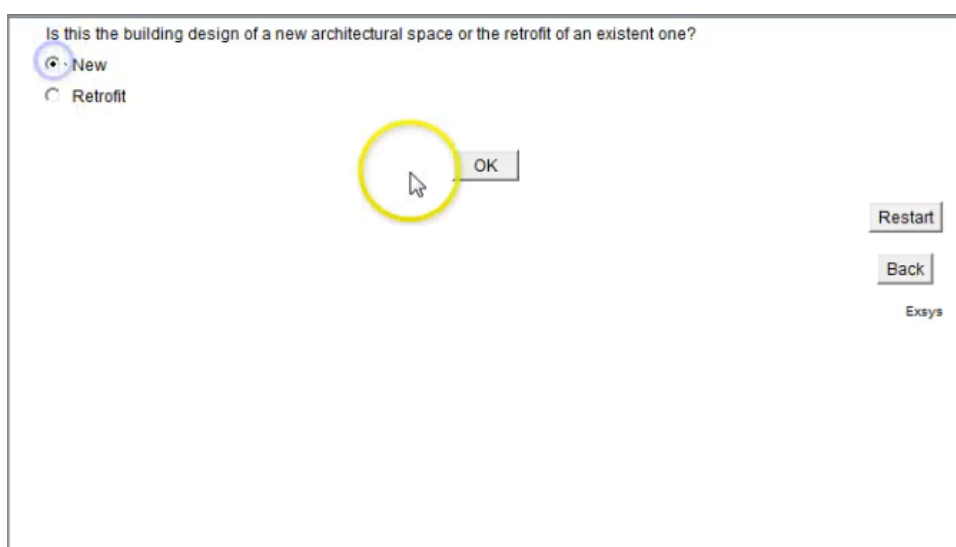


Figure 104 Exsys Corvid. User interface 3 – scope of intervention – new/retrofit

Is it possible to choose the building orientation?

☒ Yes, this is the proposal of a building in a site without significant urban restrictions

☐ No, because the building must be aligned with the street

OK

Restart

Back

Exsys

Figure 105 Exsys Corvid. User interface 4 – building orientation

The following questions are related to each of the compartments / architectural spaces with surfaces in contact with the exterior

Are exterior walls simple or double?

☒ Simple

☐ Double

OK

Restart

Back

Exsys

Figure 106 Exsys Corvid. User interface 5 – type of exterior walls

Solutions for exterior walls with exterior thermal insulation. The corresponding U-values are also indicated [W/m².°C]. A U-value, or coefficient of thermal transmittance, is the physical property of a material to conduct heat. It measures the heat transfer through a building element such as an exterior wall and roof. The lower the U-value, less heat losses will be verified. Building elements with thermal insulation have relative low U-values.

SW1_brick masonry 20-24cm or lightweight concrete 20-30cm, thermal insulation 6cm EPS - U-value 0.45

ext int ext int

SW1 SW2

What was the U-value correspondent to the selected constructive choice for exterior walls? In case of considering different constructive solutions for different exterior walls, consider the average U-value

0.45

What is the area (in square meter) of exterior walls? Consider the area of the wall without any glazing surface

12

Figure 107 Exsys Corvid. User interface 6 – area and U-value of exterior walls

Is the building/ architectural space in contact with the roof?

☒ Yes

☐ No

OK

Restart

Back

Exsys

Figure 108 Exsys Corvid. User interface 7 – contact with the roof

Exterior thermal insulation is highly advisable in order to reduce heat losses during winter and it is a relevant departing point for a low energy building. Regarding this consideration, choose one of the following constructive solutions for exterior roof with exterior thermal insulation. The correspondent U-values are also indicated [$\text{W/m}^2\text{C}$]

R1. massive concrete slab 10-20cm or lightweight concrete slab 13-15cm, thermal insulation 8cm EPS - U-value 0.36

R2. massive concrete slab 10-20cm or lightweight concrete slab 13-15cm, thermal insulation 10cm EPS - U-value 0.28

R3. massive concrete slab 10-20cm or lightweight concrete slab 13-15cm, thermal insulation 12cm EPS - U-value 0.24

What was the U-value correspondent to the selected constructive choice for the roof?

0.36

What is the area (in square meter) of the roof?

12

Figure 109 Exsys Corvid. User interface 8 – area and U-value of the roof

What is the useful floor area (in square meter) of the space that is being assessed?

12

OK

Restart

Back

Exsys

Figure 110 Exsys Corvid. User interface 9 – useful floor area

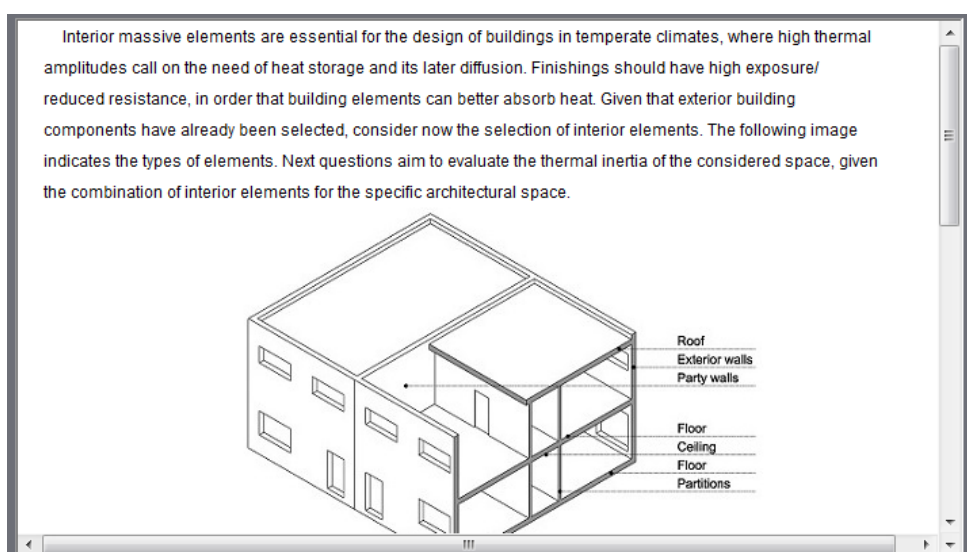


Figure 111 Exsys Corvid. User interface 10 – thermal inertia

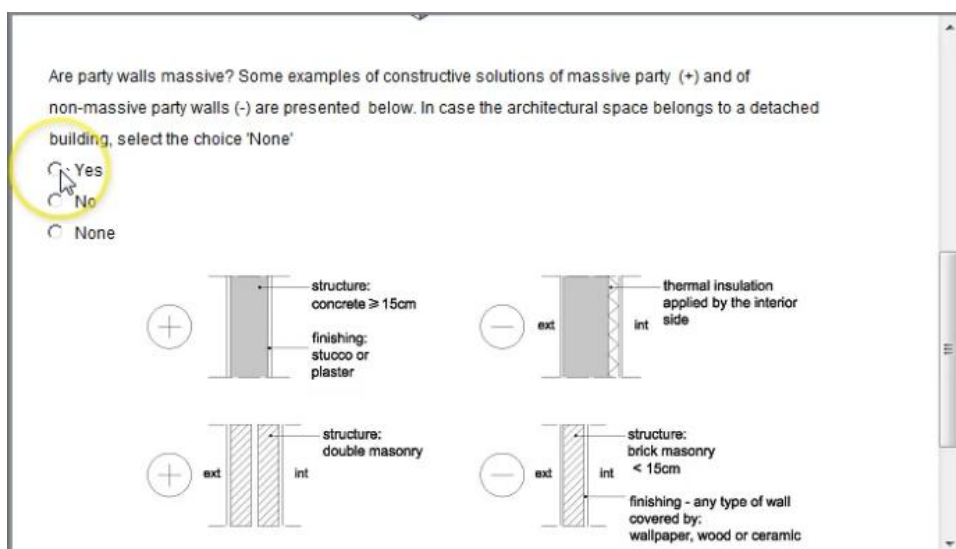


Figure 112 Exsys Corvid. User interface 11 – party walls mass

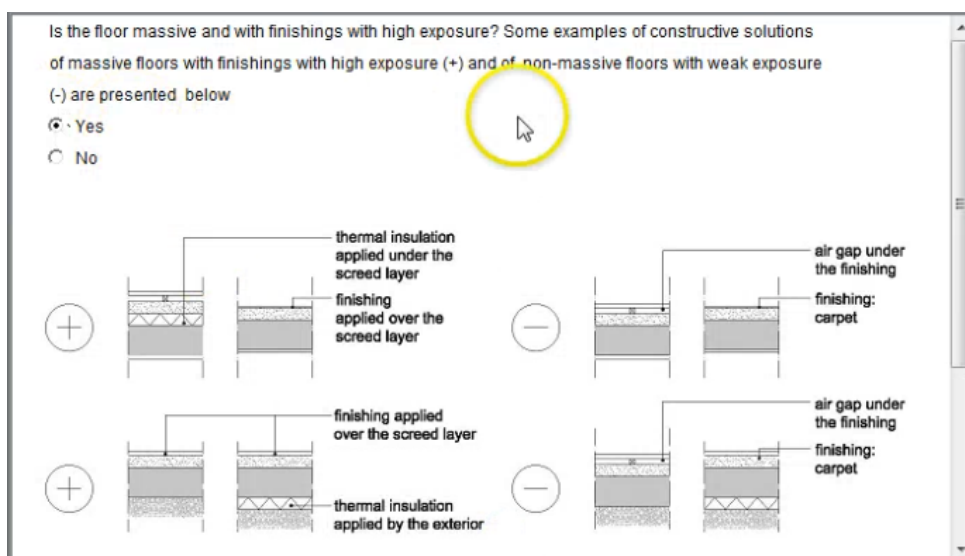


Figure 113 Exsys Corvid. User interface 12 – floors mass

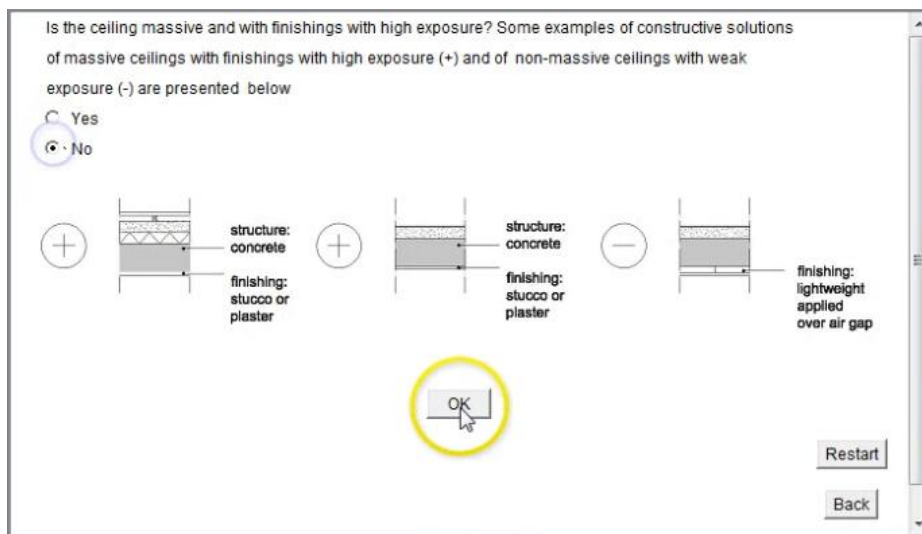


Figure 114 Exsys Corvid. User interface 13 – ceilings mass

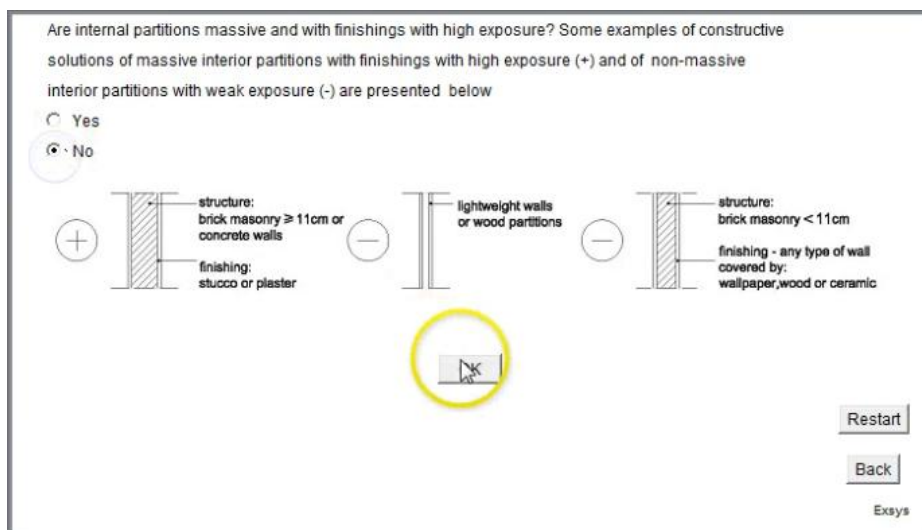


Figure 115 Exsys Corvid. User interface 14 – partitions mass

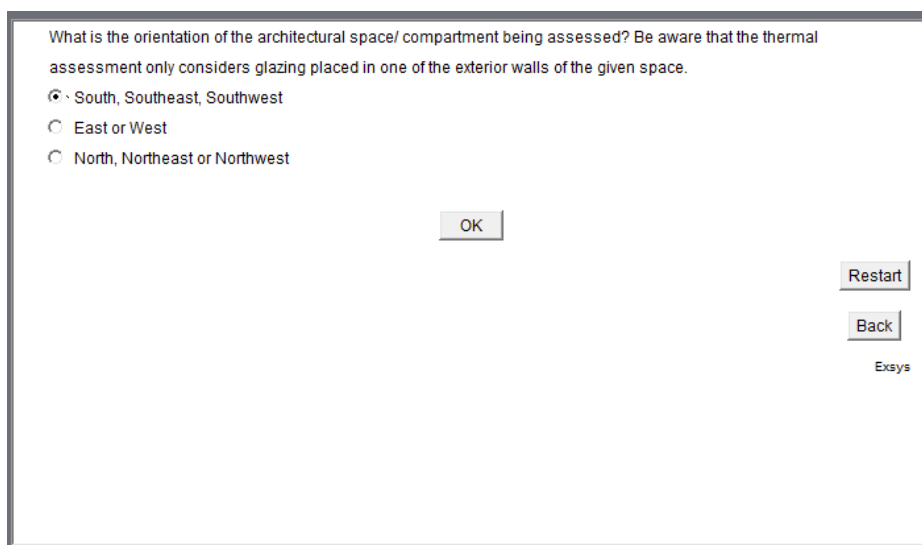


Figure 116 Exsys Corvid. User interface 15 – orientation of the architectural space



Figure 117 Exsys Corvid. User interface 16 – recommendations and results 1

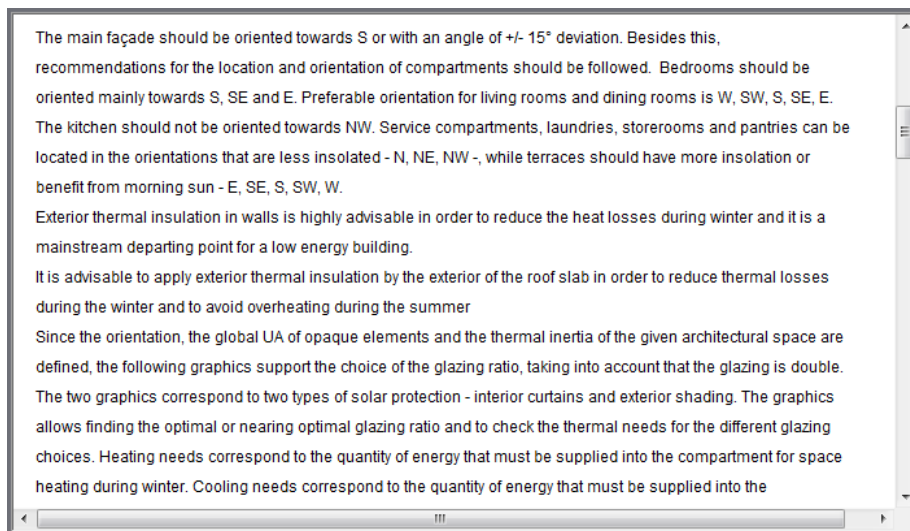


Figure 118 Exsys Corvid. User interface 17 – recommendations and results 2

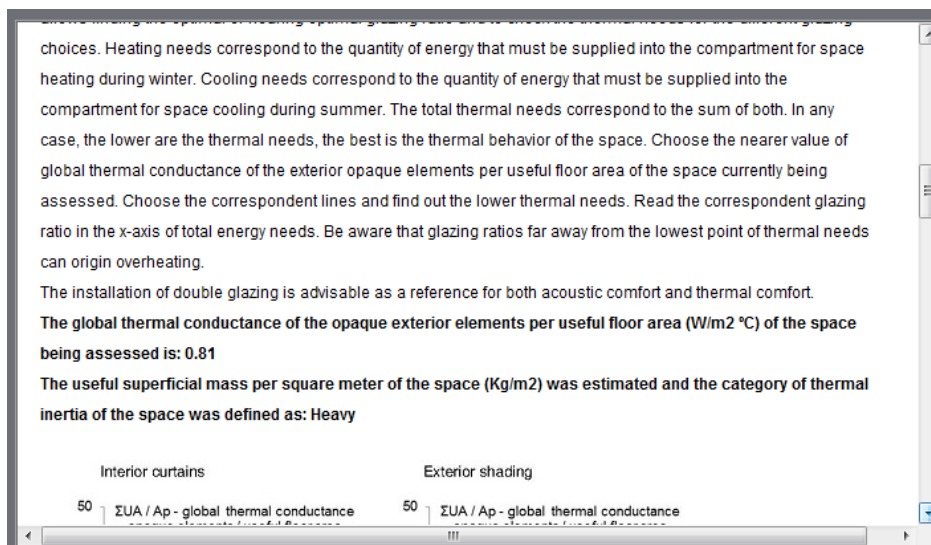


Figure 119 Exsys Corvid. User interface 18 – recommendations and results 3

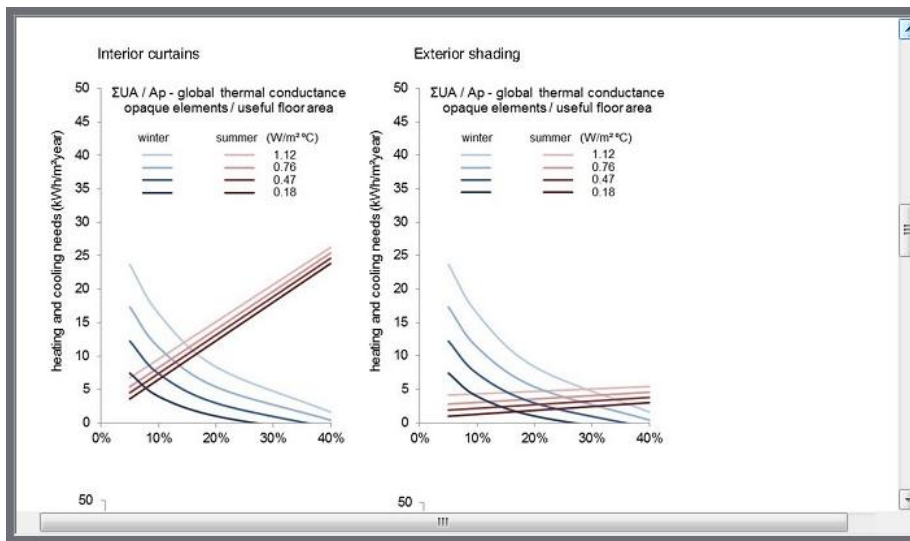


Figure 120 Exsys Corvid. User interface 19 – recommendations and results 4

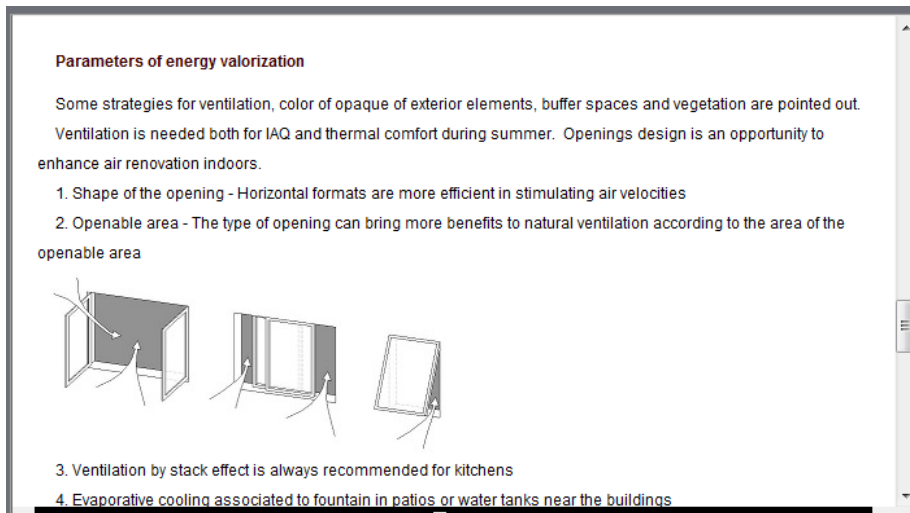


Figure 121 Exsys Corvid. User interface 20 – recommendations and results 5

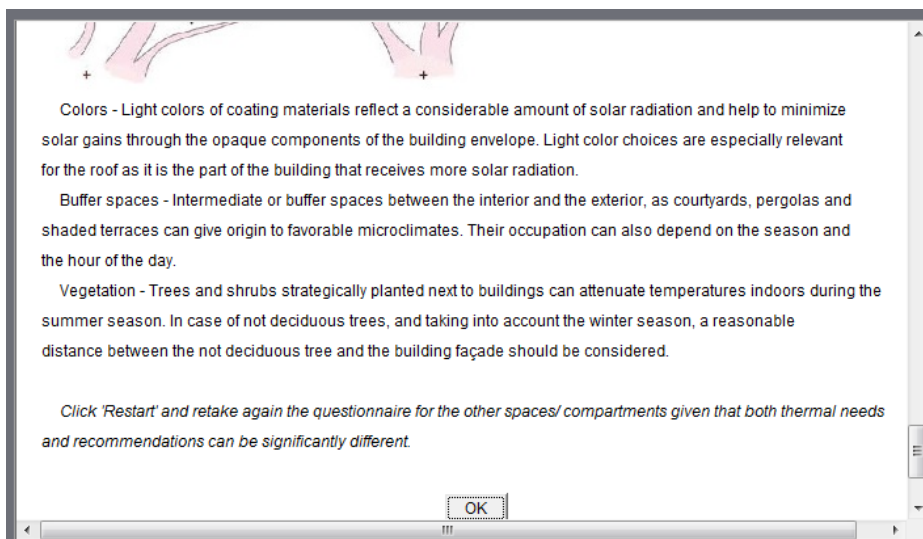


Figure 122 Exsys Corvid. User interface 21 – recommendations and results 6

8 Conclusions and perspectives

The present chapter summarizes the main findings of this thesis as a contribution for the involvement of architects in the design of low energy buildings since the early stages of the building design process, by tackling the use of critical inputs.

The main achievements obtained throughout the search of possible answers for the research questions, are the following:

1st Question: Which are the critical parameters, aggregated or not, that can be used as design inputs anticipating the thermal enhancement of the project of a residential building from the beginning of the Architecture building design practice?

1. The need of the involvement of architects in low energy buildings since the early stages of the building design is essential and can be assisted with the access to quite simple tools such as the one shown here. That involvement has great potential, when more attention is paid to the use of the critical parameters of design. What happens in current design practice is that several parameters are considered with almost the same weight. In fact, only a few of them are largely responsible for the building thermal performance.

2. The anticipation of those critical inputs in the thermal assessment of the architectural building design of residential buildings and their influence in the 'hypothetical energy needs' to satisfy pre-defined comfort targets calls on the need of a simple thermal analysis method that specifically analyses thermal energy needs and not 'energy consumed'. In fact and for these targets, the use of simulation codes is not of so much use, being time consuming and requiring details that are not still defined in the early building sketches. For that aim, tools as RCCTE 1990 show to be more appropriate. During the building sketch in the conceptual design, the most important proceeding is to calculate the potential energy needs to satisfy pre-defined comfort targets. Yet, it was found that is possible to create a pre-defined framework for Architecture work, without the need of performing calculations every time thermal assessment is needed.

3. Besides the key design parameters, it was found that the weight of site and building physics constraints play a relevant role. In fact, analysis of the design of buildings already built provided a better understanding of how the site constraints drive the design process and limit the extension of action of the thermal assessment. For instance, the analysis of already built and occupied buildings allowed to conclude that the choice of not insulating the exterior in retrofit is not so critical as choosing a non-optimized orientation (e.g. facing west) of the building.

4. Having in mind that the approach of design categories is not new, this thesis added a new one – the constraints – to the ‘categorization’ of previous studies: A. Reference values; B. Sensitive input parameters; C. Parameters of energy valorization; D. Site Constraints. The critical inputs for the design of buildings end up being A and B, without site constraints.

5. The global thermal conductance (A), the thermal inertia (A), the glazing ratio (B), the glazing orientation (B) and the shading (B) were aggregated in graphics of thermal needs that provide a complete and straightforward framework to tackle and choose simultaneously the key design inputs, having in mind their influence on the space thermal energy needs. Ventilation was excluded as it is driven by other important factors such as health and indoor air quality, and not just energy.

6. A thermal analysis was performed for four Portuguese cities in order to evaluate the influence of design parameters from A and B in the space thermal energy needs. The main findings are the following:

6.1. The relevance of studying each architectural space or compartment itself and not the whole building. Thermal energy needs are very sensitive to orientation. Moreover, differences can occur at the global thermal conductance level and massiveness of elements level from space to space. This is a relevant point both for thermal analysis in buildings that aim to assess the architectural building design, not in the end of the building design, but during its conception.

6.2. Independently from the orientation of the space, exterior shading devices are always essential for solar protection during summer. During the cooling season, exterior shading devices can reduce very significantly the cooling needs of a given space – the cooling needs of a space with exterior shading devices

represent half, or even less, of the cooling needs of a space with interior curtains, depending on the glazing area to floor area.

6.3. The cooling needs in the graphics of thermal needs (Chapter 6) for a space located in Lisboa and for the same space located in Évora are very similar.

6.4. But the major issue to underline is that the solutions of the critical inputs that most contribute to the spaces thermal behavior and to the challenge of thermal comfort are essentially the same. If we ask: 'What are the most relevant solutions for each location?' The answer is that best fundamental constructive solutions match all locations – heavy inertia, south glazing, exterior shading, and global thermal conductance as low as possible. The most specific item to be optimized is the glazing ratio and the orientation towards south.

2nd Question: In order to advance in the approach to materialize the passive architectural design or the design with the climate, how to select, arrange/aggregate and integrate those critical parameters in a straightforward usable tool that takes into account the building design characteristics?

1. It was found that the type of method for the thermal assessment of architectural building design that best suit the local climatic conditions and the most significant site constraints is a tool that stores design guidelines and incorporates procedural steps and quantification called upon when needed. In quantitative terms, key data for each type of climate should result in a straightforward encapsulation of all critical inputs
2. This aggregation was inspired in the LT method that performs the aggregation of design parameters in user-friendly graphics for architects, but adds different $\Sigma U A$ in order to provide also a comparison of the influence of envelopes with different heat losses.
3. The integration of the key or critical inputs and the presentation of different alternatives allow architects to quickly compare constructive solutions.
4. At the level of making the methodology accessible, only a method that takes into account the specificity of the architectural building design and the level of expertise

of the final users, architects and designers, will be really used and effectively followed. It was found that current tools could not properly address the following issues presented in the Exsys Corvid ES developed in this thesis:

4.1. Explanations of the concepts of the Physics of Construction, including the meaning of the U-value and how the position of the thermal insulation interferes with the U-value.

4.2. Explanations of the relevance of the thermal inertia in temperate climates and the clear identification of what are the massive and non-massive elements, as well as the influence of the finishing on the heat absorption of the building element. The results from the parametric study can provide a more detailed assessment for the inertia quantification than the simplified method of REH.

4.3. Presentation of graphic elements, which is a form of representation closer to the working mode of architects.

This can seem a simple approach but in fact it is of major relevance regarding the match of ‘bridges’ between Architecture and Engineering and Physics of construction, as architects need clear guidelines to understand the impact of their choices during the building design.

4.4. The construction of the ES in Exsys Corvid addressed a relevant issue related with both the language of design in Architecture and the language of thermal systems. While the concept of ‘type’ in Architecture is directly connected with the building structure – geometry and elements (Panerai 1999) (Moneo 1978), in thermal systems, the concept of ‘type’ is related to the energy needs of a given space (Balcomb 1986). The construction of an assessment tool based on structure elements variables such as exterior walls UA properly approaches both the Architecture and the Thermal Systems.

4.5. In computer-aided design systems, a translation to the semantics of the design is needed. Graphics of thermal needs and decision trees are integrated in the expert system shell, having in mind that the way the design knowledge is structured is essential for the construction of any expert system. The knowledge representation of the proposed ES was based on variables that structure the

thermal assessment in the design process: 'structure elements', 'structure elements variables', 'scope of assessment variables', 'behavior variables'.

The perspectives for future work are also identified, covering desirable expansions of the methodology developed in this thesis, as well as the possible enhancement of the expert system in Exsys Corvid. The following complementary issues could not be addressed in this study and should be considered in future research work:

1. To expand the work of this research to contribute for the retrofitting of existing housing buildings by exacerbating the potential of the critical inputs that only can be used under stricter conditions due to cultural restrictions and others.
2. To expand this approach and method with statistical information of actual buildings in order to establish quantified guidelines for the enhancement of the building stock using all potentialities in a continuum from passive through active energy systems.
3. To include the assessment of spaces with windows in more than one orientation, both in the thermal analysis and in the assessment through Exsys.
4. To integrate a database 'grammar of solutions' for both shading and internal mass possibilities for southern orientation. This database could even be documented with graphical information from good practices.
5. To enhance the user interface e.g. in order to present in a more straightforward way the thermal graphics. These could be not stored but generated by the system itself and present not only the reference values of $\Sigma UA/A_p$ but exactly the $\Sigma UA/A_p$ of the space being assessed.

Finally, but not the least, this system was only built for architectural spaces in the Portuguese climate, a case of a temperate climate. A system developed with the same methodology of this thesis for spaces in other types of climates could assure an application worldwide.

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