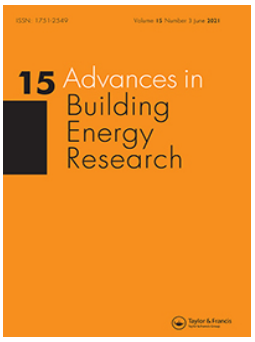

Advances in Building Energy Research

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/taer20

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To cite this article: Ricardo Gomes, Ana Ferreira, Luís Azevedo, Rui Costa Neto, Laura Aelenei & Carlos Silva (2021) Retrofit measures evaluation considering thermal comfort using building energy simulation: two Lisbon households, Advances in Building Energy Research, 15:3, 291-314, DOI: 10.1080/17512549.2018.1520646

To link to this article: https://doi.org/10.1080/17512549.2018.1520646

Published online: 11 Sep 2018.

ADVANCES IN BUILDING ENERGY RESEARCH
2021, VOL. 15, NO. 3, 291–314
https://doi.org/10.1080/17512549.2018.1520646

Retrofit measures evaluation considering thermal comfort using building energy simulation: two Lisbon households

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ABSTRACT

Retrofit measures for buildings are in general evaluated considering the energy savings and life cycle cost. However, one of the main benefits, the increase of users comfort is very seldom analysed. In this work, two residential households representative of a large share of households in Portugal, were monitored and its thermal behavior was modeled using Energy Plus. The thermal evaluation of the pre-retrofit households shows that the winter season is problematic due to construction solutions and low availability for heating. The retrofit measures analysis was performed considering different retrofit solutions regarding envelope improvement and efficient systems implementation. In order to work around the question of comparing households that do not use energy for acclimatization and therefore have very low energy consumption, in the retrofit scenarios it was considered the thermal comfort evaluation value for the real case (pre-retrofit) and compared the energy consumption to achieve that same average comfort level (in this case avoiding high discomfort peaks). The measures that more rapidly pay the investment are those related with implementing active systems. The approach used in this paper, should be used in more calibrated models in order to have overall conclusions about the retrofit process at a larger scale.

ARTICLE HISTORY
Received 30 May 2018
Accepted 11 August 2018

KEYWORDS
Building energy simulation; thermal comfort; fuel poverty; retrofit measures; building model calibration

1. Introduction

In 2010, the European Commission has published an updated version of the Energy Performance of Buildings Directive, which emphasizes the need for 'Energy Efficient Retrofitting' (EER) of existing buildings (Boermans et al., 2015). In general, EER focuses on the implementation of retrofitting measures in an existing building, aiming to reduce the total energy demand, while maintaining, or even improving, the required levels of occupant thermal comfort.

In Portugal – due to a governmental policy of the 1960s to regulate renting prices and that was only abolish in the last decade – the renting prices were artificially maintained at very low values, therefore, the rental revenues were not sufficient for house owners to perform the adequate maintenance of the buildings. This has led to a strong reduction

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of the rental market and to a significant decay of the Portuguese housing stock quality. Portugal housing is found to be one of the most energy inefficient of all housing in the EU (Healy, 2004). In fact, according to the latest census data, 33% of the Portuguese housing stock dating from the post-war period is in need of some kind of reparation (European Cooperation in the Field of Scientific and Technical, 2007), National Institute for Statistics, National Laboratory for Civil Engineering (INE and LNEC, 2013). In Lisbon, buildings represented around 62% of the primary energy consumption, and the residential buildings alone are responsible for 19% of the total primary energy in the city (Lisboa E-nova, 2016).

Over the last decade, Lisbon is now under a trend of building rehabilitation promoted by the new renting policies and by a significant growth of the tourism using the new business models where residential short-term rentals are preferred to hotels, and the number of building permits for rehabilitation has increased and it is now higher than for new construction (Figure 1).

Albeit this recent trend, there is still a large number of buildings that requite rehabilitation in Lisbon, from different typologies and constructions periods (INE and LNEC, 2013).

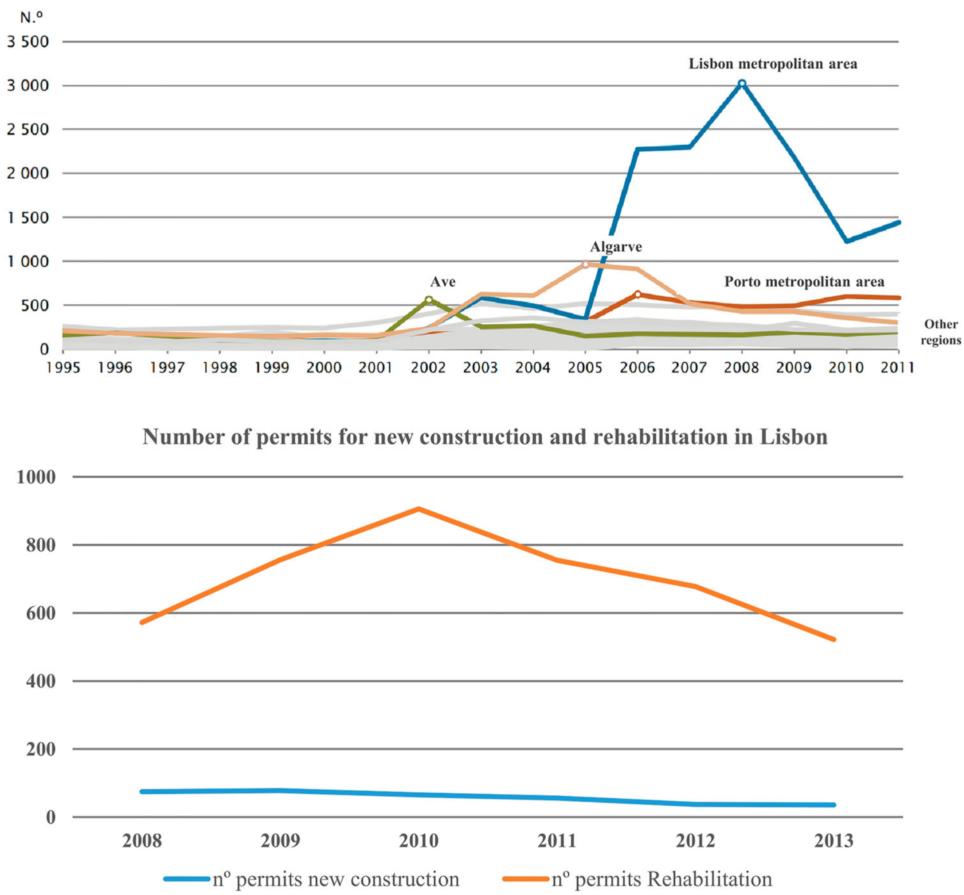


Figure 1. Renovated houses (INE and LNEC, 2013) and permits for new construction and renovation (Câmara Municipal de Lisboa, 2014).

With this in mind, it is of crucial relevance to define and study the most suitable measures to retrofit a building.

The number of studies concerning the effect and savings of EER is quite large and supports strongly its implementation in the European building stock (Androutsopoulos & Spanou, 2017; European Comission for Climate action and Energy, 2015; García-Esparza & Caballero Roig, 2016; Holck Sandberga et al., 2016; Panopoulos & Papadopoulos, 2015). The reasons are related with the low turnover rate of buildings (lifetime of 50 to more than 100 years) and the high number of already existing buildings (Kolaitis et al., 2013; Van der Veken, Saelens, Verbeeck, & Hens, 2004).

From the most commonly applied EER measures, it can be highlighted the installation of thermal insulation, glazing replacement, improvement of the building's air tightness, Heating, Ventilation and Air Conditioning (HVAC) system replacement and the introduction of mechanical ventilation with heat recovery (European Union, 2010).

However, the EER with the highest cost-benefit are hard to define and quantify due to the specificity of each rehabilitation project and budget constraints. A considerable number of studies estimate both energy consumption reductions and thermal comfort conditions, for different retrofit solutions, using building energy simulation software. While the initial focus of Building Energy Simulation (BEPS) tools was primarily on the design phase (Coakley, Raftery, & Keane, 2015), nowadays is becoming increasingly more relevant in post-construction phases of the building life-cycle, such as commissioning and operational management and control, considering sustainable low-energy solutions (Nadarajan & Kirubakaran, 2016) and also to perform retrofit measures analysis. One of the primary benefits of detailed simulation models is their ability to predict system behaviour given previously unobserved conditions. This allows analysts to alter the building design or operation while simultaneously monitoring the impact on system behaviour and performance.

For the past 50 years, a wide variety of building energy simulation programs have been developed and enhanced throughout the building energy simulation community (Crawley, Hand, Kummert, & Griffith, 2008). These building energy simulation programs have different features and various capabilities such as: general geometry modelling; definition of zonal internal loads; building envelope properties, daylighting and solar; infiltration, ventilation and multi-zone airflow; renewable energy systems; electrical systems and equipment; HVAC systems; environmental emissions; economic evaluation; climate data availability, results reporting and validation (Coakley et al., 2015; Rallapalli, 2010),

Several limitations arise related with the simulation outputs, since buildings monitoring often identifies significant gaps between the predicted and actual energy use of buildings and its thermal behaviour (Coakley et al., 2015; Jones, Fuertes, & Wilde, 2015; Karlsson, Rohdin, & Persson, 2007). Consequently, several techniques have been developed to support building simulation analysis, including parametric simulation, sensitivity analysis, simulation-based optimization, meta-model analysis, etc. The calibration process with measurements values of building models tends to be difficult and time consuming. The amount of parameters that are uncertain and could affect the outputs of the model is normally high and difficult to identify (Coakley et al., 2015).

The process of building energy model calibration is documented and studied in different research work across the last years. The calibration is normally focused in the statistical comparison of the measured data and the model outputs, considering a range of values for the inputs values (parameters). The large majority of the building calibration models research work are based upon the statistical comparison between simulated and measured data from energy meters (electricity, gas and enthalpy). Furthermore, the calibration of simulation models is considered mostly for large buildings, frequently offices or services buildings, since the effort needed to calibrate residential simulation models is too high and does not compensate when analysing simple retrofit measures especially due to budget reasons (Reddy, Maor, & Panjapornpon, 2006).

Given the need to retrofit a large stock of residential households in Portugal and properly evaluate the cost-benefit of different EER, it is necessary to develop methodologies that are able to consider the thermal behaviour of the households for different retrofit scenarios. However, one particular aspect is that in Portugal, the energy consumption in the residential sector is smaller than in Europe, especially because the use of energy for heating is very low.

Thermal discomfort is in fact one of the major concerns identified in the Portuguese building stock, having Portugal one of the highest mortality rates in Europe both for summer and for cold periods due to poor habitability conditions. One way to compare this phenomenon across different countries is to use the ratio between Excess Winter Deaths and Heating Degree Days. For Portugal, this value is 5.7, which is higher than, for example, colder European countries such as Finland (4.0), Denmark (4.8) or Estonia (3.9) (Liddell, Morris, & Thomson, 2016). This has been known as the 'excess winter mortality paradox' in which people are more likely to die during a period of cold weather if they live in southerly areas of Europe, where climates are temperate, than if they live in more northerly countries with more severe winter conditions (BPIE, 2014; Liddell et al., 2016; Simões, Gregório, & Seixas, 2016). Not only the excess winter deaths, but also mental disability, respiratory and circulatory problems, are adversely affected by fuel poverty. Although the definition of fuel poverty is not consensual, it can be referred as 'anyone who meets, in its housing, particular difficulties to have the necessary energy to meet its basic energy needs because of the inadequacy of its resources or of its housing conditions'. Fuel poverty is also briefly defined as the inability of provide household thermal comfort, particularly during the cold period (Magalhaes & Leal, 2013). It can be correlated with low household income, high energy cost and energy inefficient homes (BPIE, 2014). Figure 2 represents the European countries inability to keep homes adequately warm and Portugal is in the group of the countries with higher rank.

Portugal had the average value of 17 kWh/m^2 for heating consumption regarding the year of 2015 (ODYSSEE-MURE). When compared to other European countries, is possible to conclude that Portugal has a considerable smaller consumption regarding heating, even comparing with countries in the same climatic region, like Spain, as represented in Figure 3. The reason is not only related with lower heating needs due to a warmer climate, but also to a lower average income.

Portugal has one of the most unequal income distributions in Europe. In 2011, the Gini index, a measure of inequality commonly used, was equal to 0.341, about 2.6 percentage points above the OECD average of 0.315 (Arnold & Farinha Rodrigues, 2015). As referred before, the low income results on less energy consumption for heating and less investments on building retrofit.

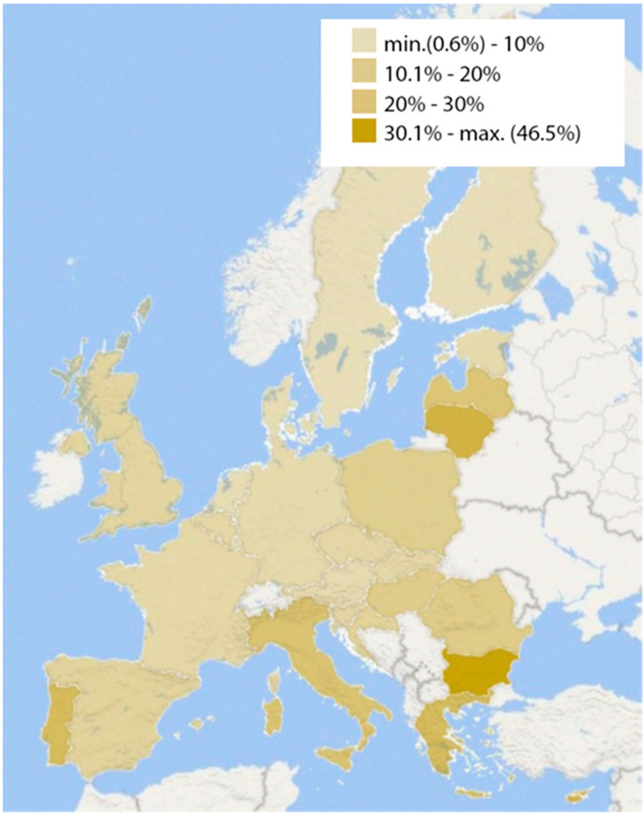


Figure 2. Inability to keep home adequately warm in Europe in 2012 (BPIE, 2014).

Briefly, according to different studies (Healy, 2004; Liddell et al., 2016; Simões et al., 2016), Portugal, Greece, Italy and Spain are the most 'fuel poor' countries in the EU. Accordingly to (Simões et al., 2016), the fuel poverty for Portugal reaches 22% of the inhabitants

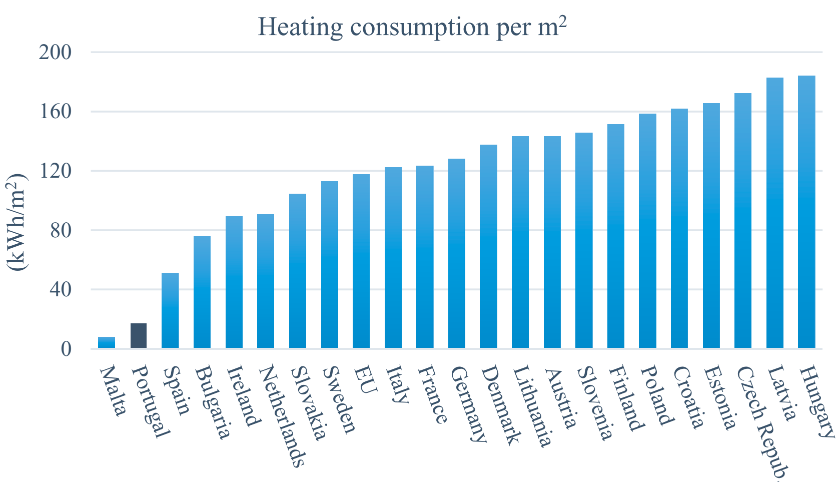


Figure 3. Heating consumption per m^2 in European Countries (2015) (ODYSSEE-MURE project).

regarding their dwellings' space heating and 29% regarding space cooling. Particularly in Lisbon, the same numbers for fuel poverty regarding space heating are 20% and space cooling 26%.

On top of these, the European population is ageing, and it is estimated that in 2050 there will be twice as many people above 65 years of age than in 1990. Elderly people are among the most exposed to fuel poverty, due to the fact that they are likely to have lower income than the active population, they need higher indoor temperatures, they are more prone to diseases and they have higher risks and less will for investing in their homes (BPIE, 2014). Portugal has the fifth highest index of population ageing of the European Union (INE, 2015).

Fuel poverty can be tackled by income increase, fuel prices regulation and energy efficiency improvements in buildings. Energy costs are growing faster than household income. Therefore, energy consumption subsidies and direct financial support for household heating cannot provide a long-term solution to the fuel poverty problem. EER can however give a long-term sustainable answer to fuel poverty (BPIE, 2014). These measures address the root of the problem and result in reduced energy costs and/or improved thermal comfort in homes, create or maintain jobs, reduce illness, rehabilitate poor districts and therefore contribute to social inclusion (BPIE, 2014).

In this paper, in order to better evaluate the real effect of the EER on the thermal comfort and energy savings of the households, we propose the use of building simulation models calibrated with indoor temperature values, given by temperature meters located in residential households.

The fact that these households have almost no actual acclimatization consumptions, would result on very high payback periods regarding the assessment of the cost benefit of EER. The investment on the retrofit measures will never result on an economic advantage if it's only based on the energy savings as the main result from its implementation. Therefore, this paper also proposes a different indicator to evaluate the thermal comfort from an economic point of view, based on the comparison of energy consumption, using the same thermal comfort Fanger value (Fanger, 1970) as the minimum comfort set-point, for the HVAC system before and after the retrofit measures.

2. Methodology

The objective of this paper is to study two households within the Suscity Project, using building energy simulation models, which are calibrated and validated with real measurements, and analyse a set of retrofit measures considering the minimum energy consumption to guarantee a certain level of occupants thermal comfort. In order to fulfil these goals, the work was divided in three parts: monitoring campaign, model simulation and calibration, and retrofit measure analysis.

The monitoring campaign gathered experimental data for the characterization of the case study households regarding occupants' behaviour and equipment usage, and other significant aspects for the simulation model and the calibration process. It included the installation of energy, temperature, humidity and CO_2 meters, as well as a survey regarding the lifestyle of occupants.

The model simulation allows the evaluation of the thermal behaviour and the energy consumption of each house. The calibration work was performed after the monitoring and simulation phases. It consisted in the statistical analysis and validation, of the relation between measured and simulated data.

The last stage of this work was the evaluation of different retrofit measures that were chosen considering common solutions for building retrofit in Portugal (Republic_Zeb project, 2015). The choices included the improvement of the building envelope, the installation of HVAC and domestic hot water (DHW) systems and lighting systems replacement. The approach used in this paper for the evaluation of the EER considers the thermal comfort level and energy consumption required to achieve it in the pre-retrofit case (Fang, Bianchi, & Crhistensen, 2012), and compares it to the energy consumptions obtained from simulation of the different combinations of EER, assuming the same thermal comfort values of the pre-retrofit case. Notice however that the pre-retrofit energy consumption is not real, as the occupants do not achieve the minimum thermal comfort. The cost benefit analysis was based in the discounted payback period indicator.

2.1. Case study

The two families considered in this study are part of a group of volunteers for house monitoring scattered around Parque das Nações, in the Olivais neighbourhood during the Suscity Project (Figure 4). The houses are located in an urban environment, predominantly residential, having the surrounding buildings between four and seven floors.

The households building typologies, construction solutions, and date of construction are similar to a large number of houses in Portugal (around 200 thousand houses (Brandão de Vasconcelos, Pinheiro, Manso, & Cabaço, 2014)).

Table 1 presents the predominant constructive solutions defined for the building envelope of each household.

2.1.1. Building simulation zoning

For this simulation, the building thermal zoning was defined for each space of the two houses, as defined by the building plans. The zones included the following spaces: kitchen, rooms and living rooms, circulation areas and bathrooms (Table 2).

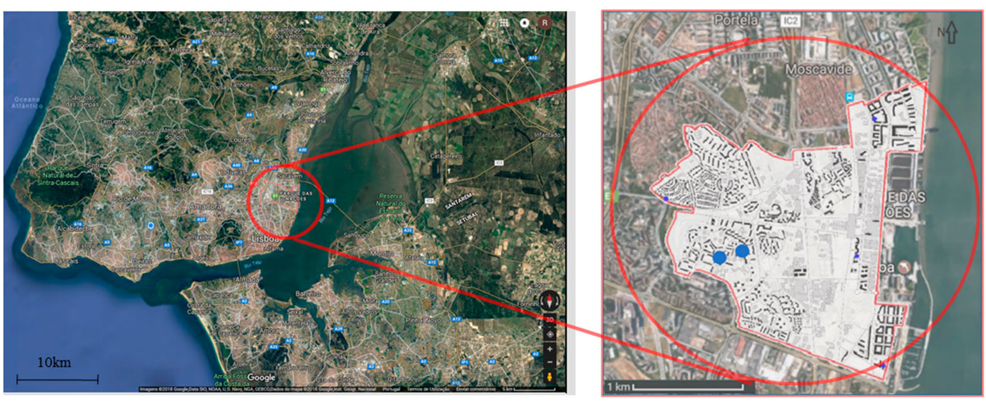


Figure 4. Lisbon and SusCity area (dots locate the households).

Table 1. Constructive solutions of the building envelope, year of construction and typology.

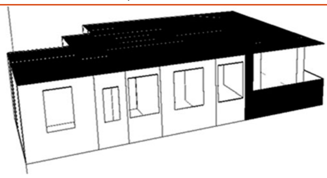
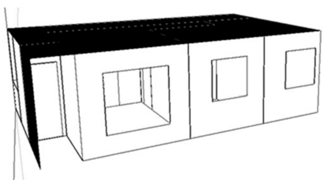
Case study		Building element	Composition	*U*-value [W/m^2 °C]
T3 household, Olivais Sul, 1971		Exterior wall	Plaster, hollow brick wall (0.22 m), plaster (colour: light brown)	1.2
	Orientation: bedrooms SW, living room NE 5th floor (intermediate floor)	Interior ceiling/ floor	Concrete slab	3.2
		Windows	Single glazing window, aluminium frame without thermal break, venetian blinds	6.5 (without shade) 3.80 (with shade)
T2 household, Olivais Sul, 1967		Exterior wall	Plaster, double hollow brick wall (0.11 m) with no insulation, Plaster (colour: light brown)	1.18
		Interior ceiling/ floor	Lightened slab with hollow clay bricks	1.7
	Orientation: East Ground floor	Windows	Double glazing window, aluminium frame with thermal break, venetian blinds	3.30 (without shade) 2.90 (with shade)

Table 2. Building simulation zone characteristics.

	Window–wall ratio (%)	Conditioned thermal zones simulated	Unconditioned thermal zones simulated
T3 household, Olivais Sul, 1971	38	4 (63 m^2)	7
T2 household, Olivais Sul, 1967	29	3 (30 m^2)	3

2.1.2. Schedules (occupation, lights, equipment)

The schedules used for simulate the occupation, lighting and equipment patterns were asked during the monitoring campaign and used in the simulation. The house is occupied between 18 and 9 h on the weekdays and it was considered occupied during the weekend.

2.1.3. Building internal gains

The internal heat gains considered for this simulation are related with people, equipment and lighting. The internal gains schedules and values were defined to be the closest to the real patterns. Table 3 presents the values for the internal gains considered in the simulation.

Table 3. Internal gains considered in the simulation.

Case study	Occupation (number of people)	Lights in occupied area	Equipment in occupied area
T3 household, Olivais Sul, 1971	Two (in different rooms)	7 W/m^2 Max. 773 W	39 W/m^2 Max. 4080 W
T2 household, Olivais Sul, 1967	Two (in different rooms)	11 W/m^2 Max. 526 W	92 W/m^2 Max. 4690 W

The values presented in the table are average values, and is relevant to say that the high equipment power values are related with the kitchen equipment. However, these equipment is used sparsely during the day as referred by the occupant inquiry and reflected in the simulation schedules.

2.1.4. Air infiltration

When modelling a building with the intention of obtaining the values of energy consumption and thermal behaviour, one of the most relevant inputs needed is the air infiltration rate value, which is difficult to measure and is strongly dependent of other factors, such as: wind values and direction, indoor temperature, envelope elements and occupants behaviour (ASHRAE, 2009; Silva & Pinto, 2011; Villi, Peretti, Graci, & De Carli, 2012). There are several methods to obtain the air infiltration rate. In this work, the method used is the tracer gas constant emission method (Cerqueira, Azevedo, & Aelenei, 2014; Laussmann & Helm, 2011). For each household, measurements of CO_2 were made in the master rooms and, in the case of couples with children, in the secondary room. The duration of the measurement was one week with a 10 min time step. Table 4 presents the average value of Air Changes per Hour (ACH) obtained for each household.

2.2. Monitoring campaign

The monitoring campaign allowed evaluating the indoor thermal conditions, energy consumption and the occupants' habits that influence both the thermal behaviour of the household and its energy consumption. The monitoring campaign comprised different parameters to characterize the outdoor thermal conditions, the indoor thermal conditions and the energy consumption. The parameters considered in this monitoring campaign to characterize the indoor conditions were indoor temperature, relative humidity and CO_2 concentration (for infiltration rates estimation). The indoor temperature was measured at least in the master bedroom, secondary room or living room. The users' occupation and usage patterns regarding room occupation, window shading, equipment, HVAC, lighting systems and electrical equipment usage were registered in inquires or through observation in loco. In addition, electric meters were installed to analyse the electric consumption.

For the outdoor conditions, one weather station was installed inside the project area. This station registered the outdoor temperature, humidity, solar radiation, and wind speed and direction. The data collected was used to update the simulation weather file.

The monitoring campaign for the indoor temperatures and for the outdoor conditions were performed during one year (between 2015 and 2016).

2.3. Model simulation software

The energy simulation software considered in this paper was the EnergyPlus version 8 (DOE, 2018) and the geometry was defined using Google Sketchup 7 (Google, 2016). EnergyPlus is a

Table 4. Average air infiltration (air changes per hour).

Case study	ACH (h^{-1})
T3 household, Olivais Sul, 1971	1.0
T2 household, Olivais Sul, 1967	0.85

modular, structured code based on the most popular features and capabilities of BLAST and DOE-2.1E. The EnergyPlus building systems simulation module, with a variable time step, calculates heating and cooling system and plant and electrical system response. This integrated solution provides accurate space temperature prediction crucial for occupant comfort and occupant health calculations (Rallapalli, 2010; US Department of Energy, 2013).

2.4. Domestic hot water (DHW) calculations

The expression considered to calculate the domestic hot water needs was the Portuguese regulation for energy performance in the residential buildings (REH, 2013):

$$E_{DHW} = 40*n*4187*\Delta T*365/3,600,000 \text{ kWh/year}, \quad (1)$$

where $\Delta T = 35°C$ temperature increase needed to prepare the DHW and $n=$ number of house hold occupants.

2.5. Weather file

The energy plus weather file for Lisbon was updated to conduct the validation of the model. The data (outdoor temperature, relative humidity, radiation, wind speed and direction) was collected from a weather station in a volunteer's house located in Olivais Sul.

For the retrofit measures analysis, the weather file for Lisbon, from the National Laboratory for Energy and Geology (LNEG), was used.

2.6. Model calibration

In general, energy model calibration is an over-parameterized and context-related process. The model calibration is commonly defined as an inverse approximation because of the need for tuning necessary inputs to reconcile the outputs by a simulation program, as closely as possible to the measured energy data. It is over-parameterized because of the large number of independent and interdependent input parameters that need to be specified, which represent the complex correlations and dynamic interactions among envelope thermal conditions, HVAC responses, exterior impacts and interior impacts, and cannot be all obtained empirically (Coakley et al., 2015; Fabrizio & Monetti, 2015; Jones et al., 2015; Karlsson et al., 2007).

During calibration process, two main sets of data are needed and compared: the simulation data set, from the building model created, and the measurements data set, from the real building monitoring.

Different indices are commonly used to evaluate the data matching and quantify the accuracy of the validation of the model. These criteria determine how well simulated data matches the measured data at the selected time interval. Statistical indices have become the international reference criteria for the validation of calibrated models. They have been recommended by three main international bodies in the following documents (Fabrizio & Monetti, 2015):

- American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guidelines 14 (St.14);

- International Performance Measurements and Verification protocol (IPMVP);
- M&V guidelines for the US Federal Energy Management Program (FEMP).

The most common statistical indices that are used are the Mean Bias Error (MBE) and the Coefficient of variation of the Root Mean Square Error (CvRMSE).

$$\mathrm{MBE}\ (\%) = \frac{\sum_{\mathrm{Period}} (S - M)_{\mathrm{interval}}}{\sum_{\mathrm{Period}} M_{\mathrm{interval}}} \times 100\%, \tag{2}$$

$$\mathrm{Cv(RMSE)}_{\mathrm{period}} = \frac{\mathrm{RMSE}_{\mathrm{period}}}{A_{\mathrm{period}}} \times 100\%, \tag{3}$$

$$\mathrm{RMSE}_{\mathrm{period}} = \sqrt{\frac{\sum (S - M)^2_{\mathrm{interval}}}{N_{\mathrm{interval}}}}, \tag{4}$$

$$A_{\mathrm{period}} = \frac{\sum_{\mathrm{Period}} M_{\mathrm{interval}}}{N_{\mathrm{interval}}}, \tag{5}$$

where M is the measured data point during the time interval, S is the simulated data point during the same time interval and NInterval is the number of time intervals considered for the monitored period.

The consideration of both indices allows preventing any calibration error due to errors compensation. The CvRMSE is the Coefficient of Variation of RMSE and is either a normalized measure of the variability between measured and simulated data and a measure of the goodness-of-fit of the model. It specifies the overall uncertainty in the prediction of the building thermal behaviour, reflecting the errors size and the amount of scatter. Lower *CvRMSE* values take to a better calibration process.

In order to consider a model calibrated, a threshold limit of the MBE and the CvRMSE must be respected. Depending on the time interval for the calibration (monthly or hourly) and in compliance with the requirements of the Standard/Protocol considered (St.14, IPMVP or FEMP), the limit threshold is subjected to slight differences, as reported in Table 5.

The presented statistical indices are more often used to the predicted building energy consumption than with indoor temperature. The compliance with the thresholds can also be achieved through different models, as the solution is not unique and may not guarantee that all the model input data are correctly tuned, reflecting that calibration is an underdetermined problem (Reddy et al., 2006).

To improve the calibration process, a sensitivity analysis was performed using the JEplus software (Zhang, 2012). The choice of the input parameters subject to a sensitivity analysis relied on the expertise of the simulation modellers but also in a statistical analysis.

Table 5. Calibration indexes limit values – adapted from: Fabrizio and Monetti (2015).

	Monthly calibration			Hourly calibration		
	St.14	IPMVP	FEMP	St.14	IPMVP	FEMP
MBE (%)	±5	±20	±5	±10	±5	±10
CvRMSE (%)	15	–	15	30	20	30

After the definition of which parameters should be studied and analysed, it was necessary to establish the range within each parameter values may vary.

2.6.1. Sensitivity analysis

The variables analysed under this parametric analysis were: (1) the air infiltration, (2) equipment and lighting power, (3) walls thermal conductance and the (4) occupation schedule. The choice is related with the experience of the authors in the weight of these variables in the simulation results. The infiltration values were changed within a ±15% range and the occupation schedule was changed within ±1 h from the reference scheduled (as given by inquiry to the occupants). The occupants' schedules affect the usage of equipment and lighting.

2.7. Thermal comfort models

Building occupants' thermal comfort is a well-studied subject, analysed in numerous studies and papers. Overall thermal comfort do not depend solely on building physical parameters. The human body's physiological and psychological responses to the environment are dynamic and integrate various physical phenomena that interact with the space (Rupp, Giraldo Vásquez, & Lamberts, 2015). In several studies concerning the most relevant aspects regarding satisfaction with the indoor environment, users rated the thermal comfort as the most important one (Rupp et al., 2015). In the area of thermal comfort, the international standards commonly used to evaluate the thermal environments are ISO 7730-2005, EN 15251-2007 and ASHRAE 55-2017. There are different approaches to evaluate it, suitable for different situations such as office environment, sports arenas, health facilities and others buildings uses. Thermal comfort can be generically defined as,

> that condition of mind which expresses satisfaction with the thermal environment. Because there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space. The environmental conditions required for comfort are not the same for everyone. However, extensive laboratory and field data have been collected that provide the necessary statistical data to define conditions that a specified percentage of occupants will find thermally comfortable. (ASHRAE 55, 2017)

In this paper two approaches are used to evaluate the thermal comfort in the households before the retrofit measures. The Adaptive Comfort Model ASHRAE 55-2017 and the most well-known thermal comfort reference, the Fanger model.

2.7.1. Adaptive Comfort Model ASHRAE 55-2017

In ASHRAE Standard 55, the prevailing mean outdoor temperature is defined as the arithmetic average of the mean daily outdoor temperatures over no fewer than 7 and no more than 30 sequential days prior to the day in question. The model defines two comfort regions: the 80% acceptability and 90% acceptability relating indoor operative temperatures and prevailing mean outdoor temperatures (Figure 5).

2.7.2. PMV model

Fanger developed the model based on the research he performed at Kansas State University and the Technical University of Denmark, where he used a seven-point form scale of

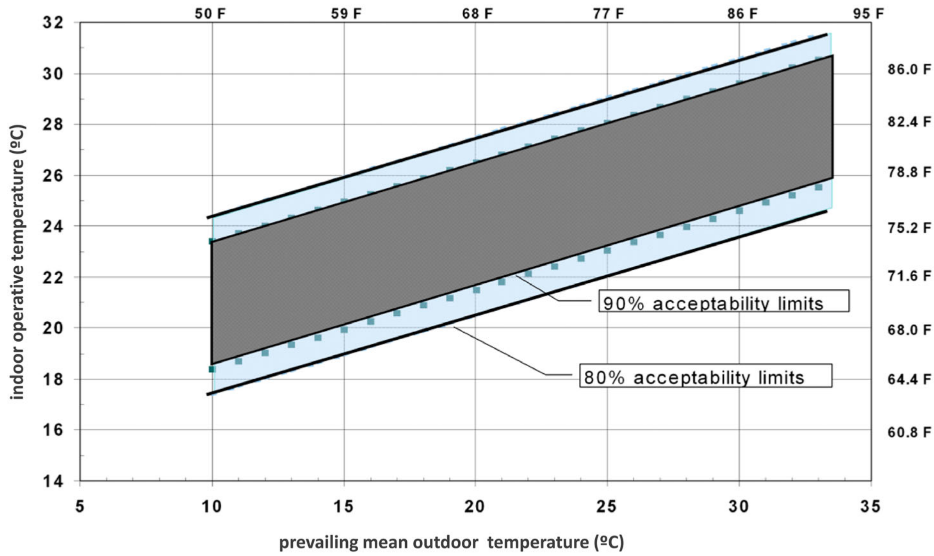


Figure 5. ASHRAE 55 limits for thermal Comfort (adapted from ASHRAE 55, 2017).

thermal sensation (3 hot, 2 warm, 1 slightly warm, 0 neutral, −1 slightly cool, −2 cool, −3 cold, −4 very cold), along with numerous experiments involving human subjects in various environments and then related the subjects in response to the variables, which influence the condition of thermal comfort. This model is also included in the thermal comfort standards considered in this work (ASHRAE 55).

Accordingly to Fanger, there are six primary factors that must be addressed when defining conditions for thermal comfort: (1) Metabolic rate; (2) Clothing insulation; (3) Air temperature; (4) Radiant temperature; (5) Air speed; (6) Humidity. The thermal comfort is then a result of an expression that relates these factors with a Predicted Mean Value of comfort (PMV). The equations for PMV calculation are presented next.

$$\begin{aligned}\mathrm{PMV} = {} & [0.303e^{-0.036M} + 0.028]\{(M - W) - 3.96E^{-8} f_{cl}[(t_{cl} + 273)^4 - (t_r + 273)^4] \\ & - f_{cl}\, h_c(t_{cl} - t_a) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] \\ & - 0.0173M(5.87 - p_a) - 0.0014M\,(34 - t_a)\},\end{aligned} \tag{6}$$

$$f_{cl} = \frac{1 + 0.2I_{cl}}{1.05 + 0.1I_{cl}}, \tag{7}$$

$$\begin{aligned}t_{cl} = {} & 35.7 - 0.027(M - W) - R_{cl}\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) \\ & - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\},\}\end{aligned} \tag{8}$$

$$R_{cl} = 0.155I_{cl}, \tag{9}$$

$$h_c = 12.1(V^{\frac{1}{2}}), \tag{10}$$

where f_{cl} clothing factor, h_c convective heat transfer coefficient, I_{cl} clothing insulation [clo], M metabolic rate [W/m^2] 115 for all scenarios, p_a vapour pressure of air [kPa], R_{cl} clothing thermal insulation, t_a air temperature [°C], t_{cl} surface temperature of clothing [°C], t_r mean radiant temperature [°C], V air velocity [m/s], W external work (assumed = 0).

In this paper, the clothing values were defined using the CBE Thermal Comfort Tool for ASHRAE 55 (Center for the Built Environment (CBE), 2018) considering the different seasons and the answers from the occupants' survey. For the air velocity it was considered the default value proposed by Energy Plus (0.15 m/s). The activity level that defines the metabolic rate was defined considering the ASHRAE values for standing, relaxed (126 W, respectively). The other parameters that influence the PMV value were calculated by the software. The comfort evaluation was performed using the output 'Zone Thermal Comfort Fanger Model PMV' of the Energy Plus simulation model.

2.7.3. PMV setpoint for the acclimatization needs

One common way to simulate the acclimatization needs with Energy Plus is to use the Ideal Air Load Systems object. This is the simplest approach to calculate the heating and cooling loads needed to achieve a defined zone setpoint for a certain schedule. In this paper, the setpoint for the Ideal Air Load System considered the comfort evaluation values of the real case scenario (pre-retrofit).The simulation object is the *ThermostatSetpoint:ThermalComfort:Fanger:DualSetpoint* (EnergyPlus, 2013). This object dials the thermostat setpoint either up or down to meet the specified value of thermal comfort (PMV).

Both families have heating equipment, i.e. electric heaters (approximately 100% efficiency) that they use only occasionally, due to the high energy costs. So, the reference pre-retrofit case model was simulated considering the indoor temperature heating setpoint of 18°C for heating, for both bedrooms and living room, during the occupied hours. This value is a reference legal value for heating concerning residential buildings, as expressed in the national decree-law n° 118/2013 (REH, 2013). On the other hand, there is no cooling equipment. Consequently, it was considered no cooling setpoint (free-float simulation).

The hourly average PMV value (PMV) was calculated by Energy Plus for the two households for both bedrooms and living rooms. For the bedrooms, the comfort was only evaluated when the occupants were not sleeping, since it was considered that when a person is sleeping, it has normally the suitable clothing for being thermally comfortable.

2.8. Retrofit measures

The measures for retrofit were chosen and adapted from the European project Republic ZEB (Republic_Zeb project, 2015) and from common retrofit measures in Portugal (Clímaco Pereira, Brown, & Ray, 2008). They are divided in: exterior walls, windows, domestic water heating (DWH), space heating and cooling, and lighting (Table 6). Due to physical limitations and condominium rules, solutions as installing PV panels or exterior shadings were not considered in this paper.

Some retrofit scenarios do not have equipment for cooling, as the pre-retrofit scenario doesn't. For the economic analysis, it was considered that the efficiency of cooling for those cases is 1, although knowing that this value isn't possible for cooling systems. With this approach the intention is to not benefit, nor penalize the measure, as it does not affect the cooling consumptions. The retrofit measures that provide cooling are affected by the efficiency of the equipment.

Table 6. Retrofit measures costs.

Retrofit measures	Description	Id.	Retrofit area	Cost
Thermal insulation in exterior walls	No insulation	I_Null	Heating and Cooling	–
	Extruded polystyrene 4 cm	I_04	Heating and Cooling	13 €/m^2 [a]
	Extruded polystyrene 5 cm	I_05	Heating and Cooling	15 €/m^2 [a]
	Extruded polystyrene 8 cm	I_08	Heating and Cooling	22 €/m^2 [a]
	Extruded polystyrene 12 cm	I_12	Heating and Cooling	30 €/m^2 [a]
Windows replacement	U 3.30 W/m^2 °C/SHGC 0.73/PVC frame	W00	Heating and Cooling	–
	U 2.80 W/m^2 °C/SHGC 0.75/PVC frame	W01	Heating and Cooling	131 €/m^2
	U 2.50 W/m^2 °C/SHGC 0.75/PVC frame	W02	Heating and Cooling	200 €/m^2
	U 2.10 W/m^2 °C/SHGC 0.75/PVC frame	W03	Heating and Cooling	270 €/m^2
HVAC and DHW systems	System referred in the national regulation ηic – electric 1/ηvc – electric 1/ηDHW – natural gas 0.84	Si_Base	–	–
	Compact heat pump for DHW ηic – electric 1/ηvc – electric 1/ηDHW – electric 4	Si_AQS1	DHW	1300 €
	Efficient natural gas water heater ηic – electric 1/ηvc – electric 1/ηDHW – natural gas 0.9	Si_AQS2	DHW	300–400 € [c]
	VRV 12,1 kW for space heating and cooling and DHW ηic – electric 4.5/ηvc – electric 6.4/ηDHW – natural gas 0.84	Si_AH_1	Heating, Cooling	8760–9660 € [c]
	Combined natural gas for space heating and DHW ηic – natural gas 0.93/ηvc – electric 1/ηDHW – natural gas 0.93	Si_AH_2	Heating and DHW	1060–1300 € [c]
	Multi-split ηic – electric 4.4/ηvc – electric 6.2/ηDHW – natural gas 0.84	Si_AHC1	Heating and Cooling	1610–2440 € [c]
	Multi-split ηic – electric 4.21/ηvc – electric 6/ηDHW – natural gas 0.84	Si_AHC2	Heating and Cooling	1495–1952 € [c]
Lighting system	LED	LED	Lighting	0.6 €/W [b]

[a]CYPE Ingenieros, S.A. (2018).
[b]Average value for light replacement and only in occupied areas.
[c]Prices range for the T2 and the T3.

In this study one of the most common financial viability indexes was used, the discounted payback period. This can be defined as the capital budgeting procedure used to determine the profitability of a project. A discounted payback period gives the number of years it takes to break even from undertaking the initial investment, by discounting future cash flows, in this case energy savings, and recognizing the time value of money (Investopedia, 2018).

After running the simulation, the values for heating, cooling, lighting and total energy costs were estimated. The discounted payback period was calculated considering the discount rate of 2.4% for the energy prices. This is the average value of inflation rate for 'houses, water, electricity, gas and other fuels' (Pordata, 2017). Table 7 presents the following energy prices for the year zero.

Table 7. Energy prices at the year zero.

	€/kWh
Natural gas	0.065
Electricity	0.2

3. Results

The results in this paper are divided in different topics: model calibration, real case scenario thermal comfort evaluation, and retrofit measures.

3.1. Model calibration and validation

The calibration focused in the analysis of the hourly indoor temperature, daily consumption and hourly consumption along one-year measurements (2015–2016). The results of the lowest CvRMSE models are presented in Table 5. As it was expected, the validation using hourly electrical energy consumption was not achieved. The main reasons for this are related with the discrepancy between the information given by the occupant regarding equipment, lighting, HVAC usage, and the real occupant behaviour. These reinforces the idea that the information about the occupants' patterns and behaviour, greatly influences the energy consumption and that for a more accurate calibration of the model, different type of sensors would be required (occupancy sensors, equipment on/off sensors, HVAC control, window opening and shading sensors). That differences are not so significant for the indoor temperature calibration (Table 8).

The sensitivity analysis results are not described here as it was a comprehensive and complex process and would not fit within the main goals of this paper. Nevertheless, it is relevant to say that the combination solutions, for both houses, resulting from the sensitivity analysis with the lowest CvRMSE were used.

The results for the CvRMSE values for the indoor temperatures of both bedroom and living room were below the reference values of the standards referred in Table 5, so the models were considered validated.

3.2. Thermal comfort evaluation of the real case (pre-retrofit)

The results presented for the evaluation of the thermal comfort of the pre-retrofit case are divided in two approaches, as proposed in the methodology section.

3.2.1. Adaptive Comfort Model ASHRAE 55-2017

Figures 6 and 7 present the simulation results for the monthly average operative temperature in the bedroom and the living room, for both households.

Figures 6 and 7 show that there is a discomfort associated with cold situations in both households, in particular for T2 household, and less discomfort for the cooling period.

3.2.2. PMV model

The average PMV values using the Fanger scale obtained from the simulation of the real case (pre-retrofit) are presented in Table 9. The starting and ending periods for both

Table 8. Calibration indexes results.

	Bedroom (°C)		Living room (°C)		Hourly electric consumption (kWh)	
ID	MBE	CvRMSE	MBE	CvRMSE	MBE	CvRMSE
T3 household, 1971	1.10%	6.50%	0.50%	6.90%	x	x
T2 household, 1967	-2.90%	5.74%	−0.20%	6.10%	x	x

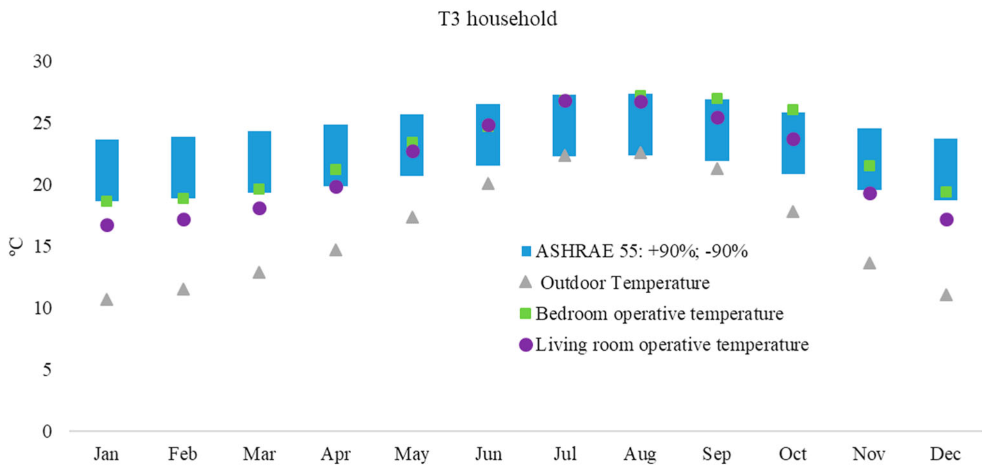


Figure 6. Bedroom and Living room monthly operative temperature and ASHRAE 55 limits for T3 household, Olivais Sul, 1971.

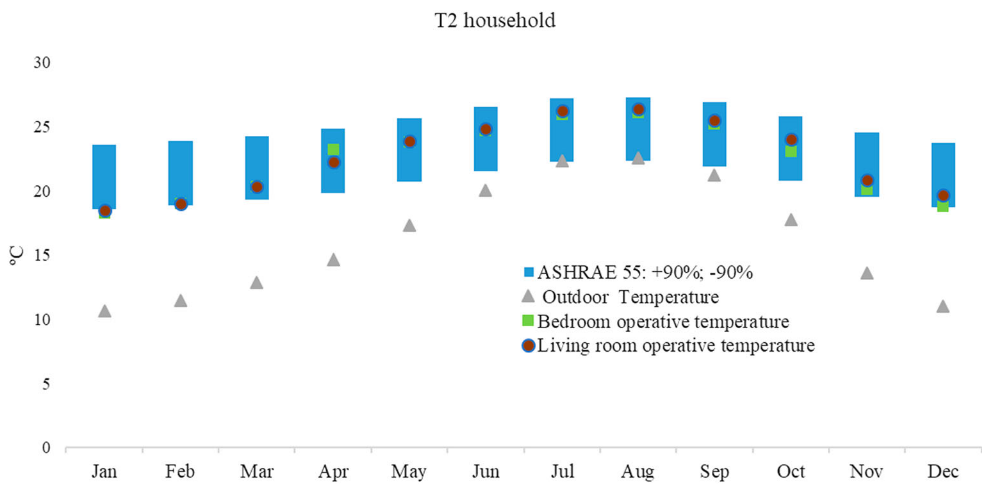


Figure 7. Bedroom and Living room monthly operative temperature and ASHRAE 55 limits for T2 household, Olivais Sul, 1967.

Table 9. Average thermal comfort values estimation from simulation (PMV).

	Living room		Bedroom	
Case study	Heating	Cooling	Heating	Cooling
T3 household, Olivais Sul, 1971	−0.97	0.66	−1.33	0.42
T2 household, Olivais Sul, 1967	−0.5	0.6	−1.62	0.5

heating and cooling season were according to the Portuguese legal standard (heating season from 1st of October to 30rd of May and cooling season from 1st of June to 30rd of September (REH, Síntese da regulamentação aplicável, 2013)).

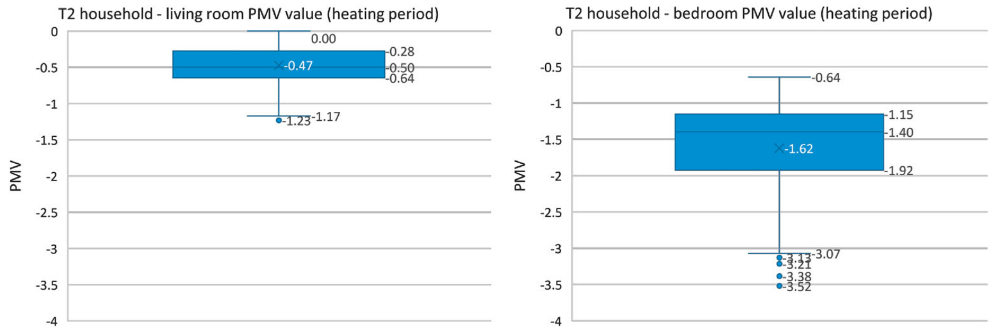


Figure 8. PMV values distribution for the heating period for the T2 household, Olivais Sul, 1967.

Again, the results show discomfort values (higher than |0.5|) for the heating period, especially in the bedrooms. The average discomfort values obtained for cooling are not so significant.

The values presented in Table 9 were used as thermal comfort setpoint for the ideal air load system object in the simulation of the retrofit measures. This approach implies that the households are at least at the reference thermal comfort values, avoiding peaks of discomfort, as occurs in reality.

The graphs of the distribution of the PMV value along one year are presented in Figures 8 and 9 for both houses. The results are focused in the heating period, since it showed worst thermal comfort results.

When analysing the previous figures, it is possible to understand that the PMV values are high for the heating period, especially in the bedrooms. The approach used in this paper, as it considers the average thermal comfort value as a reference for acclimatization, allows to reduce the number of occurrences of the more extreme discomfort values.

3.3. Energy Efficiency Retrofit measures analysis

One of the main focus of this paper is to evaluate economically the energy retrofit measures from a thermal comfort perspective. With this in mind, Tables 10 and 11 present the top 10 combinations of EER sorted by minimum discounted periods taking in consideration that it was considered the same average level of thermal comfort, as evaluated in the real case scenario.

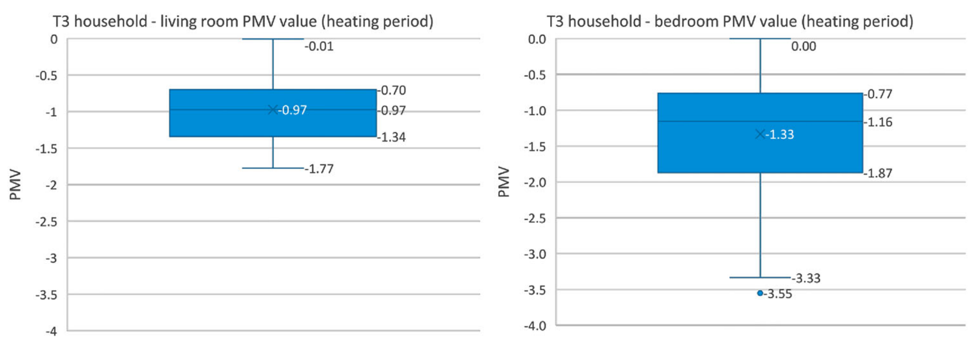


Figure 9. PMV values distribution for the heating period for the T3 household, Olivais Sul, 1971.

Table 10. Top 10 retrofit scenarios considering minimum discounted payback periods for the T3 household, Olivais Sul, 1971.

	Minimum discount payback period	Investment cost (€)	Return of investment (%)	Annual total savings (€)	Combination
1	6.2	1354	15%	202	I_Null, W00, LED, Si_AH_2
2	6.4	2006	14%	289	I_Null, W00, LED, Si_AHC2
3	7.7	2494	12%	293	I_Null, W00, LED, Si_AHC1
4	7.8	2630	12%	306	I_04, W00, LED, Si_AHC2
5	7.9	1952	12%	225	I_Null, W00, as it is, Si_AHC2
6	8.0	2726	11%	308	I_05, W00, LED, Si_AHC2
7	8.2	1978	11%	219	I_04, W00, LED, Si_AH_2
8	8.5	2074	11%	219	I_05, W00, LED, Si_AH_2
9	8.6	1300	10%	136	I_Null, W00, as it is, Si_AH_2
10	8.8	3062	10%	311	I_08, W00, LED, Si_AHC2

Table 11. Top 10 retrofit scenarios considering minimum discounted payback periods for the T2 household, Olivais Sul, 1967.

	Minimum discounted payback period (years)	Investment cost (€)	Return of investment (%)	Annual total savings (€)	Combination
1	5.7	1103	21%	233	I_Null, W01, LED, Si_AH_2
2	5.9	1060	21%	219	I_Null, W01, as it is, Si_AH_2
3	7.2	1538	18%	270	I_Null, W01, LED, Si_AHC2
4	7.3	1459	17%	247	I_04, W01, LED, Si_AH_2
5	7.4	1495	17%	256	I_Null, W01, as it is, Si_AHC2
6	7.5	1514	16%	248	I_05, W01, LED, Si_AH_2
7	7.5	1416	16%	233	I_04, W01, as it is, Si_AH_2
8	7.8	1471	16%	234	I_05, W01, as it is, Si_AH_2
9	7.9	1653	16%	270	I_Null, W01, LED, Si_AHC1
10	8.2	1610	16%	256	I_Null, W01, as it is, Si_AHC1

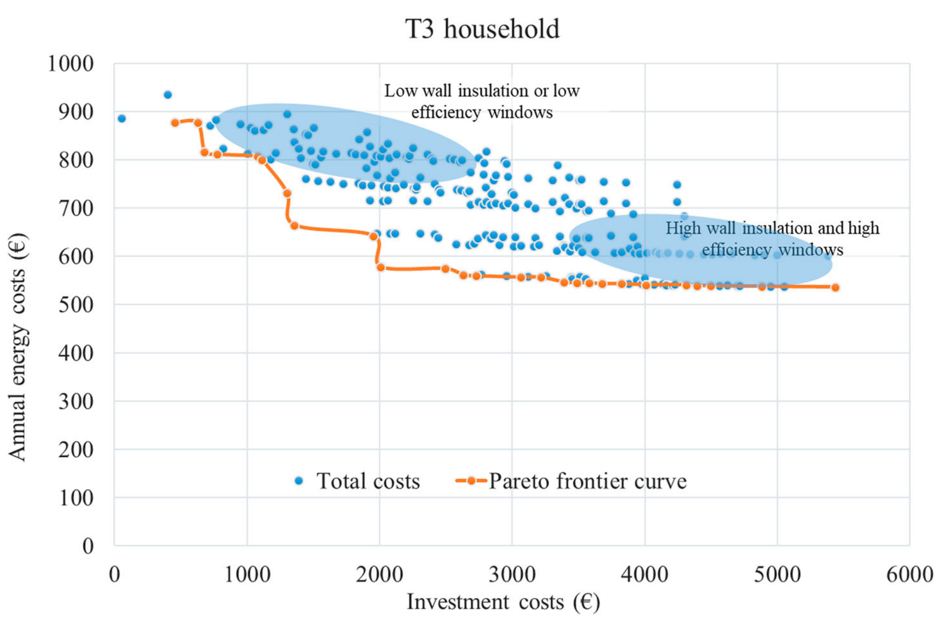


Figure 10. Annual energy costs (€) versus investment costs (€) for retrofit scenarios of T3 household, Olivais Sul, 1971.

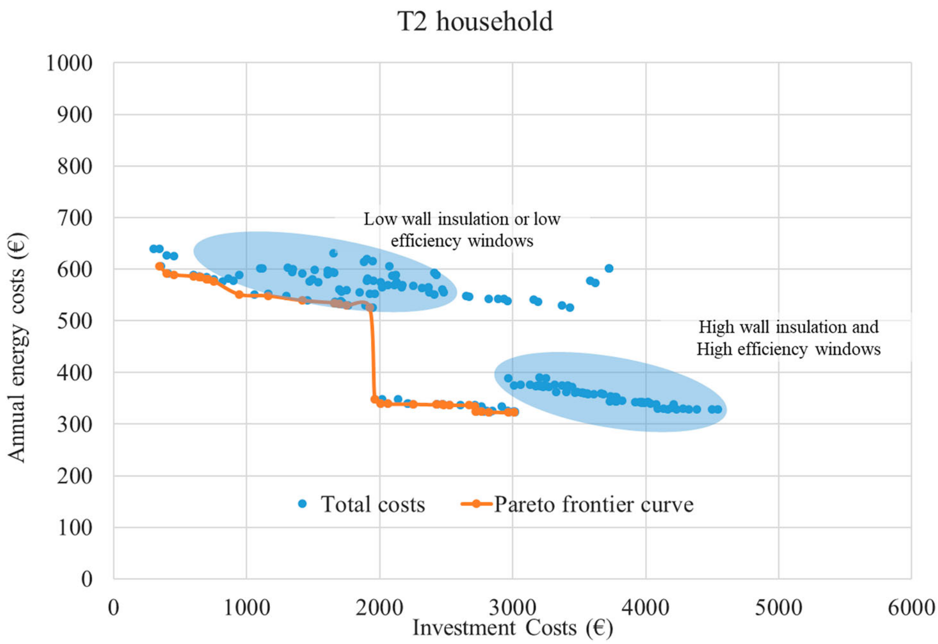


Figure 11. Annual energy costs (€) versus investment costs (€) for retrofit scenarios of T2 household, Olivais Sul, 1967.

Figures 10 and 11 present the annual energy operation costs (€) versus the investment costs (€) for all retrofit scenarios, for both households.

4. Discussion and conclusions

The thermal comfort evaluation for the real case shows that both households suffer from thermal discomfort, especially in the winter. This is in line with the concept of fuel poverty problem that in this case is translated in thermal discomfort related with both economical incapacity to heat the houses, and with the thermally inefficient construction solutions. The discomfort related with cold indoor environments is noticeable when evaluating both with the Adaptive Comfort Model from ASHRAE 55, as well as with the Fanger model. The PMV values were considerably high, especially in the bedrooms. The discomfort in the summer period is less relevant when comparing with the winter, for both houses.

Regarding the T2 household, the discomfort related with the cold results from different reasons, such as the low thermal insulation of the exterior walls, the low solar heat gains since the house is located on the ground level and has some shading from buildings nearby. Although this household owner has already invested on double glazed windows, the low internal gains and low heating levels are so low that are not enough to avoid discomfort related with cold.

Regarding the T3 household, the discomfort is more accentuated when comparing to the T2 household, both in the winter and summer period. The main differences between the two houses are related with the windows and floor height and these differences explain the higher discomfort in the winter. The windows have a higher *U*-value, so this household experience higher heat exchanges with the outdoors. This is reflected in the higher discomfort, especially in the winter period.

Again, the approach considered in this paper considered the PMV average value of the real case for the bedrooms and living rooms, as the HVAC setpoint reference value for the building simulation analysis. The thermal comfort average value as a setpoint reference allows to avoid the high peaks of discomfort, providing also a possible comparison between the real case and the retrofit scenarios in terms of energy needs to achieve that setpoint.

The payback periods presented on Tables 10 and 11 consider the thermal comfort reference values simulated for the pre-retrofit scenario. Individually, the measures that more rapidly pay the investment are those related with implementing a combined natural gas boiler for space heating and DHW, the lighting replacement and the implementation of a multi-split solution for acclimatization for both households. The payback periods range between 6 and 8 years.

Although this approach tries to reflect the economic evaluation of thermal comfort, some measures do no express it since, they are related with Domestic Hot Water or Lighting (even that it slight affects thermal indoor conditions).

The windows replacement, even considering that is a common retrofit measure in Portugal, does not appear on the 10 lowest payback periods. In the T2 household, this replacement was already done and more expensive windows do not compensate the investment. For the T3 household, it was possible to analyse that the windows replacement resulted on savings for the heating period but an increment of the cooling needs and consumption. This is explained by the fact that the double-glazed windows proposed as retrofit measure have lower thermal transmission coefficient. Thus, in the winter the household would lose less heat for the outdoors reducing the heating needs, but in the summer period the house would also lose less heat to the outdoor, especially during the night period, increasing in this way the cooling needs. Nevertheless, if some behaviour changes were adopted, such as increasing natural ventilation during the night or using more often the shading devices during the summer days, the windows replacement constitute a good solution.

Of course the values presented on Tables 10 and 11 do not represent real savings, since, as referred previously, the approach of this paper considers as a HVAC setpoint the average thermal comfort values for the pre-retrofit scenario.

In conclusion, the results show that the constructive solutions of these particular households, together with the almost absence of acclimatization consumptions, do not guarantee thermal comfort for its occupants, especially during the most extreme conditions on winter. If we consider the thermal comfort improvement, the active solutions represent the most economically viable options due to its high efficiency. In order to reduce the energy costs of using active systems, that could be significantly high to the poorest population, it is recommendable to evaluate the economic viability of policies that incentive the implementation of passive solutions, as the insulation in the exterior walls or windows replacement, reducing its investment cost. These policies may avoid in the future, high operational costs related with a possible energy cost increment, reducing also the greenhouse gas emissions related with over acclimatization.

5. Future work

Even considering that this paper is more focused on using a new approach for the residential retrofit evaluation, it is important to say that for the identification of the most suitable retrofit measures policy is mandatory to analyse a larger building sample. It is crucial to understand at a larger scale, such as the neighbourhood, which should be the most suitable retrofit measures package that would improve the thermal comfort of its occupants without severely compromise the economic viability of the investment. Also, more retrofit solutions must be analysed considering renewable energy production and architectural modifications such as exterior shadings.

Other topic that will be analysed is related with the uncertainty of the building simulation inputs and its effect on providing accurate savings and thermal comfort evaluation for different retrofit measures.

This future work will help to build a tool that will simplify the retrofit measures analysis, especially for buildings and families covered by the fuel poverty concern. The tool will provide to the stakeholders the opportunity to choose wisely and with more confidence which measures should be adopted.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The authors acknowledge Fundação para a Ciência e Tecnologia for the financial support of the SusCity project (MITP-TB/CS/0026/2013) and the PhD Scholarship PD/BD/105846/2014 through the MIT-Portugal Program. Support from the IN+ strategic Project UID/EEA/50009/2013 is gratefully acknowledged.

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