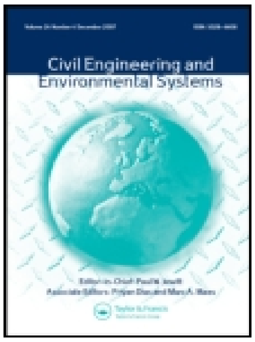

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Influence of climate change on the energy efficiency of light-weight steel residential buildings

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This paper addresses the influence of the climate change scenarios predicted by the Intergovernmental Panel for Climate Change (IPCC) for Southern Europe and the Mediterranean region on the energy efficiency of light-weight steel residential buildings. A performance-based approach is adopted to carry out this assessment using advanced dynamic simulation of the operational energy performance. Based on a typical Portuguese cold-formed steel residential building, a representative numerical model is calibrated against normative requirements for dynamic simulation of thermal behaviour and sophisticated computational fluid dynamics models. Considering climate change scenarios predicted by the IPCC, a parametric study is carried out to assess the influence of climate change on the energy efficiency of light-weight steel residential buildings representative of a warm temperate summer dry climatic region.

Keywords: light-weight steel; energy efficiency; thermal behaviour; numerical simulation; climate change

Introduction

The building sector accounts for circa 30–40% of all energy consumption (UNEP 2007). In Europe, buildings account for 36% of all energy use; residential buildings account for 27.5% of energy use. The breakdown of energy consumption is illustrated in Figure 1 for several climatic regions.

In general terms, four major categories of residential energy consumption can be identified: heating, cooling, lighting and others. It can be seen that the share of energy consumption dedicated to achieving thermal comfort criteria (heating and cooling) is substantial and ranges from 55% to 74%, depending on the climatic region (Figure 2).

The thermal comfort criteria for buildings (European Directive 2002/91/CE 2003, Decreto-Lei n°80/2006, EN ISO 13790, 2008) aim at ensuring minimum indoor winter temperatures (20°C according to the Portuguese code of practice, for example) and maximum indoor summer temperatures (25°C according to the Portuguese code of practice, for example). Historically,

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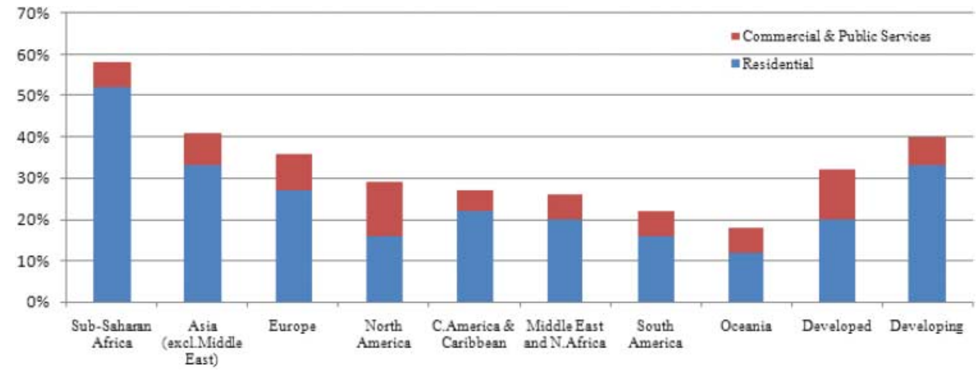


Figure 1. Residential and non-residential energy consumption for several geographical regions (UNEP 2007), percentage of total energy use.

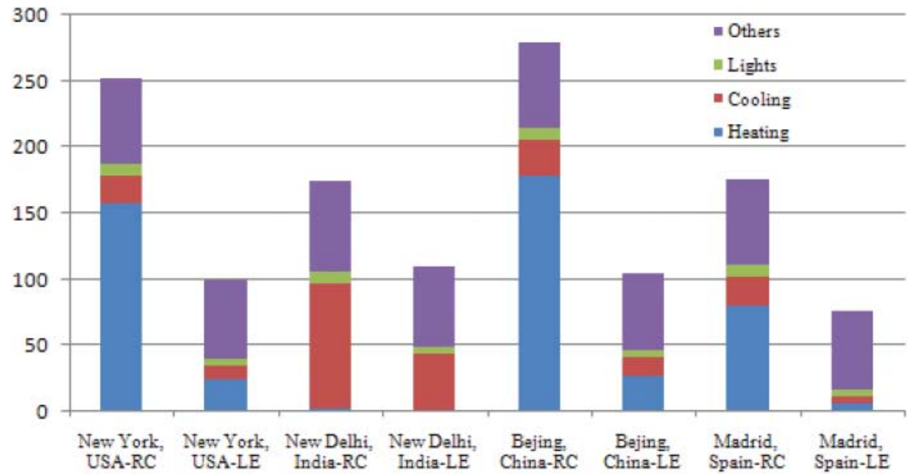


Figure 2. Breakdown of energy consumption in residential buildings (typical RC and LE) (UNEP 2007).

these targets were only explicitly set in recent years, but implicitly society (and consequently the real-estate sector) has continuously raised its comfort levels since the Second World War, in line with the increase of the standards of living in developed countries and developing countries. As an example, Portuguese households in the 1960s and 1970s were not fitted with air-conditioning, although Portugal has summer temperatures that induce indoor temperatures in excess of the current summer limit of 25°C. Nowadays, a large proportion of new residential buildings are offering air-conditioning as a standard feature.

Already in 1971, the Group of Rome (Meadows *et al.* 1972) predicted climate changes induced by mankind, a prediction that today, at the beginning of the twenty-first century, becomes more and more perceived by society. The fourth assessment of the Intergovernmental Panel for Climate Change (IPCC) (IPCC 2007) establishes science-based scenarios for climate change for the next 100 years that globally predict increases of the global mean air temperature in the range of 2°C to 4.5°C. Given that buildings are designed for service lives of 50 years and very often last well beyond that, it is clear that buildings must perform according to the thermal comfort criteria not only for current criteria but also according to future climatic scenarios that will occur in the next 50 years.

The influence of climate change on the energy efficiency of buildings has been addressed by several authors. Gaterell and McEvoy (2005) performed energy simulations on buildings in order to investigate the potential impact of climate change uncertainties on the performance of insulation measures applied retrospectively to an existing residential dwelling in the UK. They considered two greenhouse emission climate scenarios: low and high. Four insulation measures were considered: cavity wall, loft insulation, curtains and double glazing. They concluded that thermally, double glazing is the best option, while loft insulation is the worst.

Christenson *et al.* (2006) investigated the impact of climate warming on Swiss building energy demand by means of the degree-days method. They developed a procedure to estimate heating degree-days (HDDs) and cooling degree-days (CDDs) from monthly temperature data and applied it to four representative Swiss locations. They concluded that winter time heating costs will significantly decrease. However, more expensive electrical energy will be needed for air-conditioning during the cooling season. They were not able to conclude whether the total energy costs for building operation in Switzerland will decrease or increase. Nevertheless, they sentenced that current building design needs to take into account future climatic boundary conditions, in particular, with the aim of reducing the future cooling energy demand.

Urge-Vorsatz and Novikova (2008) investigated the potential for CO_2 emission mitigation and associated costs in buildings at worldwide level. The main conclusion was that substantial cost reductions can be achieved over the coming years in energy-related CO_2 emissions in the building sector. If this potential is realised, the building-related CO_2 emissions would stay constant until 2030. These stabilisation levels (if also achieved by all other sectors) would cancel about 3°C of temperature increase.

A building design response to climate warming for dwellings was studied by Arup on behalf of the UK Department of Trade and Industry (Bill Dunster Architects 2005) in order to assess the benefits of high-mass (heavy-weight) versus low-mass (light-weight) construction in London, Manchester and Edinburgh. Besides a light-weight and a heavy-weight construction, a medium-weight construction was also analysed. A medium–high greenhouse gas emissions climate change scenario was used in order to obtain weather data for three future ‘timeslices’: 2020s, 2050s and 2080s. First, an ‘unadapted’ house model was considered in order to represent the manner in which the house would normally be used in the present. Then, two ‘passive’ measures were considered in order to improve the thermal performance of the building, namely the control of solar gains and control of ventilation. It was concluded that there is a relatively poor thermal performance of the light-weight construction and that the mitigation of climate change effects can be achieved by designing with thermally massive passive features.

In Finland (Jokisalo and Kurnitski 2005), the effect of thermal inertia and various building and HVAC factors was assessed on a residential apartment building using a dynamic thermal simulation software IDA-ICE and the calculation method in accordance with the EN 13790 (EN ISO 13790, 2008). Five different types of building structures were simulated in the study, with distinct thermal inertia, but with a constant steady-state thermal transmittance of the envelope. It was concluded that the thermal inertia has an insignificant effect on energy efficiency in a Finnish residential apartment building (0.4% of total energy consumption); the tightness of the building results in an increase of the energy consumption of 8% at $3\,h^{-1}$ leakage; the shading by surrounding buildings increases the total energy consumption by 7%. On the other hand, a ventilation system has a very significant role in energy efficiency. A building with a traditional exhaust ventilation system uses up to 32% more energy than one with a balanced ventilation system with heat recovery equipment (60% temperature ratio).

These studies are not directly comparable because the influence of climatic region is overwhelming. Switzerland, UK and Finland correspond to different climatic regions and require distinct design strategies to minimise the energy consumption. In addition, the influence of some parameters, for example, thermal inertia, is not consensual, leading to some contradictory conclusions (Bill Dunster Architects 2005, Jokisalo and Kurnitski 2005). Besides this, the thermal behaviour and the energy efficiency of buildings depend on many factors including the building envelope and the building use. This fact highlights the need for more studies covering a wider range of climate zones and building types.

Low-rise residential buildings correspond to a significant market share of the residential/building sector (National Board of Housing, Building and Planning, Sweden and Ministry for Regional Development of the Czech Republic 2005). Among these, a light-weight steel construction (a leading structural solution in the USA and Japan, for example) offers many advantages and potentialities. Light-weight-steel-framed constructions are composed of studs and beams made from thin C-, U- or Z-shaped cold-formed sections. The thicknesses of the sheet can range between 0.6 and 2.5 mm for a maximum mass per unit length of 0.075 kN/m (European Light Steel Construction Association (LSK) 2005).

The objective of this paper is to assess the thermal efficiency of a typical light-weight steel residential building built in central Portugal, using advanced simulation techniques. Subsequently, a parametric study is carried out for various climate scenarios for climate change representative of warm temperate summer dry (Cs) climatic region (Kottek *et al.* 2006) to assess how the thermal performance of the building will be affected.

Climate

Climatic data

Geographically, continental Portugal is located between latitudes 37° and 42° N and longitudes 9.5° and 6.5° W. The maximum altitude is 2000 m. The country has a diverse climate from the North to the South and from the East to the West Coast. The north part of the country has an Atlantic climate with cold and wet winters. The central regions have a mixture of Atlantic and Mediterranean climates, with mild winters and hot and dry summers, particularly, in the inner regions. The southern part of the country has a very dry climate with mild winters.

According to the Portuguese Weather Institute (Website Portuguese Weather Institute 2010), the annual average of the air temperature varies regularly over the year, reaching the highest values in August and the minimum values in January. In the summer, the values of the average maximum temperature vary between 16°C in the highest mountain (inner central-northern region) and 32–34°C in the inner central-southern part of the country. The values of the average minimum temperature, during the winter, vary between 2°C in the inner high lands and 12°C in the south. The rainfall varies from the northern part to the southern part of the country. On average, about 42% of the annual rainfall occurs during the winter (December–February), while the lowest values are observed during the summer (July and August) with a share of 6% of the annual rainfall.

Coimbra is located in central Portugal. The annual variation of the outside temperature, according to data from EnergyPlus (Website Software Energy Plus 2010), is shown in Figure 3. The length of the heating season is 6 months and the corresponding degree-days are 1834 (base 20°C).

The air temperature in Portugal has been steadily rising over the last 30 years. The statistical analysis of the air temperature climatic series, between the years 1931 and 2004, illustrated in Figure 4, shows that the values of the annual average temperature have been increasing since 1972. The year 1997 was the warmest over the last 74 years. Furthermore, the six hottest years occurred in the last 12 years, and the year 2004 has, for the 18th consecutive year, a minimum air temperature above the 1961–1990 average.

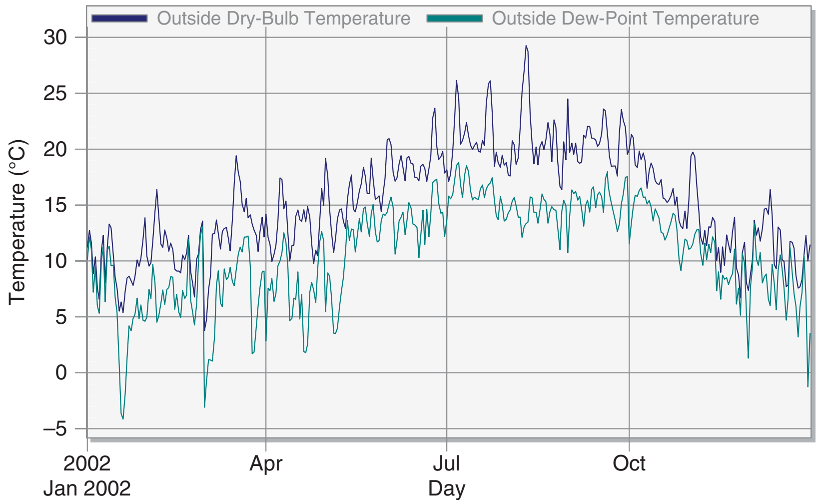


Figure 3. Annual outside air temperature for Coimbra (reference year 2002).

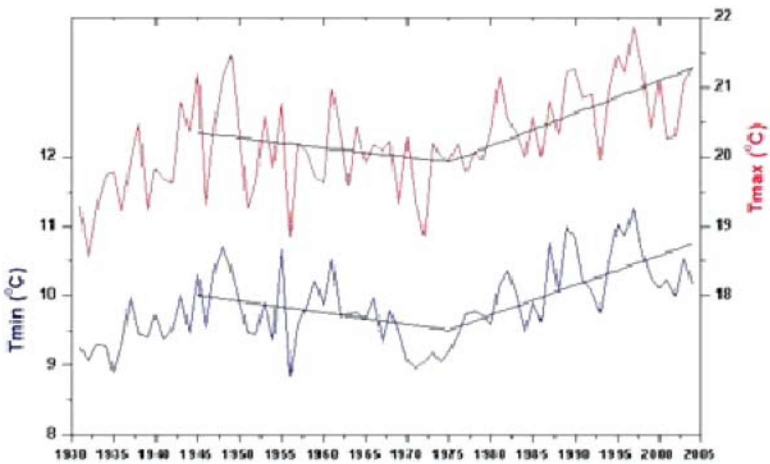


Figure 4. Variability of the annual average air temperature, minimal and maximal (1931–2004) (Website Portuguese Weather Institute 2010).

Climate change scenarios

The fourth assessment of the IPCC (IPCC 2007) narrowed down previous predictions for climate change for the next 100 years. Globally, the following climate changes are predicted:

(1) increase in global mean air surface temperature (2.0–4.5°C, with a most likely value of 3°C, corresponding to doubling of the atmospheric concentration of CO_2;
(2) increase in temperature extremes (more intense heat waves, significant decrease of cold episodes and faster decrease of daily minimum temperatures when compared with daily maximum temperatures, leading to a decrease of diurnal temperature amplitudes);
(3) changes in mean precipitation (global increase of averaged mean water vapour, evaporation and precipitation, with regional increases of precipitation in tropical, tropical pacific and high-latitude regions and decreased precipitation in sub-tropical regions);

(4) changes in precipitation extremes and drought (global increased intensity of precipitation and increased summer droughts in mid-continental areas);
(5) changes in carbon cycle (additional anthropomorphic concentration of CO_2 of 20–220 ppm by 2100, totalling 730–1020 ppm);
(6) increase in ocean acidification (decrease in pH of 0.14–0.35);
(7) increase in sea level (rate of sea level increase of 1.8 ± 0.5 mm/year, reaching +0.02 m by 2050 and +0.15 m by 2100).

At the regional level, Southern Europe and the Mediterranean region are representative of a Cs climatic region. Table 1 and Figure 5 summarise the predicted changes in temperature, precipitation and extreme events for this region. Table 1 shows the minimum, maximum, median (50%) and 25% and 75% quartile values for temperature (°C) and precipitation (%) change.

The mean temperature increase varies between 2.6°C and 4.1°C, with the maximum increase occurring for the summer quarter (June, July, August). According to the predictions of IPCC, a characteristic value of the temperature increase for the four quarters is 5.1°C, considering a 5% probability of exceedance.

Table 1. Predicted changes in temperature, precipitation and extreme events by 2100 for Southern Europe and the Mediterranean region (adapted from IPCC (2007)).

		Temperature response (°C)						Precipitation response (%)						Extreme seasons (%)		
Region	Season	Min	25	50	75	Max	*T* years	Min	25	50	75	Max	*T* years	Warm	Wet	Dry
SEM 30N, 10W to 48N,40E	DJF	1.7	2.5	2.6	3.3	4.6	25	−16	−10	−6	−1	6	>100	93	3	12
	MAM	2.0	3.0	3.2	3.5	4.5	20	−24	−17	−16	−8	−2	60	98	1	31
	JJA	2.7	3.7	4.1	5.0	6.5	15	−53	−35	−24	−14	−3	55	100	1	42
	SON	2.3	2.8	3.3	4.0	5.2	15	−29	−15	−12	−9	−2	90	100	1	21
	Annual	2.2	3.0	3.5	4.0	5.1	15	−27	−16	−12	−9	−4	45	100	0	46

Notes: SEM, Southern Europe and Mediterranean region; DJF, December, January, February; MAM, March, April, May; JJA, June, July, August; SON, September, October, November.

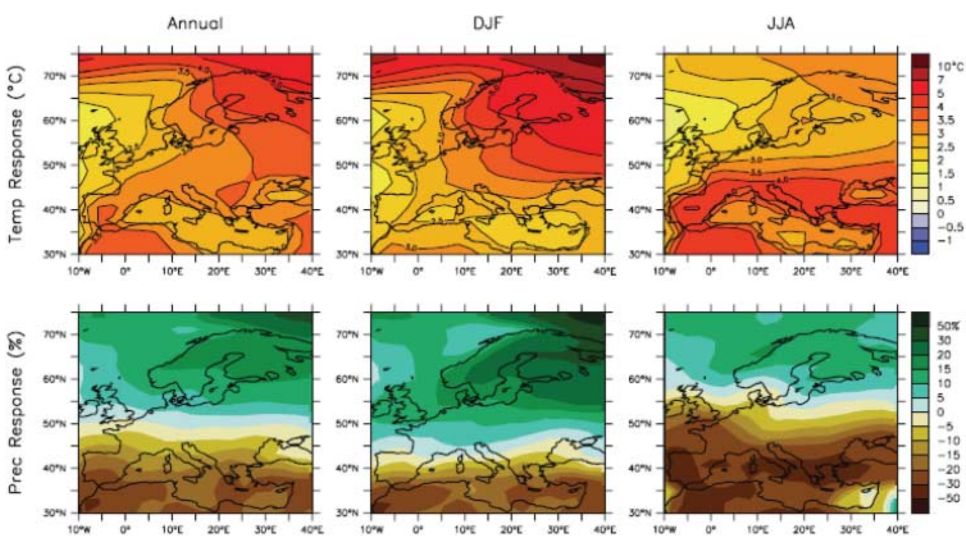


Figure 5. Temperature and precipitation changes over Europe (IPCC 2007).

Energy efficiency

Introduction

The operation of residential buildings accounts for a major part of all energy consumption during the life cycle of a building. Consequently, substantial efforts (political and technical) have been invested in developing practical solutions for low-energy (LE) buildings. The widely accepted targets for energy efficiency of buildings are the following (Website Passive House Institute 2010):

(1) buildings with cultural or historical value: reduction of energy consumption by 25% through efficient use of energy, high-technology controls, low-voltage and low-power systems, and energy-efficient lighting;
(2) existing buildings from post-war era to the 1990s that represent about half of the residential building stock: reduction of energy consumption by 50% through efficient use of energy, high-performance systems, high-technology controls, and improved thermal insulation;
(3) new buildings and refurbishment/minimum-energy buildings:
   - $15\,\text{kWh/m}^2$ for both heating and cooling in the South European warm climates and $120\,\text{kWh/m}^2$ for total primary energy;
   - combined heating and cooling energy demand and total primary energy demand of 15 and $120\,\text{kWh/m}^2$, respectively, in Central European climates;
   - heating energy demand of $20–30\,\text{kWh/m}^2$ and primary energy demand of $120–130\,\text{kW/m}^2$ depending on the location in the Nordic climates;
(4) New buildings/energy-neutral buildings: building produces at least as much energy as it consumes in a year. All energy is renewable energy.

Table 2 summarises the minimum requirements for a passive house (building that is able to maintain a comfortable interior climate without active heating and cooling systems).

In this paper, an existing residential building is adopted as a case study. It does not meet the requirements of a passive house, but its thermal efficiency satisfies current Portuguese regulations (Decreto-Lei n°80/2006) published in 2006. It is representative of current practice in energy efficiency and thermal performance and it is estimated to correspond to 10% of the total building stock.

Table 2. Characteristics of a passive house (from Website Passive House Institute 2010).

Compact form and good insulation	U-factor $\leq 0.15\,\text{W/m}^2\,\text{K}$
Orientation and shade considerations	Passive use of solar energy
Energy-efficient window glazing and frames	U-factor $\leq 0.80\,\text{W/m}^2\,\text{K}$ (glazing and frames, combined) solar heat-gain coefficients around 50%
Building envelope air-tightness	Air leakage $\leq$ 0.61/h
Passive preheating or fresh air	Fresh air supply trough underground ducts that exchange heat with the soil. This preheats fresh air to a temperature above 5°C, even on cold winter days
Highly efficient heat recovery from exhaust air	Heat recovery rate over 80%
Hot water supply using regenerative energy sources	Solar collectors or heat pumps
Energy-saving household appliances	LE refrigerators, stoves, freezers, lamps, washers, dryers, etc. are indispensable in a passive house

Validation of advanced simulation procedures (sub-dynamic)

Introduction

The advanced simulation thermal and energy analysis is performed using the EnergyPlus software (Website Software Energy Plus 2010). However, since EnergyPlus is a stand-alone simulation program without a 'user-friendly' graphical interface (reads input and writes output as text files), we made use of the DesignBuilder software (Website Software DesignBuilder 2010) graphical interface, which incorporates the EnergyPlus simulation engine. EnergyPlus was developed in 1996 and is a trademark of the United States Department of Energy. This software is an energy analysis and thermal load simulation program that models heating, cooling, lighting, ventilating and other energy flows as well as water in buildings and includes some important simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, water use, photovoltaic systems and natural ventilation. EnergyPlus has been extensively validated (Crawley *et al.* 2008) and is considered a reference software for building energy performance simulations.

Calibration against EN 15265

The procedures to compute the heating and cooling energy needs for a building were verified using the standard EN 15265 (EN 15265, 2007). In this standard, the validation tests are applied to a single room with specified dimensions and envelope components. The unique exterior wall includes window glazing facing west. Figure 6 illustrates the DesignBuilder model implemented for the calibration against EN 15265. The hourly mean values of the climatic data to be used in the calibration examples are given in Annex A of EN 15265, for a given location (Trappes, France). These data include the following: the time (hour of the year starting 1 January), external air temperature, direct normal solar radiation, diffuse horizontal solar radiation and global solar radiation on a vertical, west-facing wall. However, the weather data file required by EnergyPlus needs additional climatic values, such as dew point temperature, relative humidity, atmospheric pressure, wind direction and wind speed. Therefore, the EnergyPlus weather data file (FRA_PARIS_ORLY_IWEC.epw) was used, replacing the four sets of climatic values specified in the standard. This weather file corresponds to Paris–Orly, the closest location to Trappes available in the EnergyPlus database.

The test cases are divided into four initial tests (informative) and eight validation tests (normative). The differences between these test cases are related to some important thermal parameters

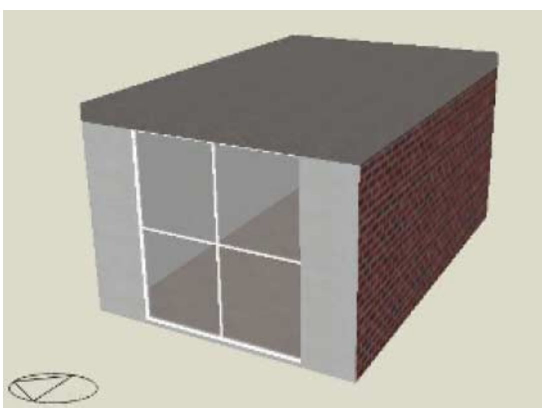


Figure 6. Front view of the DesignBuilder standard room model.

Table 3. Heating and cooling ratio values.

	rQ_H	rQ_C
(Informative)	Test 1 Reference case	
	0.13	0.09
	Test 2 Change inertia	
	0.09	0.14
	Test 3 No internal gains	
	0.13	0.03
	Test 4 No solar protection	
	0.00	0.33
Intermittent HVAC (normative)	Test 5 = Test1 + HVAC only 8–18 h from Monday to Friday	
	0.05	0.09
	Test 6 = Test2 (change inertia) + HVAC only 8–18 h from Monday to Friday	
	0.10	0.12
	Test 7 = Test3 (no internal gains) + HVAC only 8–18 from Monday to Friday	
	0.08	0.01
	Test 8 = Test4 (no solar protection) + HVAC only 8–18 h from Monday to Friday	
	0.06	0.31
Intermittent HVAC + external roof (normative)	Test 9 = Test5 (Test1 + intermittent HVAC) + external roof	
	0.01	0.07
	Test 10 = Test6 (Test2 (change inertia) + intermittent HVAC) + external roof	
	0.02	0.04
	Test 11 = Test7 (Test3 (no internal gains) + intermittent HVAC) + external roof	
	0.05	0.01
	Test 12 = Test8 (Test4 (no solar protection) + intermittent HVAC) + external roof	
	0.09	0.25

such as thermal inertia, internal gains, solar protection, intermittent heating and cooling and internal (ceiling) or external (roof) exposition of the top slab. The validation criteria for heating and cooling are based on $\mathrm{r}Q_\mathrm{H}$ and $\mathrm{r}Q_\mathrm{C}$ ratios, respectively, given by

$$\mathrm{r}Q_\mathrm{H} = \mathrm{abs}(Q_\mathrm{H} - Q_\mathrm{H,ref})/Q_\mathrm{tot,ref}, \quad (1)$$

$$\mathrm{r}Q_\mathrm{C} = \mathrm{abs}(Q_\mathrm{C} - Q_\mathrm{C,ref})/Q_\mathrm{tot,ref}, \quad (2)$$

where Q_H and Q_C are the calculated energy annual results for heating and cooling in kWh and the subscript ref denotes the reference values (H, heating; C, cooling; and tot, total energy) specified in the standard. Three levels of accuracy are defined: levels A, B and C, corresponding to the ratios (Equations 1 and 2) in the validation tests (5–12) lower than or equal to 5%, 10% and 15%, respectively.

Table 3 shows the heating and cooling ratios obtained according to the 12 test cases in EN 15265. These ratios denote a reasonable accuracy of the DesignBuilder models. However, the cooling energy predicted by EnergyPlus in the tests with no solar protection (tests 4, 8 and 12) is considerably lower than the standard reference values, leading to an increase in these cooling ratios.

Calibration against CFD simulations

EN 15265 does not include reference results for detailed daily simulations. In the present work, computational fluid dynamics (CFD) simulations were made for a single compartment, using the commercial code CFX 11.0 SP1, from ANSYS (ANSYS CFX 11 2006).

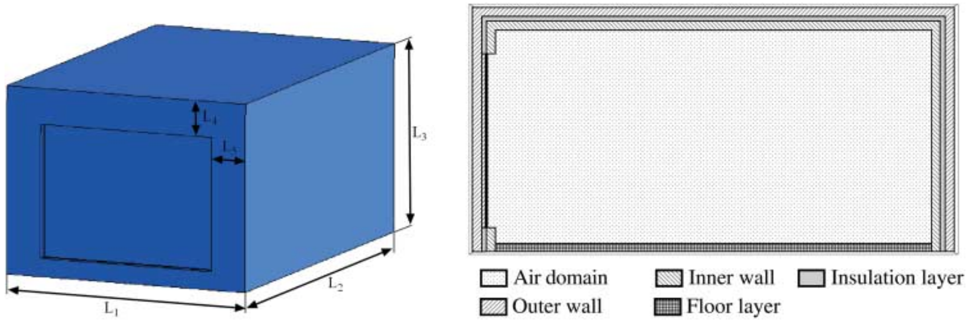


Figure 7. Schematic representation of the single room: symmetry plane. $L_1 = 4.18\,\mathrm{m}$, $L_2 = 6.08\,\mathrm{m}$; $L_3 = 3.18\,\mathrm{m}$; $L_4 = 0.74\,\mathrm{m}$; $L_5 = 0.59\,\mathrm{m}$.

Table 4. Physical characteristics of the different layers.

	Thickness (mm)	U (W/m$^2\cdot$°C)	ρ (kg/m^3)	cp (J/kg · °C)	Emissivity
Inner wall	115	0.79	1600	850	0.9
Insulating layer	60	0.04	30	850	–
Outer wall	115	0.79	1600	850	0.9
Floor	100	1.4	2000	850	0.9

Note: cp means specific heat capacity.

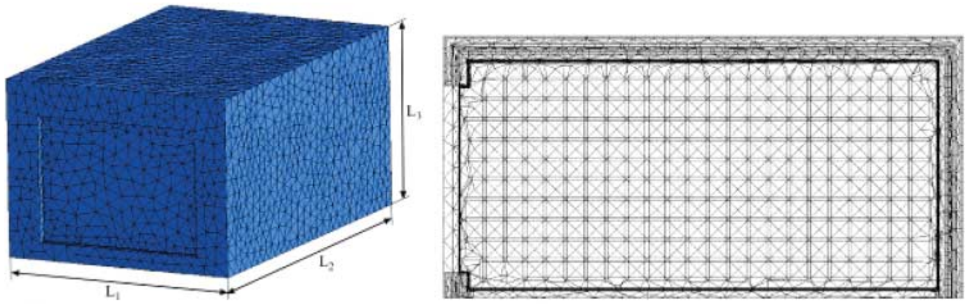
The CFD methodology consists in solving the governing differential equations in a discrete manner, both in space and in time. A solution is provided for the equations of momentum, mass and energy conservation.

Turbulence effects upon the mean flow field are taken into account through the shear stress transport turbulence model (Menter 1993, 1994), which is a weighted blending of the $k-\omega$ model (Wilcox 1993) and the standard $k-\varepsilon$ of Launder and Spalding (1974), according to the boundary layer region where the solution takes place.

For modelling the entire radiation phenomena, the spectral radiative transfer equation must be solved. The Monte Carlo model, used in the present study, simulates the time history of the sample of photons selected at each photon source. Each time a photon experiences an event, such as absorption and surface intersection, the physical quantities of interest are updated.

The physical problem. Considering the goal of establishing a comparison between two simulation models, a simplified room geometry was adopted. The single-room geometry, schematically depicted in Figure 7, consists of an inner air domain, surrounded (laterally and above) by an inner wall layer, an insulation layer and an outer wall layer. The physical characteristics of each layer are given in Table 4. A glass window is placed on the wall facing south. The glass is considered to have a virtually zero thickness, in the sense that refraction and absorption of solar radiation are not considered. The radiation reflection coefficient of the outer glass surface depends on the incidence angle, according to the Fresnel formulas.

In order to take into account the radiation properties of glass as function of the wavelength, a multiband spectral model is incorporated in the radiation model: a infrared band ranging from 2 to 1000 μ in wavelength and a solar band ranging from 0 to 2 μ in wavelength. The window boundary is assigned emissivities of 0.95 and 0.4 for the solar band and the infrared band, respectively. Heat transfer by convection at the exterior surfaces is modelled by imposing a heat transfer coefficient of 17.5 $\mathrm{W/m^2\,K}$, a typical value for this type of situations, and taking the available data for the air



Surface grid at the outer surfaces Volume grid at the symmetry plane.

Figure 8. Grid arrangement.

temperature. Domain interface boundaries (solid–solid and fluid–solid) are assigned an interface conservative flux condition. The outside surface of the floor is taken as adiabatic.

The spatial and temporal discretisation. For the CFD simulations, the spatial domain is discretised with a mainly non-structured grid composed of a mixture of tetrahedral and hexahedral elements, ensuring at least five grid layers across each solid domain (Figure 8). The core fluid (air) domain is nearly structured, with higher refinement near the solid boundaries (2 mm grid spacing), in order to correctly resolve the boundary layer and heat transfer phenomena taking place at the interface. A total of 55582 nodes were employed for the spatial discretisation of the whole geometry. After some preliminary tests, a time step of 60 s was adopted for the temporal discretisation.

Results. Simulations were performed for a 24 h period, corresponding to the 10 August 2002. Initialisation is done at 0 a.m., adopting a thermal equilibrium with the outside air temperature. Computations are then carried out for several days with the same time evolution of boundary conditions, until the daily pattern of the results is self-similar. Figure 9 shows the time evolution of the volume-averaged temperatures obtained by CFX in each calculation volume region. It is interesting to note the delay in the maximum temperature evolution when compared with the outside air temperature and solar radiation evolution. Heating is dominated by solar radiation: this explains the higher maximum values for the exterior walls and for the floor.

Figure 10 shows the time evolution of the spatially averaged temperature at several locations. EnergyPlus slightly overpredicts the air temperatures during the initial stages of the cooling phase when compared with the CFX. This behaviour is reversed towards the end of the cooling phase. Maximum temperature difference between both predictions for air is only 0.76°C. Temperatures of inner wall surfaces show a similar trend. The highest discrepancy between both softwares was found in the outer surface of the top wall, with a maximum difference of about 12°C. Table 5 presents, for each location, the average and the maximum values for the temperature difference between both predictions, as well as the corresponding temperature amplitude as computed by CFX. One may state that, globally, the agreement is good.

In Figure 11, the temperature distribution is indicated by the solid surfaces, obtained by CFX, at 9 a.m. and 4 p.m. In the morning, the outer surfaces are characterised by lower temperatures when compared with the inner surfaces, while the opposite is verified in the afternoon. The temperature difference between both sides of the insulation layer is quite noticeable, especially at the top of the compartment. Note the floor heating near the window due to the incident radiation.

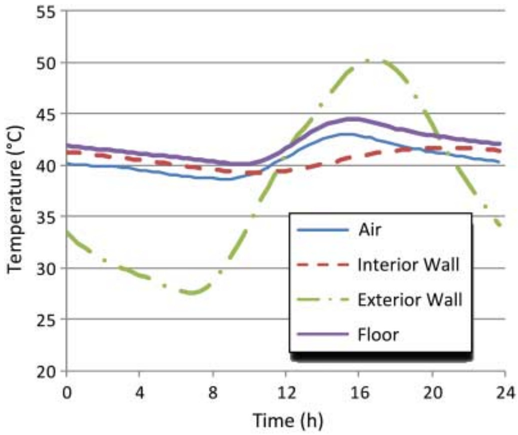


Figure 9. CFX: volume-averaged temperature in each of the calculation volume region.

Table 5. Comparison of the CFX and EnergyPlus temperature predictions (°C).

Location	Temperature amplitude (CFX predictions)	Average difference between CFX and EnergyPlus	Maximum difference between CFX and EnergyPlus
Air	4.36	0.33	0.76
Inner wall surfaces	2.72	0.30	0.58
Outer wall surfaces	27.36	1.87	5.00
East outer wall surface	23.07	1.13	5.27
West outer wall surface	30.41	1.17	4.40
South outer wall surface	26.46	0.80	2.22
North outer wall surface	14.05	0.60	1.57
Top outer wall surface	44.57	5.98	12.21
Floor inner surface	4.94	0.48	0.91
Floor outer surface	4.15	0.87	2.05
Windows	11.52	0.61	1.86

Portuguese housing characterisation

According to Portuguese Statistics Institute (Website Portuguese Statistical Institute 2010), the Portuguese housing stock in 2007 was estimated at 3.4 million buildings and 5.6 million dwellings. Furthermore, in 2005–2006, 45% of the construction works corresponded to buildings, with a share of about 22% for residential buildings and of 23% for non-residential buildings.

The most common typology of a single-family house that is bought or built is a three-bedroom dwelling (T3) as illustrated in Figure 12, where the percentage of permits of new buildings (2007) is shown. This typology is also preferred whatever be the type of building, apartments or family house building and represents almost half of the constructions. However, in the less populated areas, the T4 typology is preferred because in these areas the land prices are lower. Besides, the small typologies (T0, T1 and T2) are more likely to be found in apartment buildings and the large typologies (T4 and greater) in single-family houses.

The most used construction type in Portugal is the reinforced concrete (RC)-framed structure with ceramic or concrete masonry walls. It is very well characterised by labour-intensive, low-technology solutions that result in long construction times. In Portugal, for example, the average construction time for a residential building is 25 months. This reflects the fact that the Portuguese construction sector constitutes the less industrialised industrial activity.

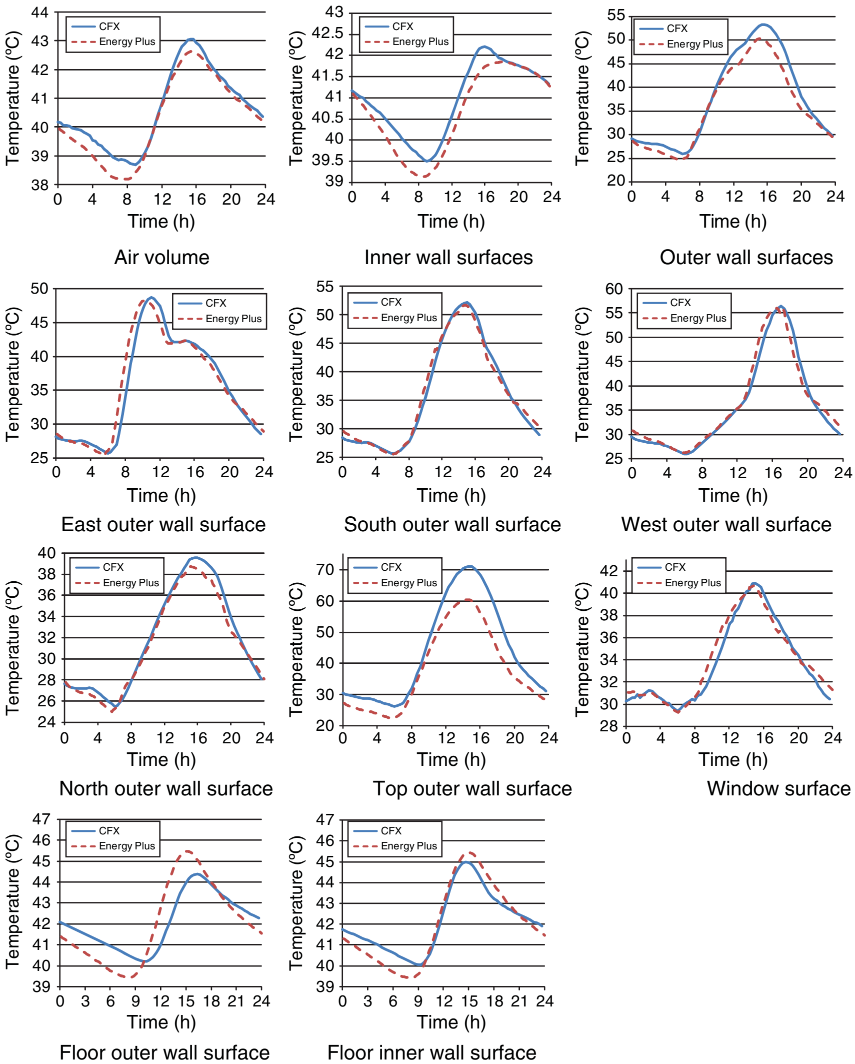


Figure 10. Comparison of the CFX and EnergyPlus predictions.

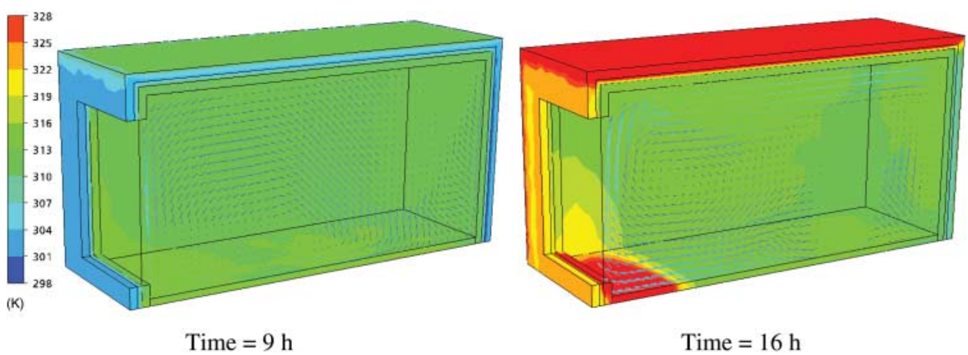


Figure 11. Visualisation of temperature distribution in the compartment walls and air velocity field at the symmetry.

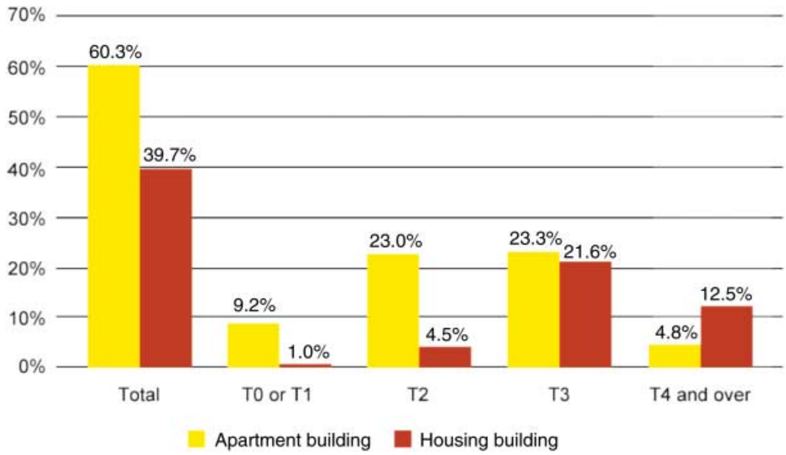


Figure 12. Permits of new buildings for residential housing per typology in 2007 (Website Portuguese Statistical Institute 2010).

The construction sector in Portugal plays an important role in the economy, representing about 15% of the business sector, 11% of the total workforce and a large number (over 50,000) of small- to medium-sized construction companies (DELOITTE 2008). However, since 2002 (Website Portuguese Statistical Institute 2010), the construction activity in Portugal has decreased at an average rate of 5% per year because of economic conditions, leading to an increased focus on innovation and quick erection times. Consequently, alternative industrialised 'dry-construction' building solutions with light-weight-steel-framed structures are becoming more popular, presenting some advantages (economical, functional, environmental, etc.) in comparison with the traditional construction techniques (Santos *et al.* 2010). Light-weight steel construction solutions for low-rise residential buildings are very light, exceptionally solid in relation to weight, provide easier architectural typological flexibility and adaptability, present excellent stability of shape in case of humidity, excellent thermal behaviour (Santos *et al.* 2011), and rapid on-site erection, are easy to prefabricate allowing for better quality control, and offer great potential for recycling and reuse. Furthermore, the number of companies specialised in executing these types of solutions is increasing and the prices are becoming more competitive, leading to a fast-growing market share, not only in Portugal but all over the world (European Lightweight Steel-framed Construction 2005).

Case study: light-weight steel residential building

General description

The case study focuses on a single-family house with two main floors, with an area of 165 m^2 each, and a smaller top floor with a area of 115 m^2 located in central Portugal (Figure 13).

It consists of a steel structure formed by cold-formed steel profiles, designed for a service life of 50 years according to the Structural Eurocodes (EN 1993-1-3, 2006). The total internal net space is 361 m^2. The ground floor is composed of a living–dining room, a small office, a kitchen, a small pantry, two bathrooms and stairs (Figure 14). The first floor has four bedrooms, four bathrooms and stairs. The top floor has one master office and one bathroom. The main facade of the house faces south.

The characteristics of the building components are described in the following paragraphs. The external walls (Figure 15(a)) are made of an outside layer of oriented strand board (OSB) panels

Figure 13. Front view and rear view of the dwelling.

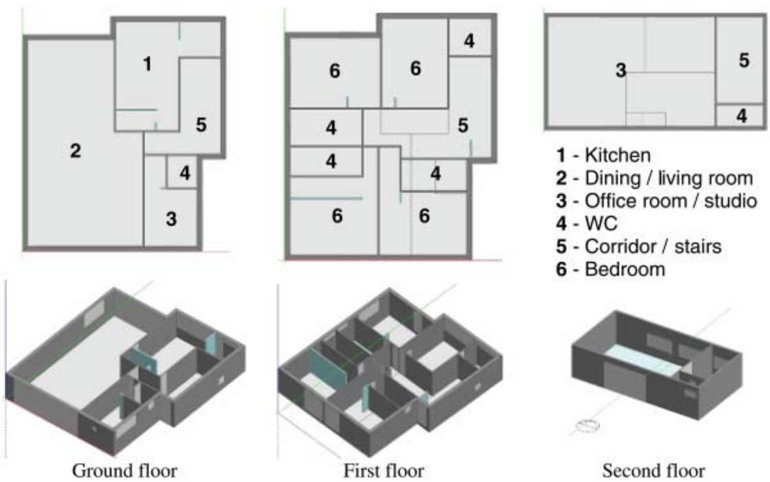
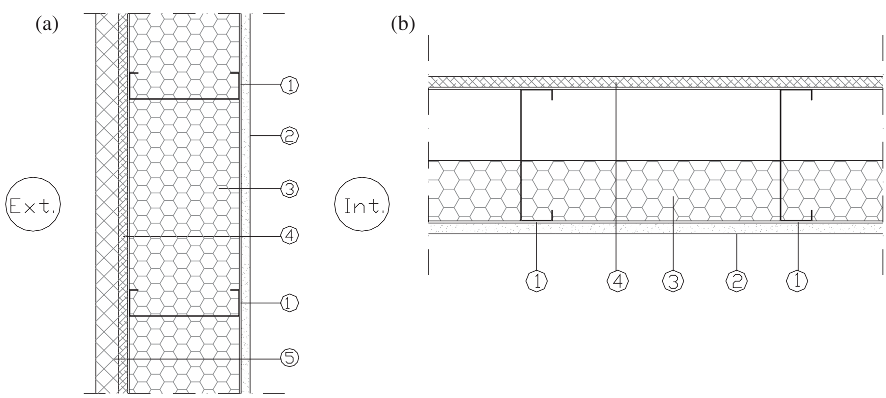
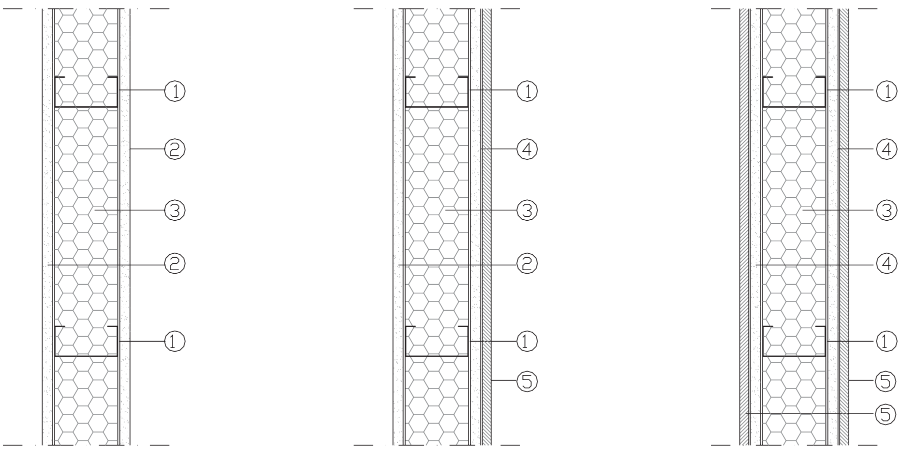


Figure 14. Layout of the floors.



1, C150 profile (walls) and C250 profile (slabs); 2, gypsum plaster board BA15; 3, Rock wool (140 mm); 4, OSB 11 (walls) and OSB 18 (slabs); 5, exterior insulation and finish system (EIFS).

Figure 15. (a) External wall. (b) Internal slab.



1, C90 profile; 2, gypsum plaster board BA15; 3, rock wool (70 mm); 4, gypsum plaster board WA13; 5, ceramic.

Figure 16. Internal walls.

with a thickness of 11 mm and an inside layer of gypsum boards with a thickness of 15 mm. The gap between the two panels is filled with rock wool that is 140 mm thick. The internal slabs (Figure 15(b)) are made of composite panels with a top layer of OSB panels (18 mm), an intermediate layer of rock wool (140 mm) and a bottom layer of gypsum boards (15 mm).

The internal walls (Figure 16) are made of gypsum boards with a thickness of 15 mm and a layer of rock wool with a thickness of 70 mm. The ground floor is made of a light-concrete slab over a gravel layer. The terrace slab is similar to the internal slab (Figure 15(b)), but with an additional layer of cast concrete on top of the slab, with an average thickness of 40 mm, and a ceramic finish. The roof slab is made of panels with a top layer of OSB panels (11 mm), an intermediate layer of rock wool (140 mm) and a bottom layer of gypsum boards (15 mm). The composite panels are covered with ceramic tiles.

The rock wool insulation panels completely clad the steel frame ensuring that the house achieves high thermal and acoustic behaviour according to regulatory requirements. The envelope of the house is covered by an exterior insulation and finish system (EIFS).

The window frames are in PVC with double glass, 6/14/4 mm, while the ground-floor exterior doors are made of wood (35 mm thick). Table 6 presents the geometric characteristics of the building main construction elements and the corresponding thermal properties.

Model and analysis options

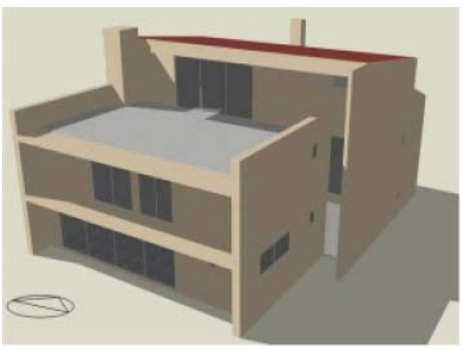
The building was modelled using the DesignBuilder software (Website Software DesignBuilder 2010), where the dynamic thermal simulation engine is the EnergyPlus software (Website Software Energy Plus 2010). Figure 17 shows two external views of the building model.

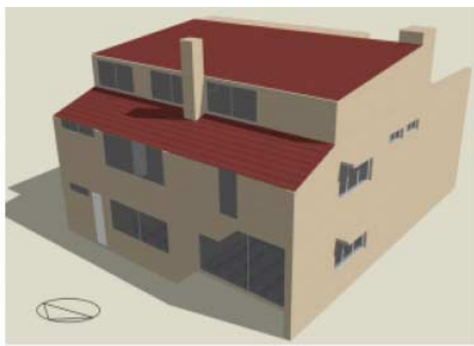
The building model was assembled using 15 thermal zones, corresponding to the internal partitions of the building (Figure 14). The ground floor has four thermal zones; the second floor has eight thermal zones, while the top floor has two zones. Besides these 14 thermal zones, there is another one that is common to the three floor levels and includes the corridors and the stairways.

It was assumed that the house is occupied by five persons with typical luminance requirements and standard internal gains with the occupation and equipment schedule given in Table 7, adapted from Bill Dunster Architects (2005) to match the southern European lifestyle. The natural

Table 6. Thermal transmittances of the building main construction components.

	Material	Thickness (mm)	U (W/m^2 · °C)
External walls	Gypsum board	15	0.218
	Rock wool	140	
	OSB	11	
	EIFS	33	
Internal walls	Gypsum board	15	0.479
	Rock wool	70	
	Gypsum board	15	
Roof	Gypsum board	15	0.262
	Rock wool	140	
	OSB	11	
	Ceramic tiles	15	
Terrace	Gypsum board	15	0.253
	Rock wool	140	
	OSB	18	
	Cast concrete	40	
	Ceramic	10	
Internal floor	Gypsum board	15	0.252
	Rock wool	140	
	OSB	18	
Ground floor	Concrete pavement	120	1.118
	Gravel	150	
	Tile bedding	200	
Windows	Double-pane clear glass	6/14/4	2.733





Southern and eastern views

Northern and western views

Figure 17. Elevation views of the building DesignBuilder model.

ventilation infiltration is 0.6 air changes per hour (minimum value imposed by the Portuguese code (Decreto-Lei n°80/2006)), while the heating and cooling set point temperatures are 20°C and 25°C, respectively. The exterior climatic conditions were simulated using the EnergyPlus weather data for Coimbra, Portugal (PRT_COIMBRA_IWEC.epw). The number of HDDs and CDDs are 1294 (base 18°C) and 2040 (base 10°C).

In order to establish a basis for the assessment of the influence of climate changes on the energy efficiency of the building, a reference case is first analysed. It consists of two simulations for the summer and winter design conditions (sub-hour simulations for a worst summer and winter week without the consideration of heating or cooling equipment). Subsequently, following the identification of the violation of the set point temperatures, the energy requirements

Table 7. Occupation and equipment schedules.

	% of maximum for each profile											
Hour	LIVWD	LIVWE	KITWD	KITWE	BEDWD	BEDWE	BATWD	BATWE	HTWD	HTWE	ZERO	CONST
0–1	0	0	0	0	100	100	0	0	0	0	0	100
1–2	0	0	0	0	100	100	0	0	0	0	0	100
2–3	0	0	0	0	100	100	0	0	0	0	0	100
3–4	0	0	0	0	100	100	0	0	0	0	0	100
4–5	0	0	0	0	100	100	0	0	0	0	0	100
5–6	0	0	0	0	100	100	0	0	0	0	0	100
6–7	0	0	0	0	100	100	0	0	100	100	0	100
7–8	0	0	0	0	75	100	25	0	100	100	0	100
8–9	0	0	25	0	25	100	50	0	100	100	0	100
9–10	0	0	75	25	0	50	25	25	100	100	0	100
10–11	0	25	0	50	0	0	0	25	0	100	0	100
11–12	0	50	0	50	0	0	0	0	0	100	0	100
12–13	0	50	0	0	0	0	0	0	0	100	0	100
13–14	0	0	0	50	0	0	0	0	0	100	0	100
14–15	0	25	0	25	0	0	0	0	0	100	0	100
15–16	0	50	0	0	0	0	0	0	0	100	0	100
16–17	0	50	0	0	0	0	0	0	100	100	0	100
17–18	50	50	0	0	0	0	0	0	100	100	0	100
18–19	25	25	25	25	0	0	0	0	100	100	0	100
19–20	0	0	100	50	0	0	0	0	100	100	0	100
20–21	50	25	25	75	0	0	25	0	100	100	0	100
21–22	50	25	25	25	0	0	0	0	100	100	0	100
22–23	50	50	0	0	0	0	0	0	100	100	0	100
23–24	0	50	0	0	50	100	0	0	0	0	0	100

Note: LIV, living room; KIT, kitchen; BED, bedroom; BAT, bathroom; HT, heating; WD, weekdays; WE, weekend days; ZERO, no occupation; CONST, constant full occupation.

for heating and cooling equipment and the corresponding CO_2 emissions are calculated. These simulations are carried out initially for the ZERO and CONST schedules that provide lower and upper bound limits for the internal energy gains, followed by a simulation using the REAL schedule.

The reference case is complemented by a second set of simulations that addresses the whole summer (4 months) and winter (6 months) periods, on a daily incremental basis, carried out using the same criteria.

This scheme is then repeated for the various climate change scenarios.

Reference case: results and discussion

The interior temperature result presented in all cases is the operative temperature, that is, the average of air and surface temperatures. Figure 18 presents the weekly results for the winter design week and the detailed 24 h results for the winter design day, for the living room, bedroom NW, bedroom SE and bedroom studio, for the three occupation and equipment schedules, without heating or cooling (passive thermal conditions). Comparing the several room temperatures, the major and the minor daily thermal amplitudes occur in the office studio (second floor) and in the bedroom NW, respectively. As expected, when there is no occupation, the interior operational temperatures are lower than those when there are the real and the full constant occupations, given the lack of internal thermal gains.

Figure 19 illustrates the prediction of the interior temperatures inside some rooms and also the temperature violations in the winter season, that is, the number of hours that the interior temperature is below a predefined reference temperature. For this season, two reference temperatures were

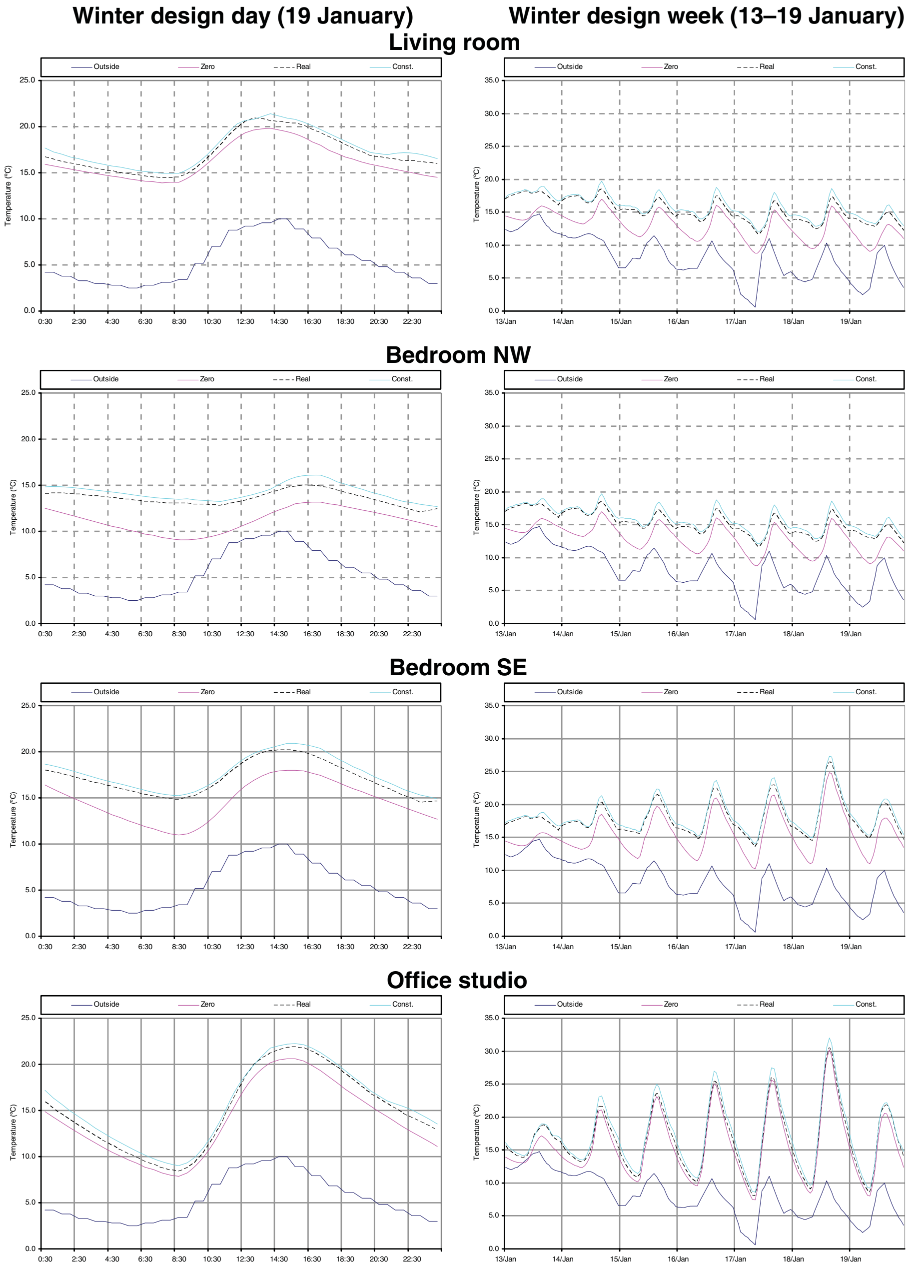


Figure 18. Temperatures variation inside and outside the building (winter passive thermal conditions).

used: 20°C (winter comfort temperature) and 15°C. When there is no occupation, the bedroom NW is the coolest and most thermally uncomfortable room. However, when there is full constant occupation, the office studio exhibits the major number of hours below 15°C.

Figures 20 and 21 exhibit similar results, but for the summer day, week and season. These results show that the living room is the coolest room of the house in the cooling season, given the vicinity of the ground floor. On the other hand, the hottest room is the bedroom NW and, therefore, the most uncomfortable. These higher temperatures could be justified by the solar gains

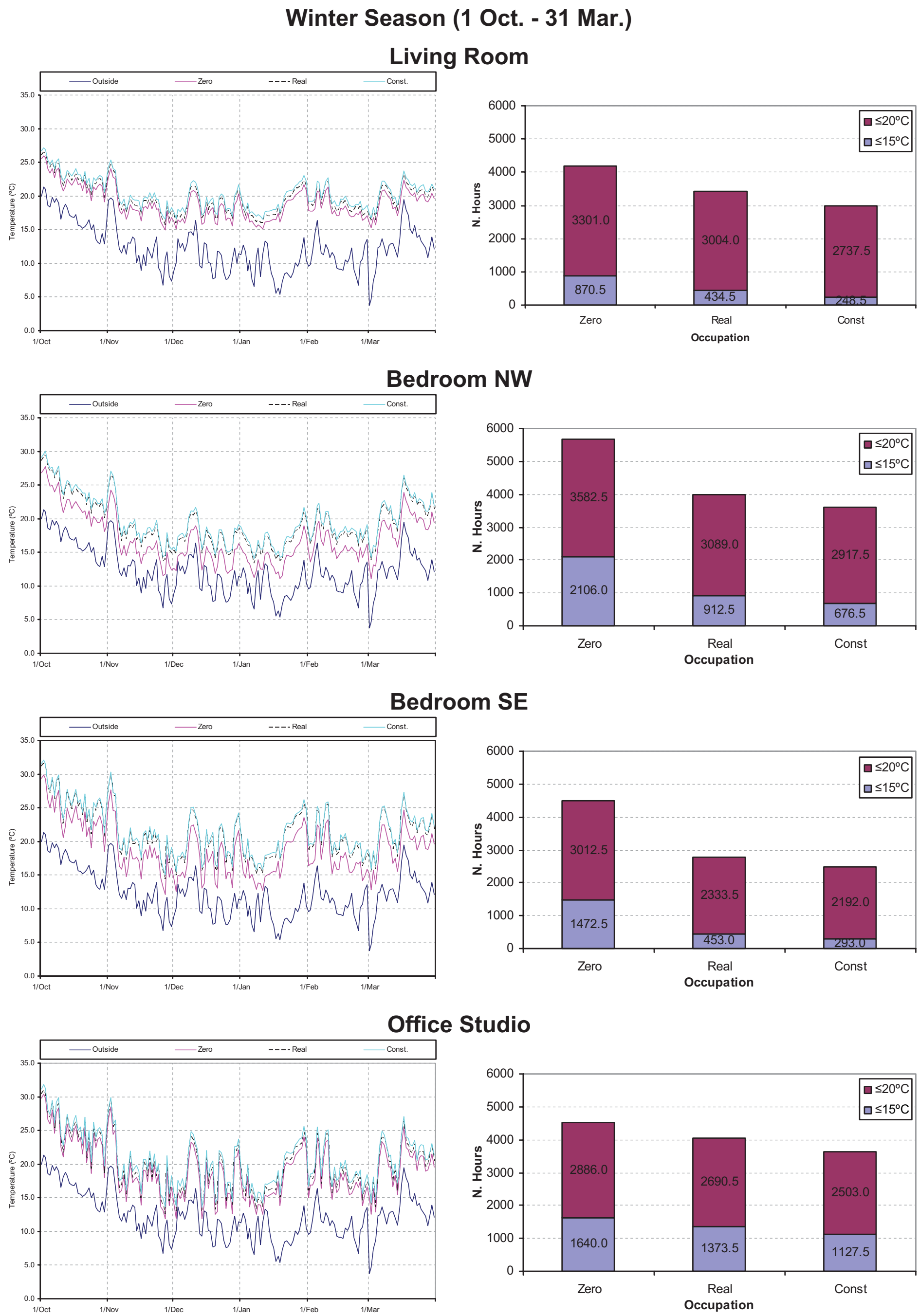


Figure 19. Temperatures variation and violation (winter passive thermal conditions).

in the afternoon at the window facing west given the lower sun angle of incidence and the reduced dimensions of the horizontal overhang, making it ineffective.

Figure 22 illustrates the simulation results with the heating or cooling equipment turned on according to the schedule presented in Table 7 for the real house occupation and the full constant occupation. The HVAC equipment is electric (CoP 1) and only exists in the main rooms of the

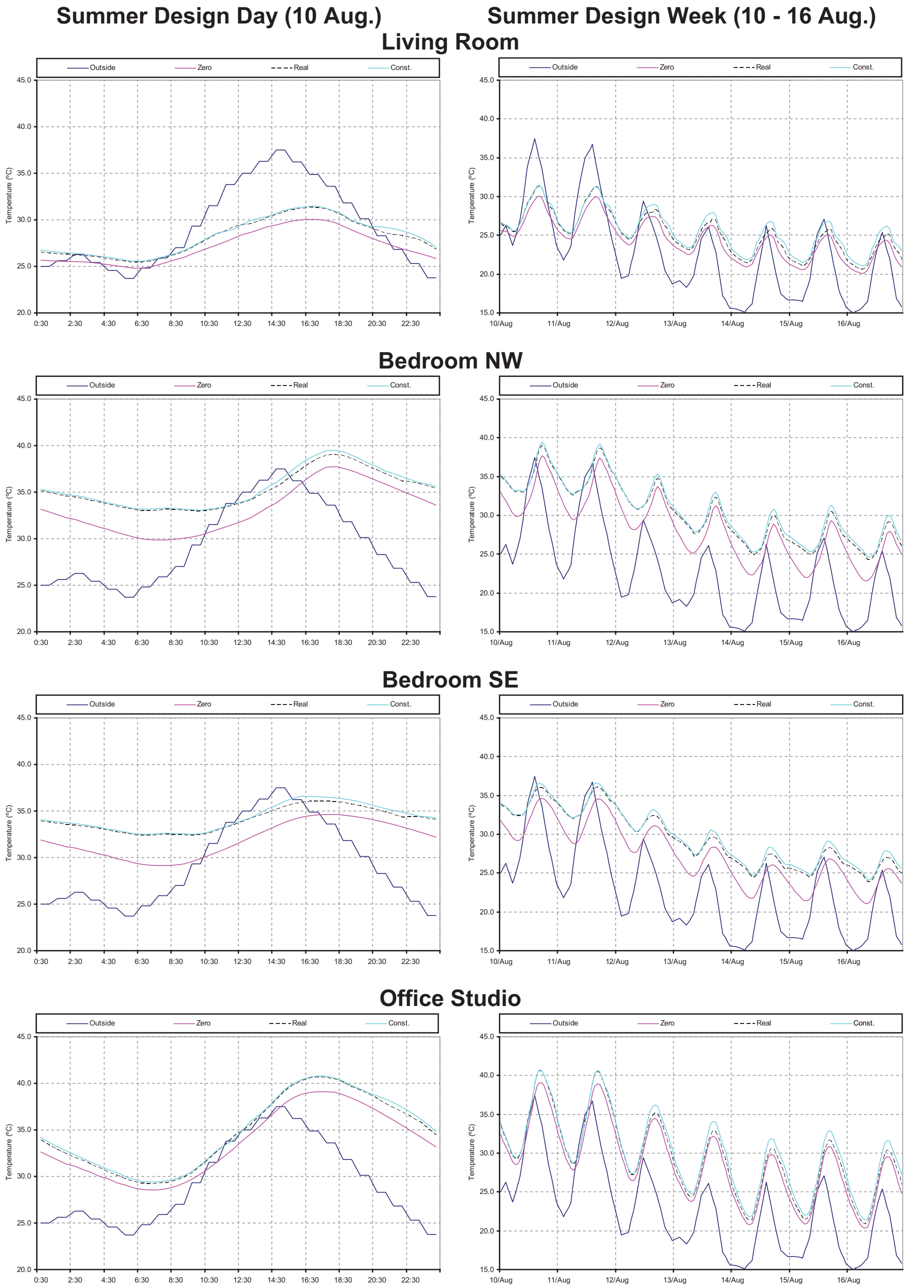


Figure 20. Temperatures variation inside and outside the building (summer passive thermal conditions).

house, for example, living room, bedrooms and offices.

For the real occupation schedule and for the winter and summer seasons, the required heating or cooling energy and total CO_2 production are 3517.5 kWh, 4187.3 kg and 2102.9 kWh, 2628.9 kg, respectively. Note that the total CO_2 production also includes the room electricity and lighting. If the occupation is scheduled to full constant, the obtained values change to 3057.7 kWh, 4996.1 kg and 2932.2 kWh, 3953.5 kg, respectively.

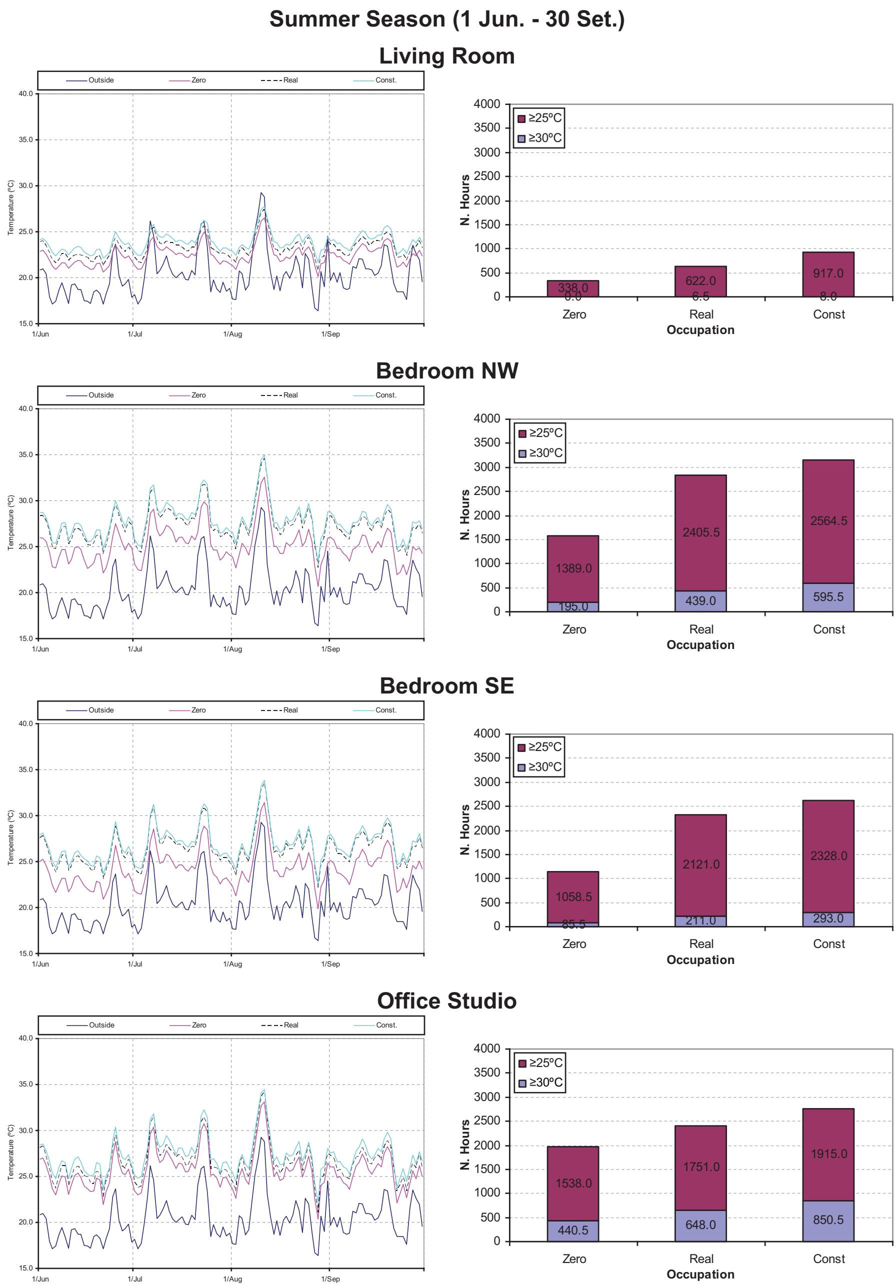


Figure 21. Temperatures variation and violation (summer passive thermal conditions).

Comparing the heating season values between both occupation schedules, the required heating energy decreases with the increment of internal gains due to higher occupation time. However, the total energy consumption and the CO_2 production become greater given the higher room electricity and lighting utilisation. In the cooling season, the increase in the house occupation leads to an increase in the cooling energy and also in the total energy and CO_2 production.

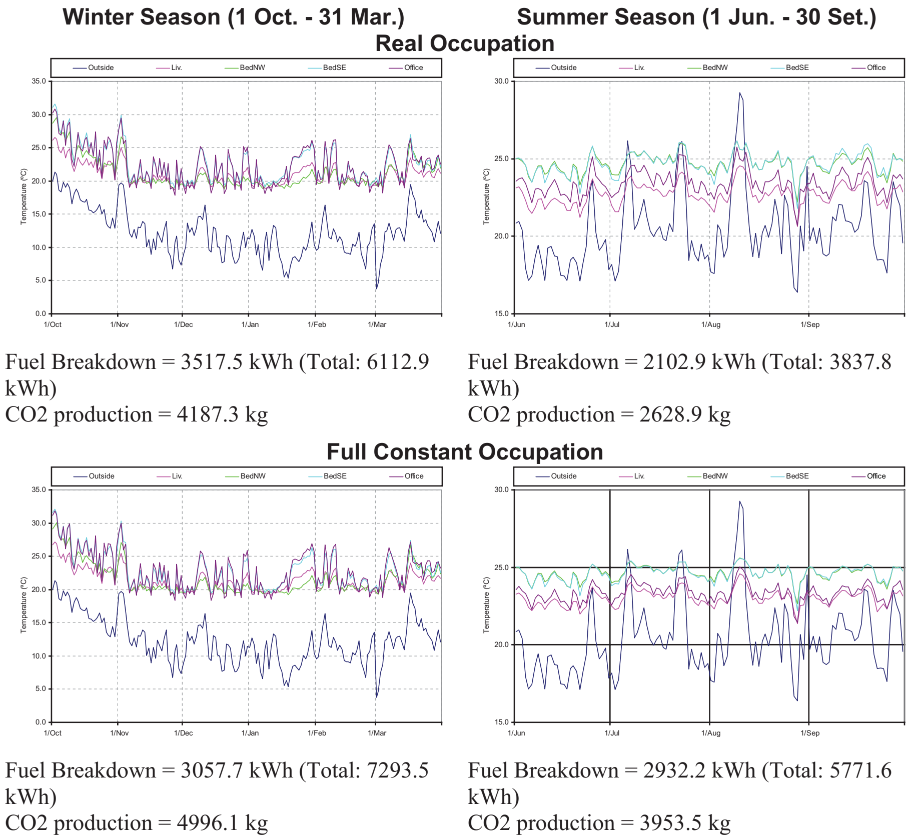


Figure 22. Temperatures variation inside and outside the building with the HVAC equipment turned on (heating and cooling set point temperatures: 20°C and 25°C, respectively).

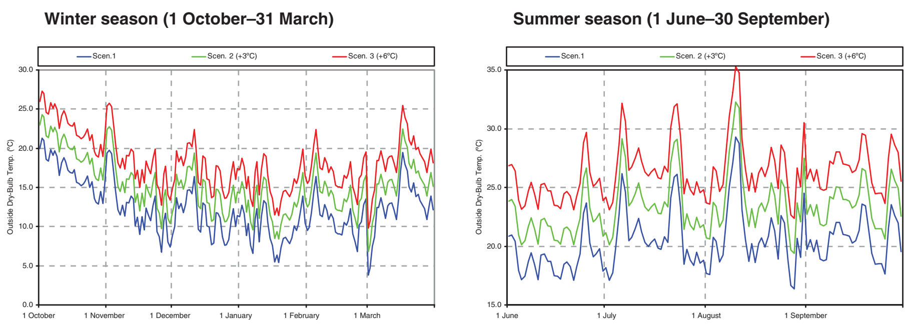


Figure 23. Outside dry-bulb temperatures for the three climate scenarios.

Parametric study: influence of climate change

Shifting the temperature records for the winter and summer seasons by 3°C and 6°C (that approximately correspond to the mean and the 95% quantile of the values of the temperature increase given in Climate change scenarios) yields the outside temperatures shown in Figure 23.

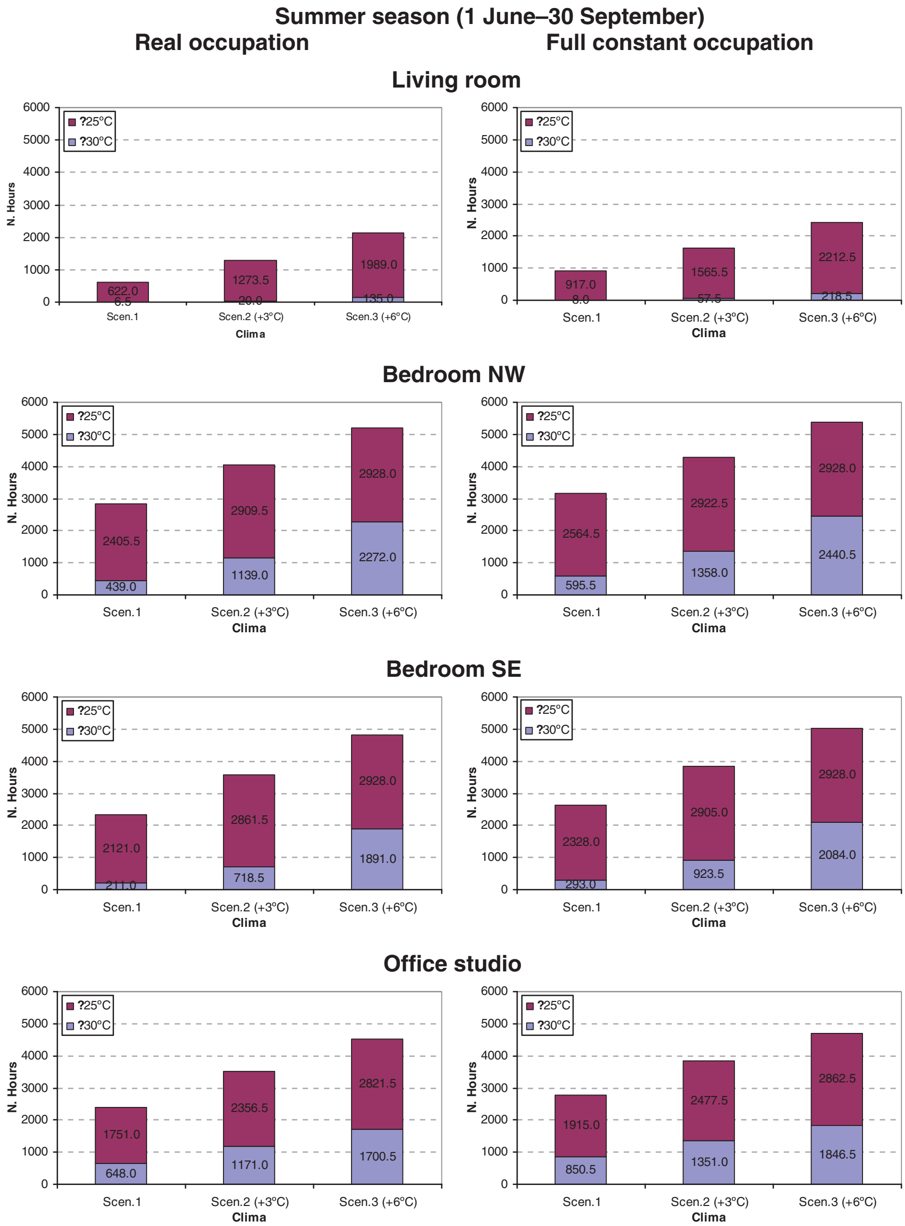


Figure 24. Temperatures violation under summer passive thermal conditions for the three climate scenarios and for two occupation schedules.

In order to assess the impact of climate change on thermal comfort inside the main dwellings of the house, Figure 24 exhibits the operational temperature violations under passive thermal conditions for the three climate scenarios and for two different occupation schedules. Since the climate warming is favourable in the winter season, only summer results are presented.

As expected, the two warming-up scenarios lead to a significant temperature increase inside the dwellings and a consequent increase of discomfort hours, that is, above the summer set point temperature (25°C). Inside the first-floor bedrooms (NW and SE), the operational temperatures

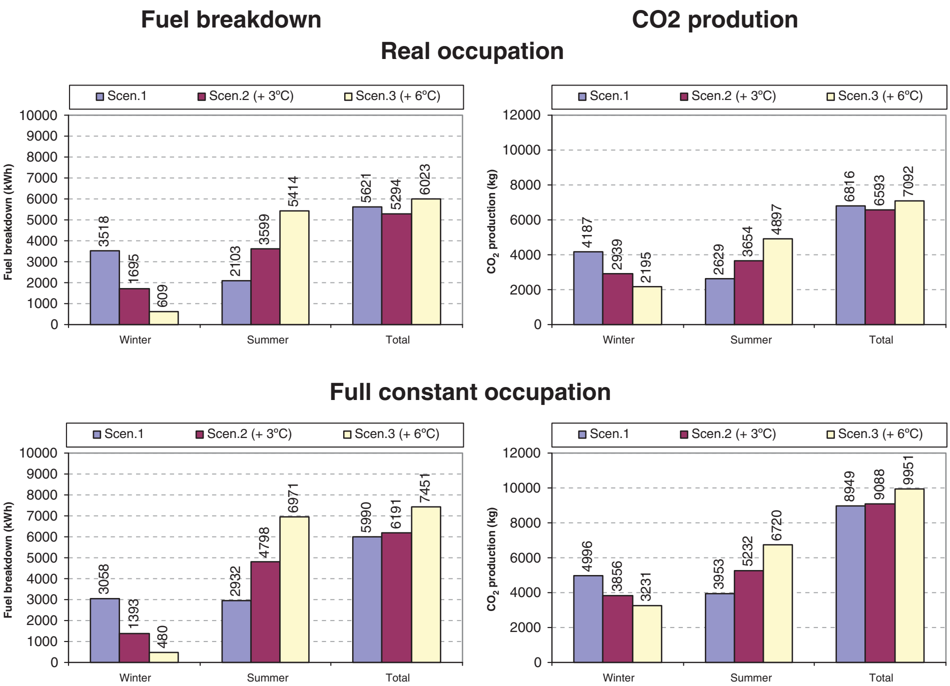


Figure 25. Fuel breakdown and CO_2 production for the three climate scenarios and for two occupation schedules.

are always above 25°C for Scenario 3, with these dwellings being the hottest ones of the building. The coolest compartment is the living room at ground level.

Another interesting feature, observable in Figure 24, is that for the same climate scenario, there is an increase of the dwelling temperature with the increment of the occupation level of the building, until it reaches 2928 h (always above summer comfort temperature). This interior temperature increase is justified by the additional internal gains generated inside the building, for example, lighting and equipments.

In order to assess the impact of global warming on the case study residential house HVAC energy demand throughout the year, several computations were made for the winter and summer seasons for 20°C and 25°C set point temperatures, respectively. Figure 25 shows the heating/cooling energy consumption for the three different scenarios and for the real and the full constant house occupations. This figure also displays the total CO_2 production, including lighting and room electricity. As expected, when the exterior temperature increases, the heating energy demand decreases and the cooling energy increases. The total energy obtained by the summation of these two energy components slightly increases. However, in Scenario 2, there is even a little decrease in the total fuel breakdown. This may be explained by the larger Portuguese duration of the winter season (6 months) when compared with the summer season period (4 months).

Again, and as mentioned earlier, the full constant house occupation leads to an increase of the total energy consumption and CO_2 production. This is observed for all external temperature scenarios.

Given the high uncertainty of the climate change predictions and the variability of the temperature increase values throughout the year as presented earlier in Table 1, a set of winter and summer climate scenario combinations were obtained for the annual fuel breakdown and CO_2 production for the real building occupation scenario. These sets of results are shown in Figure 26, where the values highlighted in bold correspond to the results shown in Figure 25. However, now it is

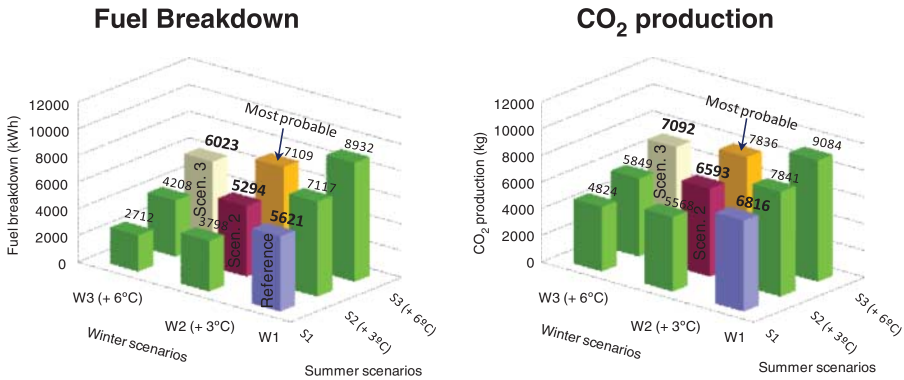


Figure 26. Annual fuel breakdown and CO_2 production for all analysed summer and winter climate scenario combinations (real occupation).

possible to see the consequences of a worst-case scenario (Scenario 1 for winter and Scenario 3 for summer) for the annual fuel breakdown (8932 kWh) and CO_2 production (9084 kg), in this case under real occupation scenario. For the full constant occupation scenario, these values would increase to 10029 kWh and 11716 kg, respectively (not illustrated).

According to the IPCC predictions, the temperature increase during the summer will be higher than that in the winter. Therefore, the most reliable of all the studied scenarios will be Scenario 2 for winter and Scenario 3 for summer, leading to a fuel breakdown annual value of 7109 kWh, resulting in a CO_2 production of 7836 kg. These values will be increased to 8364 kWh and 10576 kg, respectively, assuming a full constant occupation building scenario (not illustrated).

Conclusions

The operational energy consumption of residential buildings represents a large proportion of the total energy (embodied and operational) consumption (Gervásio *et al.* 2010). A reliable assessment of the heating and cooling energy demands requires advanced simulation techniques. In this paper, an advanced simulation model of a light-weight steel residential building was calibrated against the CEN standard EN 15265 and sophisticated CFD simulations. This calibrated model was then used to predict the thermal performance of a light-weight steel residential building in Portugal for typical occupation scenarios.

It is concluded that an accurate estimate of the required heating and cooling energy to meet the specified temperature comfort targets for winter and summer requires a detailed daily simulation because daily fluctuations of the operative temperature are significant. This is not possible with the simplified steady-state approaches prescribed by most national regulations (Decreto-Lei n°80/2006) or EN 13790 (EN ISO 13790, 2008), as was shown by Gervásio *et al.* (2010). Furthermore, the results depend on the occupation schedule, a conclusion that was also stated in the report by Bill Dunster Architects (Bill Dunster Architects 2005).

The influence of climate change on the energy efficiency of light-weight residential buildings was the main objective of this paper. Not surprisingly, especially for a southern European country, the heating demand significantly reduces (51.8% and 82.7%, respectively, for Scenarios 2 and 3), while the cooling demand increases (71.1% and 157.4%, respectively, for the same scenarios).

Taking into account the selected climate change scenarios, several annual combinations of winter and summer scenarios were analysed. Since the IPCC scenarios predict a higher temperature increase in the summer than in the winter, the most probable scenario leads to an increase of the total energy demand of 26.5% (average probability of occurrence) for the real occupation scenario. The energy demand increases to 47% if a characteristic value is adopted (5% exceedance) for the climate change scenarios.

This significantly increased energy demand due to global warming predictions requires urgent action from the building sector with respect to thermal behaviour and energy efficiency. Noting that the conclusions from this paper relate to a specific climate zone (Csb, representative of Southern Europe (Santos *et al.* (2011)), and were obtained for a specific sub-sector of the construction sector (low-rise residential), the following aspects are highlighted:

- Real practical results can only be achieved with sustainability-driven concerted action that combines legislative measures (to ensure that society and the economic sector react), innovation (to ensure that from an economic point of view, competitive and improved construction solutions and processes coupled with efficient life-cycle operational methodologies are made available) and information (to ensure that society as a whole embraces the political goals and/or pushes governments to implement and support appropriate policies).
- At European level, despite the current economic difficulties, a strong effort is currently underway to implement the above-mentioned concerted actions: (i) from a legislative point of view, the new EPBD targets for 2018/2020 that impose that all new buildings are 'nearly zero-energy' buildings (European Directive 2010/31/EU 2010) are very challenging; (ii) from the innovation point of view, the strong focus of the 7th Framework Programme and the future 8th Framework Programme (Van Holm *et al.* 2011) on energy efficiency, coupled with pan-European standardisation initiatives led by CEN, is already providing competitive solutions that are pushing construction companies and real-estate developers to change their traditional and conservative practices; and (iii) from the information point of view, the media are constantly pushing for increased global awareness of the importance of sustainable development.
- Steel-framed constructions (and light-weight steel construction for the low-rise residential sector, in particular) have the potential to support holistic construction solutions in a life-cycle framework that can meet the objective of zero-energy buildings. In addition, the industrialisation potential of light-weight steel construction means that from an economic point of view it can provide significant economic gains through continued innovation.

This paper has shown a quantitative assessment of the impacts of global warming on the energy demand of residential buildings for a specific climatic region. This assessment should ideally be carried out on a more global basis (at least at continent level) in order to provide more precise guidance for the implementation of efficient measures that can ensure compliance with the political targets to deal with climate change that are on the table for 2020 and 2050. Otherwise, given the important share of buildings on GHG emissions (near 40%), an environmental point of no return may be reached with disastrous consequences for the planet and humankind.

Acknowledgement

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References

ANSYS CFX 11, 2006. *User's manual*. Canonsburg, USA: ANSYS Incorporated.

Bill Dunster Architects, 2005. *UK Housing and climate change. Heavyweight vs. lightweight construction.* London: Arup Research and Development.

Christenson, M., Manz, H., and Gyalistras, D., 2006. Climate warming impact on degree-days and building energy demand in Switzerland. *Energy, Conversion and Management*, 47 (6), 671–686.

Crawley, D., *et al.*, 2008. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment*, 43 (4), 661–673.

Decreto-Lei nº80/2006. *Regulamento das Características Térmicas dos Edifícios* (*RCCTE*) (in Portuguese). Lisboa, Portugal: Diário da Républica.

DELOITTE, 2008. *European Powers of Construction 2008 – analysis of key players and markets*. London: The Creative Studio at Deloitte.

EN ISO 13790, 2008. *Energy performance of buildings – Calculation of energy use for space heating and cooling*. Geneva, Switzerland: International Organization for Standardization.

EN 1993-1-3, 2006. *Eurocode 3*. Brussels, Belgium: CEN – European Committee for Standardization.

EN 15265, 2007. *Energy performance of buildings – calculation of energy needs for space heating and cooling using dynamic methods – general criteria and validation procedures*. Brussels, Belgium: CEN – European Committee for Standardization.

European Directive 2002/91/CE, 2003. *Directive 2002/91/CE of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings*. Brussels, Belgium: Official Journal of the European Communities.

European Directive 2010/31/EU, 2010. *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*, Brussels, Belgium: Official Journal of the European Union.

European Light Steel Construction Association (LSK), 2005. *European lightweight steel-framed construction*. Bruxelles: Arcelor House.

Gaterell, M.R. and McEvoy, M.E., 2005. The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. *Energy and buildings*, 37 (9), 982–995.

Gervásio, H., *et al.*, 2010. Influence of thermal insulation on the energy balance for cold-formed buildings. *Advanced Steel Construction, an International Journal*, 6 (2), 742–766.

IPCC, 2007. *Climate change 2007: the physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge, UK: Cambridge University Press.

Jokisalo, J. and Kurnitski, J., 2005. *Effect of the thermal inertia and other building and HVAC factors on energy performance and thermal comfort in Finnish appartment buildings* (Teknillinen korkeakoulu. Konetekniikan osasto. LVI-tekniikan laboratorio). Espoo: Helsinki University of Technology, Report B79.

Kottek, M., *et al.*, 2006. World map of the Köppen–Geiger climate classification updated. *Meteorologische Zeitschrift*, 15 (3), 259–263.

Launder, B.E. and Spalding, D.B., 1974. The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics and Engineering*, 3 (2), 269–289.

Meadows, D.H., *et al.*, 1972. *The limits to growth. A report to the Club of Rome*. London: Earth Island Limited.

Menter, F.R., 1993. Multiscale model for turbulent flows. *In*: *24th fluid dynamics conference*, July 1993. Orlando, USA: American Institute of Aeronautics and Astronautics, 1311–1320.

Menter, F.R., 1994. Two-equation eddy viscosity turbulence models for engineering applications. *AIAA Journal*, 32 (8), 1598–1605.

National Board of Housing, Building and Planning, Sweden and Ministry for Regional Development of the Czech Republic, eds., 2005. *House statistics in the European Union, 2004*. Karlskrona: Boverket.

Santos, P., *et al.*, 2010. Affordable houses (part II): functional, structural and technological performance. *In*: P.J. da Sousa Cruz, ed. *ICSA2010 – International Conference on Structures and Architecture*, 21–23 July, Guimarães, Portugal. Kirjastus: Taylor & Francis Ltd, 1298–1306.

Santos, P., *et al.*, 2011. Parametric analysis of the thermal performance of light steel residential buildings in Csb climatic regions. *Journal of Building Physics*, 35 (1), 7–53.

UNEP, 2007. *Buildings and climate change – status, challenges and opportunities*. Paris, France: United Nations Environmental Programme.

Urge-Vorsatz, D. and Novikova, A., 2008. Potentials and costs of carbon dioxide mitigation in the world's buildings. *Energy Policy*, 36 (2), 642–661.

Van Holm, M., *et al.*, 2011. Energy Efficient Materials for Buildings. Roadmapping Exercise on Materials for the European Strategic Energy Technology Plan, European Commission, February 2011.

Website Passive House Institute, 2010. Available from: http://www.passivehouse.com/ [Accessed 3 June 2010].

Website Portuguese Statistical Institute, 2010. Available from: http://www.ine.pt [Accessed 15 June 2010].

Website Portuguese Weather Institute, 2010. Available from: http://www.meteo.pt/pt/clima/clima.jsp [Accessed 21 July 2010].

Website Software DesignBuilder, 2010. Available from: http://www.designbuilder.co.uk/ [Accessed 8 September 2010].

Website Software Energy Plus, 2010. Available from: http://www.energyplus.gov [Accessed 30 October 2010].

Wilcox, D.C., 1993. *Turbulence modeling for CFD.* La Canada, California: DCW Industries, Inc., 460 p.