Chapter 3

Energy Efficiency of Lightweight Steel-Framed Buildings

Paulo Santos

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/66136

Abstract

The market share of lightweight steel-framed (LSF) construction system has grown over the last decades, mainly in low-rise residential buildings, due to its advantages such as having small weight with high mechanical strength; reduced disruption on-site and speed of construction; great potential for recycling and reuse; high architectural flexibility for retrofitting purposes; easy prefabrication, allowing modular construction; economy in transportation and handling; superior quality given off-site manufacture control; and excellent stability of shape in case of humidity and resistance to insect damage. However, given the high thermal conductivity of steel and the lightness of this type of construction, it may also have some drawbacks if not well designed and executed. Therefore, special attention should be given to the LSF building envelope in order to minimize thermal bridges. Moreover, given the usual reduced thermal mass, several strategies could be implemented to increase thermal inertia, consequently reduce indoor temperature fluctuations, enhance the occupants comfort and increase energy efficiency. In this chapter an overview of the main features related to the thermal behaviour and energy efficiency of LSF buildings is provided alongside some related case studies.

Keywords: LSF buildings, energy efficiency, thermal behavior, thermal bridges, thermal inertia, case studies

1. Introduction

Sustainable development and energy efficiency are two of the most relevant concerns of today's humankind. Therefore, the demand to reduce energy consumption and to use more environmental friendly materials is increasing. In fact, today there is no doubt about the link between the burning of fossil fuels and the consequent release of carbon dioxide with climatic changes, for example, global warming and extreme climate events. Buildings exhibit an enormous potential to mitigate greenhouse gas (GHG) emissions when compared with other activity sectors [1]. Thus, the use of renewable energy sources (RES) and the reduction of energy consumption are two top priorities, being these the major challenges of the twenty-first century for emerging and developed countries.

In this context, several objectives were established by the European Union in the Energy Performance Building Directive—EPBD (European Directive 2010/31/EU [2]) regarding "nearly zero-energy buildings" for the year 2020. The EPBD addressed both the increase in RES and the improvement in buildings energy efficiency.

Several alternatives to traditional reinforced concrete structure and brick wall buildings have emerged, including the lightweight steel-framed (LSF) buildings. Given its advantages (economical, functional, environmental, etc.), the market share of LSF construction system grew significantly, mainly in low-rise residential buildings, making this kind of construction more attractive and popular [3]. Some of these advantages are as follows: high architectural adaptability [4, 5]; reduced weight; cost-efficiency [6]; exceptionally solid relative to weight; rapid on-site erection; excellent stability of shape in case of humidity; easy to prefabricate; and great potential for recycling and reuse, increasing building sustainability [1, 3, 7]. Section 2 of this chapter presents a brief overview of the LSF construction system, which includes the materials used, its classification regarding the position of thermal insulation, and the methods for manufacturing and framing.

Regarding sustainability, to perform a life cycle analysis of a building is essential to quantify both embodied and operational energies. To increase the sustainability label, it is vital to reduce both types of energies. This chapter focuses on the operational energy related to thermal behaviour improvement in LSF elements or components and energy efficiency of LSF buildings.

Some advantages of LSF construction system have been mentioned. However, when not correctly addressed during design stage, the LSF construction system may have also some drawbacks which could penalise its thermal behaviour and energy efficiency. Thermal bridges (TB), originated by the steel studs and the reduced thermal inertia (TI), are two major examples of these possible drawbacks. These issues related to the thermal behaviour of LSF elements are further detailed in Section 3.

Since the assessment of the energy efficiency of LSF buildings depends on so many factors and should be made in a holistic manner, this is not straightforward [1]. The parameters with influence on thermal performance and energy efficiency of LSF buildings could be grouped into four key factors [1]: climate [8, 9]; building envelope; occupants behaviour; and buildings systems. In Section 4 of this chapter, each one of these key factors will be further analysed.

Several tools to evaluate the energy and environmental performance of buildings in steel have been implemented. One example is the SB_Tool, also designated as ESSAT (early stage sustainability assessment tool), and developed by SB_Steel research project partners, mainly by the University of Coimbra research team, for the evaluation of the life cycle environmental performance of a building, which is freely available online [10]. This tool was an outcome of the European research project "*SB_Steel—Sustainable buildings in steel*" [11–13].

Some case studies related to the thermal behaviour of LSF elements and the energy efficiency of LSF buildings are briefly presented in Section 5 of this chapter.

2. Overview of LSF construction system

This section provides a brief description of the lightweight steel-framed (LSF) construction system. First, an overview of the main materials used in this construction system (structural cold-formed steel sections, sheathing panels and insulation materials) is presented. It continues with the typical classification of LSF construction components, concerning that the thermal insulation location within these components is described and concludes with a concise overview of the manufacturing processes and the framing methods.

2.1. Materials

The LSF dry construction system typically makes use of the following three main types of materials [1]: (i) structural cold-formed steel sections; (ii) sheathing panels (e.g. gypsum plasterboard and OSB—oriented strand boards; and (iii) insulation materials (e.g. expanded polystyrene for ETICS—external thermal insulation coating system—and mineral wool used within the walls and slabs). There are also some complementary additional materials like self-drilling screws for joining and fastening, air tightness and waterproof membranes, and of course the finishing cover layer. **Figure 1** illustrates a low-rise LSF residential building under construction, namely the cold-formed steel structure frame (**Figure 1a**) and after the setting up of OSB sheathing layer (**Figure 1b**). Notice that, as usual, to avoid ground humidity related problems, there is an elevated reinforced concrete ground floor [14].

(a) (b)

Figure 1. Example of a low-rise LSF residential building at construction stage [14]. (a) Steel frame; (b) OSB external layer.

2.1.1. Cold-formed steel profiles

There are several cold-formed cross-sectional steel profiles, most of them identified by a letter (e.g. U, C, Z). The structural and functional performance depends on this cross-sectional shape, existing some special profiles with increased thermal (e.g. slotted web profiles) and acoustic performance (e.g. resilient profiles). To avoid corrosion and to increase durability, the steel studs are usually galvanised. The galvanisation process is often the hot-dip zinc immersion technique [3]. These steel studs are used in all LSF building components, namely external and internal walls, roofs and slabs, except ground floor slab, which is usually in reinforced concrete, as previously mentioned and illustrated in **Figure 1b**.

2.1.2. Sheathing panels

OSB and gypsum plasterboards are the most standard sheathing panels for the outer and inner layers of LSF construction elements (e.g. walls), respectively (**Figure 2**). Notice that, besides their covering function, these panels may have also a relevant structural role in load-bearing walls regarding horizontal loads, for example, wind [15]. Besides walls, OSB panels could also be used in slabs (e.g. floors and roofs), its thickness being usually greater than in walls. Furthermore, to increase thermal inertia/mass and reduce floor vibrations, the use of a top thinner concrete/mortar layer (e.g. 50 mm) could be advantageous [1].

Legend:

❶ Gypsum plaster board

❷ Cold-formed steel profiles

❸ Mineral wool

❹ OSB

❺ ETICS with EPS

Figure 2. Materials in a LSF wall crosssection [30]. Legend: Gypsum plaster board; Cold-formed steel profiles; Mineral wool; OSB; and ETICS with EPS.

2.1.3. Joining and fastening

There are several methods for joining and fastening construction elements (e.g. two steel profiles or panels to LSF structure), being this issue very relevant for the speed of erection and for the mechanical resistance of the assembled structure. The use of self-drilling screws is the most usual fastening method, given its advantages, for example, stronger connection and higher durability, when compared with the use of nails [3]. Self-drilling screws are usually fabricated from heat-treated carbon steel or from stainless steel. There are several thread types for thread-forming screws, including for fastening thin sheets to thin sheets and for fixing to steel bases of greater thicknesses (greater than 2 mm or up 4 mm) [1].

2.1.4. Thermal insulation materials

As mentioned before, mineral wool is very often used between the steel sections as thermal and acoustic insulator (**Figure 2**). Besides, this insulation material is incombustible providing an improved fire resistance to LSF components. The use of expanded (EPS) or extruded polystyrene (XPS) is also very usual in the ETICS given its suitability to reduce thermal bridging-originated by the steel frames since, unlike the mineral wool batt insulation, it is a continuous thermal insulation layer (**Figure 2**) [16].

2.1.5. Wind and air tightness membranes

The adequate use of wind and air tightness membranes is very relevant to control heat losses due to air infiltrations in LSF buildings, mainly in cold climates [1]. In order to make sure that these air tightness membranes are correctly installed and the air infiltration rate is reduced, a "blower door test" or fan pressurisation method should be performed [1]. Besides heating energy reduction, another advantage of the adequate use of these membranes is the mitigation of the risk for interstitial condensation, given the resulting reduction in the moisture content inside the LSF element [3].

2.1.6. Finishing options

The most usual finishing coating layers are ETICS and gypsum plasterboards for outer and inner sides of exterior walls, respectively, being the gypsum plasterboards also very common in ceilings. However, the LSF construction may have any finishing covering layer as a traditional building with reinforced concrete structure and ceramic brick walls [3].

2.2. Classification of LSF construction

Usually, depending on the position of thermal insulation materials, the LSF construction elements are classified as cold, hybrid and warm frame construction [7], as illustrated in **Figure 3**. When all the thermal insulation is placed between steel studs (batt insulation), it is called "cold frame construction" (**Figure 3a**), since there is higher heat loss across the steel thermal bridge and consequently the steel temperature decreases leading to a higher risk of interstitial condensation, which could be particularly relevant in colder climates. The most usual LSF construction type is the hybrid one (**Figure 3b**) where, besides the batt insulation, there is also a continuous layer of thermal insulation, usually in the outer side (ETICS). In cases when all the thermal insulation is placed outside the steel framing, the steel frame is warmer (compare **Figure 3c** with the other two **Figure 3a, b**) and therefore, it is called "warm frame construction". Regarding the characteristics of thermal-hygrometric behaviour, the best option is warm frame construction, given the continuous thermal insulation and consequent lower thermal transmission value (U), reducing the risk of interstitial condensation [1]. However, in this option, the walls are thicker, and therefore, the net floor area could be diminished.

2.3. Manufacturing and framing methods

The main LSF construction framing methods are [1]: (i) stick-framing (or stick-built); (ii) panelised (or areal, "2D"); and (iii) modular (or volumetric, "3D"). Stick-framing was the first framing method to be used, where the steel studs are assembled together on-site, increasing flexibility and reducing planning needs. Given the great suitability of LSF construction for industrial modular prefabrication and consequent higher erection speed and improved quality control, the panelised and the volumetric system is being used more often. In these framing methods, the wall panels, floor cassettes and the 3D modules are prefabricated in factory with suitable dimensions to be transported to the construction site, where they will be assembled.

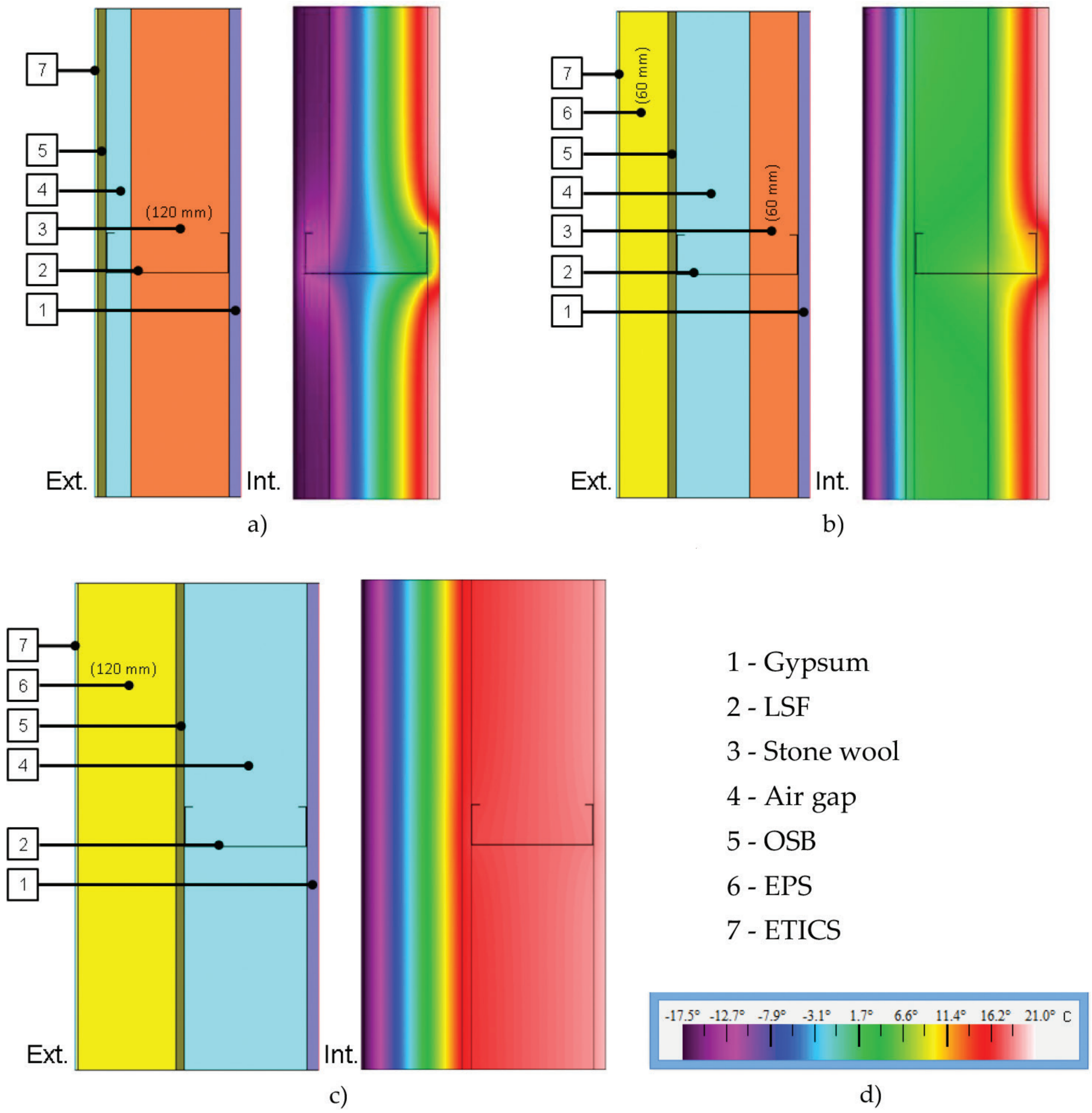


Figure 3. Classification of LSF walls, inside temperature distribution and thermal transmittance values (U). (a) Cold frame construction; U = 0.5255 W/m²/K. (b) Hybrid construction; U = 0.3856 W/m²/K. (c) Warm frame construction; U = 0.2828 W/m²/K. 1—Gypsum. 2—LSF. 3—Stone wool. 4—Air gap. 5—OSB. 6—EPS. 7—ETICS. (d) Materials and colour legend.

In order to take advantages of both 2D panel and 3D modular LSF construction, the "Hybrid" modular and panel could be also used as detailed for a case study building in UK by Lawson and Ogden [17]. Moreover, to extend the use of LSF construction to taller multi-storey buildings, it is possible to make use of an additional primary steel frame in order to provide the adequate structural stability to the building [17].

http://dx.doi.org/10.5772/66136

3. Thermal behaviour of LSF elements

This section includes a brief description of the thermal behaviour of LSF elements. It is easy to design LSF building envelope elements (e.g. walls, floors and roofs) with high thermal resistance values, even using lower thicknesses, while saving net construction areas. This goal is achieved by using thermal insulation materials [1]. Given the specificities of LSF construction [7], special attention should be given to the design stage in order to mitigate thermal bridges (originated by steel studs) and increase thermal inertia (if needed). These two key issues are addressed next.

3.1. Thermal bridges

Given the high thermal conductivity of steel, the design of building envelope components should follow certain rules in order to minimize the effects of thermal bridges (TB). Some examples of these design rules are [1]: if possible, avoid any interruption of the insulating layer; at least one third of the thermal insulation should be continuous (preferably external insulation as mentioned before in Section 2.2); at junctions of building elements, the insulating layers have to join at full width; if interrupting the insulating layer is unavoidable, use a material with the lowest possible thermal conductivity; keep façade geometry simple; and openings (windows and doors) should be installed in contact (at least partially) with the insulation layer.

Moreover, there are some specific parameters with direct influence in the thermal transmission of LSF construction elements including: the crosssection and number of steel frames; the thickness of the steel; the spacing of the steel studs; and the length of the web and flanges. Furthermore, there are several additional measures to mitigate the TB effects as illustrated in **Figure 4**. Since the major heat losses may occur across the steel frames, the use of thermal break strips along the studs (**Figure 4a**) is a possible strategy. The efficiency of this TB mitigation measure will increase with the use of high-performance thermal insulation strips (e.g. aerogel). Another approach could be the use of slotted steel studs as illustrated in **Figure 4b**. This strategy will increase the thermal performance of LSF elements (lower U-value) but will also decrease its mechanical resistance, which should also be taken into account for load-bearing studs [15]. The third example presented in **Figure 4** is the use of flange stud indentation. The geometry of the flange reduces the contact area between the sheathing panels originating a sort of thermal break given the small air gap created. The increase in the flange indentation size will also improve the thermal performance as illustrated in **Figure 4c**. In this case, the wall thermal resistance improvements were 9 and 16%, having as reference a standard steel stud.

Thermal bridges may have a very important influence on the energy efficiency of buildings, particularly in cold climates regarding the energy for space heating [1]. This issue is even more relevant in LSF buildings given the high thermal conductivity of steel [16]. Therefore, special attention should be given to thermal bridges mitigation at design stage, and as exemplified here, there are today several strategies available.

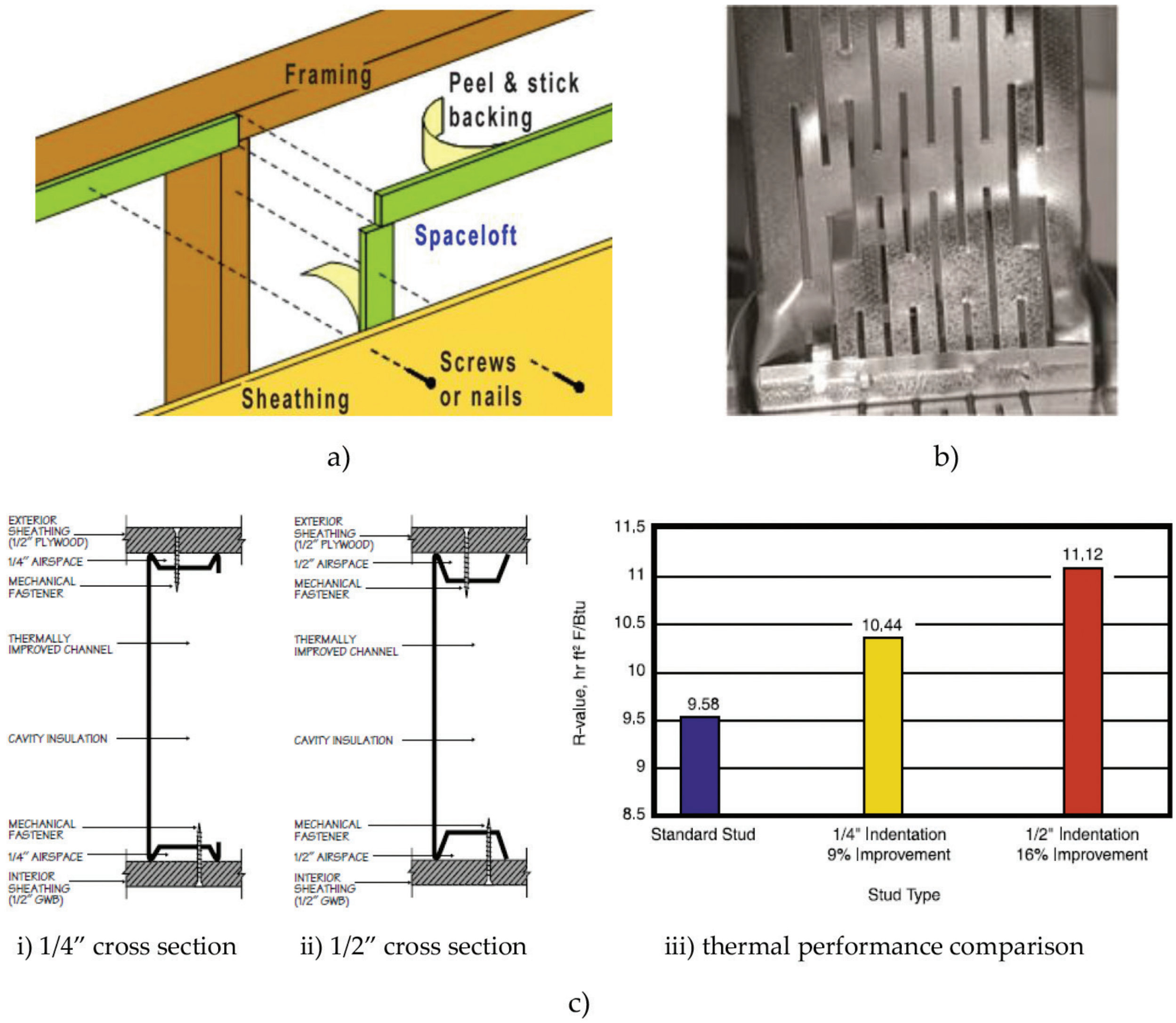


Figure 4. Strategies to mitigate thermal bridges in LSF construction elements. (a) Thermal break strips [18]. (b) Slotted steel stud [19]. (c) Flange stud indentation [20]: (i) 1/4″ cross section. (ii) 1/2″ cross section. (iii) thermal performance comparison.

3.2. Thermal inertia

LSF buildings exhibit lower thermal inertia (TI) when compared with traditional buildings with reinforced concrete structure and ceramic brick walls, given its reduced weight and consequent minor thermal mass. In practice, this means that LSF buildings may have higher internal temperature fluctuations. Therefore, it is important at design stage to adequately delineate the dimensions, exposure and shading strategies of glazed openings, with the aim to control solar heat gains, mainly during cooling season to prevent overheating.

It should be noted that a higher TI in buildings is not always advantageous regarding energy efficiency. Whenever the building has an intermittent occupation, as happens in many of the residential buildings during weekdays, this apparent drawback could be an advantage! In conventional low thermal mass LSF buildings, when the airconditioning system is turned on it will be much more easy and quick to cool/heat the building and achieve the required comfort temperature, thus reducing energy consumption and increasing energy efficiency.

However, if we are to take advantage of passive solar heating, a "mechanism" that stores solar thermal energy during the day and releases it during the night will be required. In this case, the thermal mass inside the building would be very useful. Therefore, sometimes in this circumstance, it is convenient to increase the thermal mass inside buildings, that is, its TI. **Figure 5** illustrates several strategies to increase TI inside LSF buildings. The use of ETICS (**Figure 5a**), that is, external thermal insulation allows not only to increase TI but also to mitigate TB, since it is a continuous thermal insulation layer. The second example illustrated in **Figure 5** is the use of massive materials (e.g. stones) in order to absorb and store heat. In this example, the stone wall was placed in front of a window to easily capture the solar heat, similarly to an internal Trombe wall. **Figure 5c** displays the average outside air and ground monthly temperatures (2 m deep) for Coimbra (PT) [21], as well as the difference between both temperatures. This temperature difference is not constant and is more significant during winter and summer time, reaching a value of +7.8°C in December and -7.0°C in July. Notice that, the ground is cooler during the cooling season and warmer during the heating season, that is, favourable in both seasons. There are several ways to take advantage of this air-ground temperature difference. The use of a ground-source heat exchange (GSHE) system based on air [22] or liquid (e.g. glycol fluid) flow through buried pipes is a possible strategy.

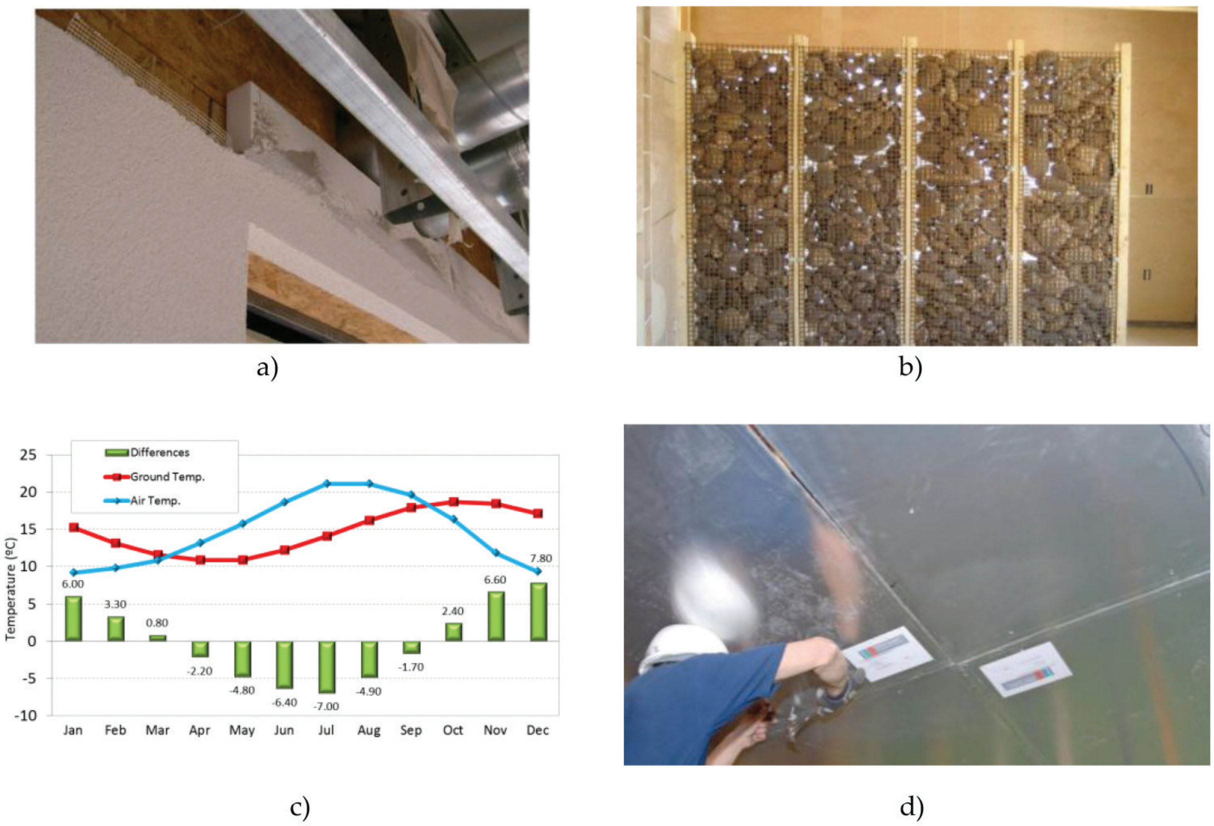


Figure 5. Some strategies to increase thermal inertia of LSF buildings. (a) External thermal insulation. (b) Use of massive construction materials [31]. (c) Make use of the enormous ground thermal mass. (d) Use of PCMs [23].

To conclude this set of examples, **Figure 5d** illustrates the use of a phase change material (PCM) in a ceiling (aluminium laminated PCM panel [23]). PCMs are able to store and release an enormous amount of heat whenever there is a temperature change that originates a phase change (melting or solidifying) given the so-called latent heat [24]. This latent heat allows the material to absorb or release heat without raising the material temperature, thus increasing the thermal inertia of the surrounding compartment.

Nowadays, a wide range of building materials or components containing PCMs can be found in the market [1]: boards for dry wall construction; plasters (e.g. gypsum, cement, clay); suspended ceiling tiles; internal window louvres; heat storage tanks; and under-floor heating system, etc.

Given the usual lower thermal mass in LSF buildings, the performance of PCMs is enhanced in this type of construction. However, the efficiency of PCMs in buildings depends on a lot of factors. Some relevant aspects should be taken into account such as [25]: (i) location in the building; (ii) their volume and thermophysical properties; (iii) the phase change temperature range; (iv) the latent heat capacity; (v) the climatic conditions; (vi) internal and solar heat gains; (vii) reflectivity and orientation of the surfaces; (viii) ventilation rates; (ix) HVAC controls; and (x) architectural characteristics. A case study will be briefly presented in Section 5.2 regarding the space heating/cooling energy performance optimization resulting from the incorporation of PCM drywalls in LSF residential buildings for different climates.

3.3. Energy efficiency of LSF buildings

Thermal behaviour and energy efficiency of buildings depend on a lot of factors. Moreover, its assessment should be performed in a holistic way, making its accurate evaluation/prediction very challenging. These parameters could be grouped into a set of four main key factors as illustrated in **Figure 6**: (i) climate; (ii) building envelope; (iii) building services; and (iv) human factors. These factors will be briefly described in the next sections.

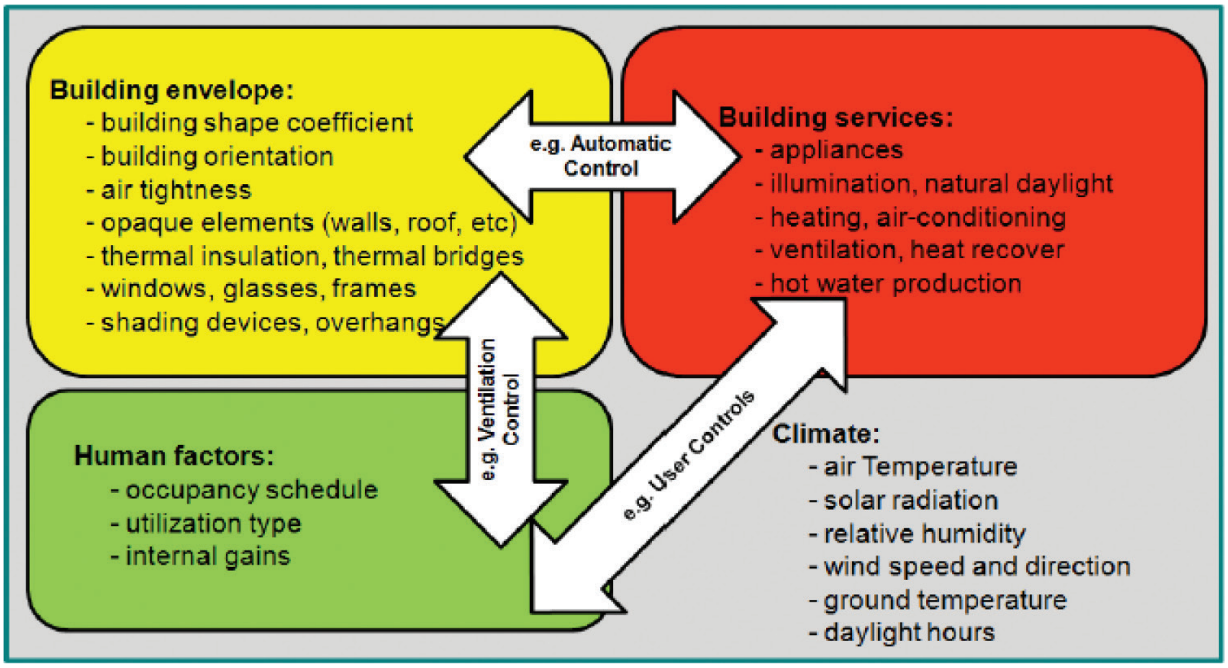


Figure 6. Key factors with influence on buildings energy consumption [1].

3.4. Climate

Climate is an external key factor with an impact on thermal behaviour and energy efficiency of buildings, mainly regarding energy for space heating and cooling. Obviously, climate depends on the building location. The main climate parameters are as follows: air temperature; solar radiation; relative humidity; wind speed and direction; ground temperature; and daylight hours.

The Köppen-Geiger climate classification [26] is one of the most widely used. In this climate classification, each climate is identified by a set of three letters. The first one represents the main climate classification: A—equatorial; B—arid; C—warm temperate; D—snow; and E—polar. The second set identifies the usual amount of precipitation: W—desert; S—steppe; f—fully humid; s—summer dry; w—winter dry; and m—monsoonal. Third one categorises the temperature: h—hot arid; k—cold summer; a—hot summer; b—warm summer; c—cool summer; d—extremely continental; F—polar frost; and T—polar tundra.

A common approach to characterise climate and relate outside temperature with the energy predictions for heating/cooling purposes is to make use of heating and cooling degree-days (HDD and CDD, respectively) having as reference a base temperature, for example, 18°C. **Figure 7** illustrates the average annual heating and cooling degree-days computed for the most relevant five European Köppen-Geiger climatic regions. The Figure clearly shows colder climates typical of Central (Cfb and Dfb) and Nordic (Dfc) European countries, where heating energy needs are largely greater than cooling needs. For southern European countries (i.e. Csa and Csb climate regions), the HDD are still high than CDD, but with much lower values when compared with the previous climate regions. Several case studies about the impact of climate on thermal behaviour and energy efficiency of LSF Buildings will be presented in Section 5.2.

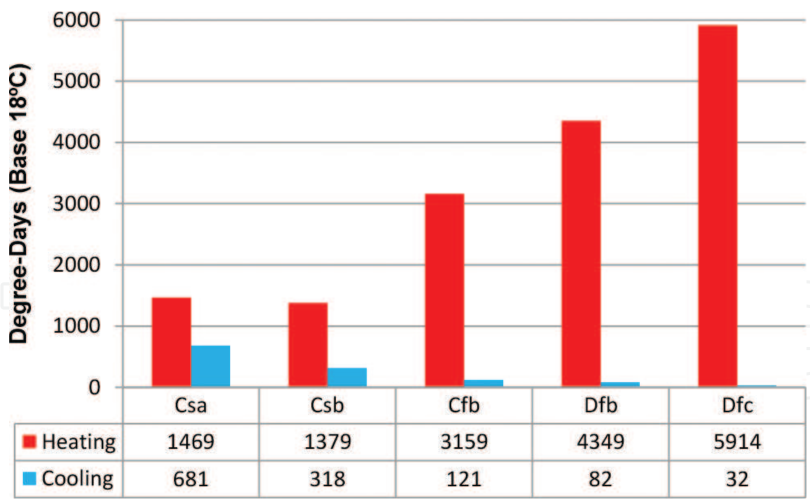


Figure 7. Average annual heating and cooling degree-days for five climatic regions [1].

3.5. Building envelope

The building envelope is another key factor to take into account the energy consumption of buildings [1]. As previously illustrated in **Figure 6**, some of the most important building envelope features are as follows: building shape coefficient; building orientation; air tightness;

characteristics of the opaque elements (e.g. walls, roof and floors) including thermal insulation and thermal bridges (see Section 3.1); thermal mass and thermal inertia (see Section 3.2); translucent elements (e.g. windows) including thermal and optical characteristics of glazing and frames; and shading devices, overhangs and sidefins.

The building envelope component responsible for the major heat losses during winter and solar heat gains during summer is usually the glazed openings (e.g. windows and doors). These undesirable heat transfer/gains could be mitigated by selecting glazing with lower thermal transmittance values and frames with thermal breaks, using insulated window shutters during night-time, designing adequate shading overhangs and sidefins, and suitable controllable shading devices (external ones are more efficient). Moreover, besides the thermal behaviour and energy performance of the building, the glazed building envelope is also very important for the thermal and visual comfort of building occupants as illustrated in **Figure 8**. In fact, the building indoor environment, for example, glare control, daylight and views, strongly depends on glazing features.

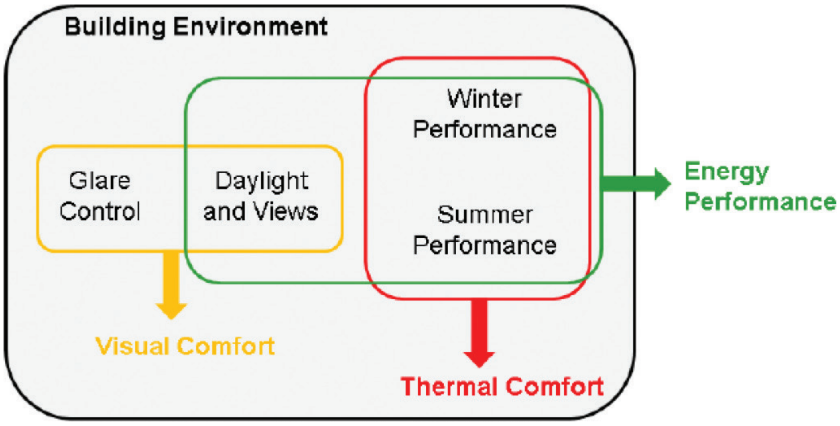


Figure 8. Glazing importance: energy performance and building environment [1].

Given the higher suitability of the LSF system for modular construction, Murtinho et al. [4] developed an architectural concept for multi-storey apartment building with LSF, which is illustrated in **Figure 9**. The main features of this design concept are modularity, easiness to build, energy efficiency and affordability, ensuring special flexibility, net area optimization and adaptability.

3.6. Occupants behaviour

The occupants behaviour is another very important issue regarding energy efficiency of buildings. In fact, buildings are inhabited and controlled by people who may contribute to increase or decrease energy consumption in the building. Some related examples are the occupation schedule (e.g. day, night or 24 h/day), the type of use (e.g. offices, residential, hospital) and the internal gains (e.g. the number of occupants, its metabolic activity level and equipment use). Obviously, the same building occupied by different people may have very different energy consumption values, given the differences in the occupants behaviour and comfort requirements regarding, for example, the heating and cooling air-conditioned temperature setpoints.

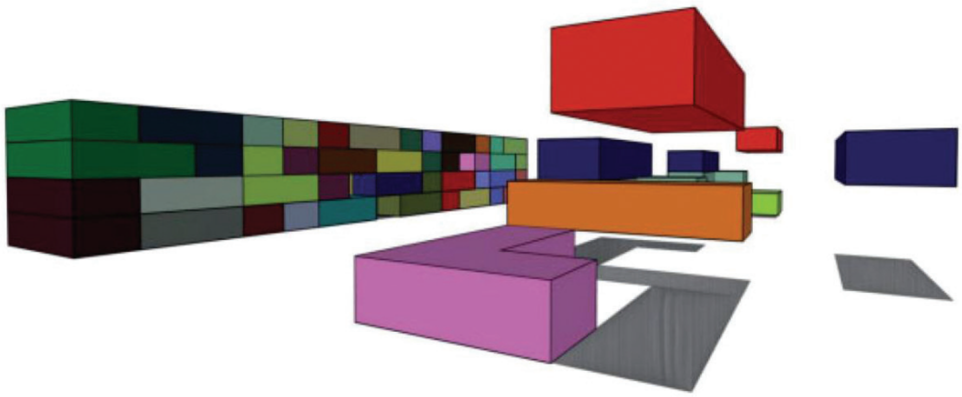


Figure 9. Modular architectural concept for multi-storey LSF buildings [4].

Offices have usually higher internal heat gains due to the intensive use of information technology equipment (e.g. computers and monitors) and consequent heat release. Moreover, offices are usually occupied during daytime, when external temperatures are higher. These two office features may lead to a higher cooling energy need when compared with other building typologies. A good example related to the metabolic activity of occupants is a gymnasium. In this case, the heat and moisture released by occupants could be very high due to the high metabolic activity and perhaps given the higher people density. Thus, cooling energy could increase and ventilation should be reinforced, not only to remove the air moisture but also the released metabolic CO_2. Moreover, these occupants may need a lower setpoint temperature to feel thermally comfortable, and this is an additional reason why energy for space cooling could be higher in gymnasiums.

3.7. Building systems

Another relevant energy efficiency key factor is the building systems. Some examples are as follows: illumination (control and efficient lamps); appliances; space heating and cooling; mechanical ventilation; hot water production; and mechanical ventilation heat recover. The control and efficiency of the equipment in use should be as good as possible in order to decrease energy consumption in the building. For instance, the electricity consumption of a thermal resistance heater ($COP \cong 1$) when compared with an air conditioning system in heating mode ($COP \cong 4$) will be about four times higher for the same amount of heat generated in the building. Moreover, the equipment systems should, whenever possible, make use of renewable energy sources. Two examples are solar collectors to produce domestic hot water and a biomass boiler for heating.

4. Case studies

In this section, several case studies related to thermal behaviour of LSF elements (e.g. walls) or components (e.g. earth to air heat exchanger—EAHE) will be briefly presented, namely the relevance of flanking thermal losses in LSF walls [27], the effectiveness of thermal bridges mitigation strategies [16] and the performance of an EAHE system located in the vicinity of a LSF building located in Coimbra, PT [22]. Furthermore, some additional case studies related to LSF buildings thermal behaviour and energy efficiency will be described, namely the "*Affordable Houses*" research project [5, 6], a parametric study regarding the thermal performance of LSF houses in Csb climatic regions [28], the impact of climate change on the energy efficiency of a LSF residential building [9] and the optimization of incorporation of PCMs in LSF houses in different climates [25].

4.1. LSF elements/components

4.1.1. Thermal bridges mitigation effectiveness assessment

In order to quantify and compare the effectiveness of several TB mitigation strategies in a LSF wall, Martins et al. [16] performed a parametric study using a 3D finite element method model previously validated against measured data [27]. **Figure 10** illustrates the studied reference wall model including the materials and the layer thicknesses (**Figure 10a**) and also the heat flux values predicted for the external surface of the LSF wall (**Figure 10b**). Several models were developed allowing the evaluation of the following TB mitigation strategies: (Model B) thermal break rubber strip; (Model C) vertical male or female studs; (Model D) slotted steel studs; and (Model E) fixing bolts instead of horizontal steel plate connection. The results (**Figure 11**) showed that the combination of all those TB mitigation strategies (Model G) leads to a reduction of 8.3% in the U-value, comparatively to the reference case (**Figure 10**), corresponding to 75% of the total impact of the steel thermal bridges.

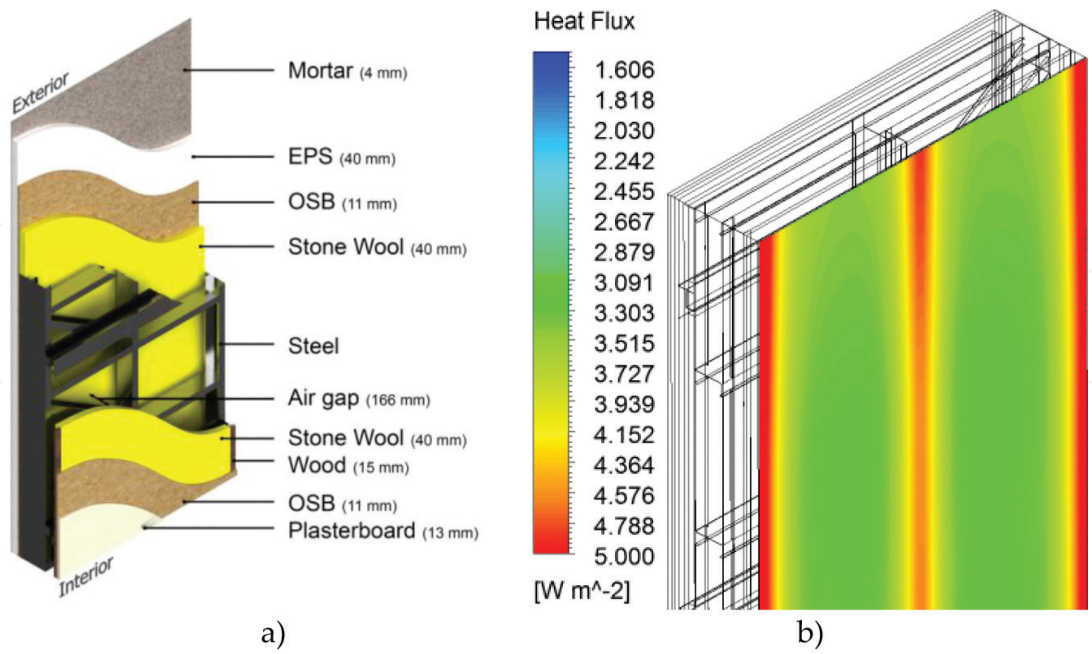


Figure 10. Reference LSF wall model used in the parametric study [16]. (a) Materials and thicknesses and (b) heat flux values on external surface.

http://dx.doi.org/10.5772/66136

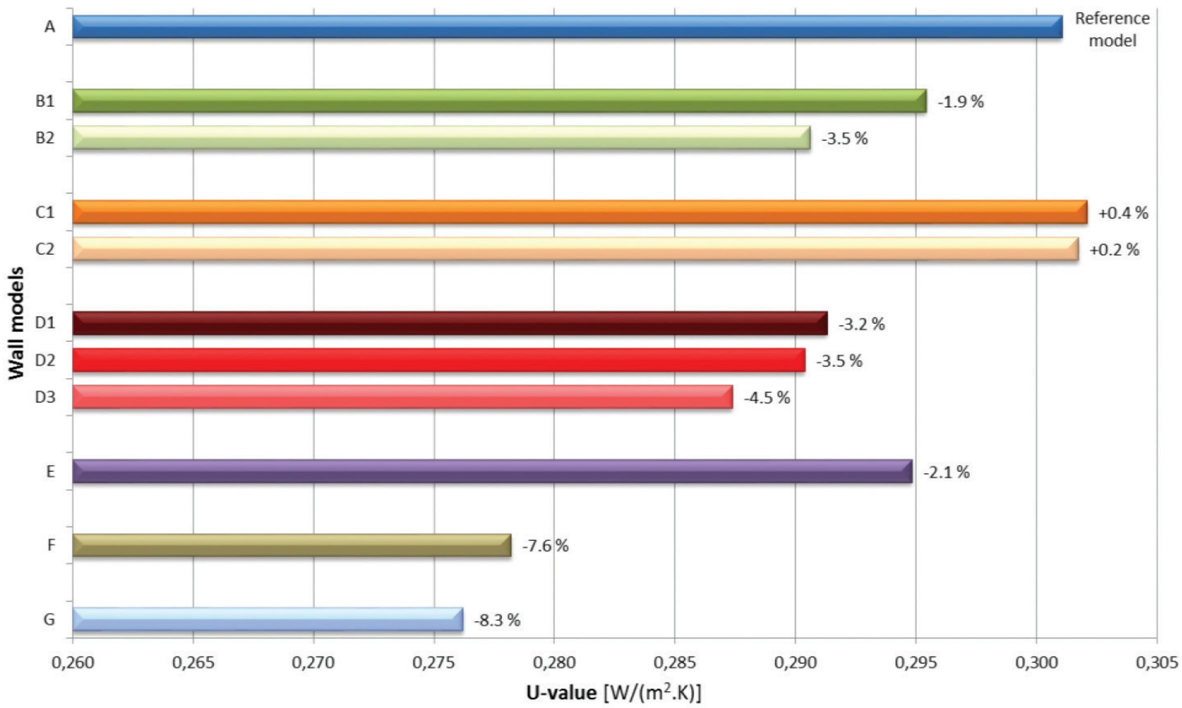


Figure 11. Results of the parametric study regarding the strategies for TB mitigation [16].

Additionally, making use of new insulation materials (aerogel and vacuum insulation panels) combined with the previously mentioned TB mitigation approaches, it was possible to significantly reduce the U-value of the wall (-68%), relatively to the reference case.

Martins et al. [16] also suggested some design rules for LSF elements: (i) at least 1/3 of thermal insulation should be continuous; (ii) the importance of the assessed single TB mitigation strategies is very reduced if the previous condition is verified; (iii) choose thermal profiles with higher number of narrow slots since they are more efficient; and (iv) use two layers of perpendicular steel profile studs avoiding trespassing the entire wall cross section with two parallel steel studs.

4.1.2. Flanking thermal losses assessment

Another issue instigated by the high thermal conductivity of steel is the increased importance of flanking thermal losses in the thermal performance of lightweight steel-framed walls. Santos et al. [27] performed an experimental evaluation of flanking thermal losses in a modular LSF wall tested in a steel gantry (**Figure 12**). Using an initial validated 3D detailed FEM model and also several others derived from this first model, they were able to evaluate the importance of several parameters in the flanking thermal losses, by computing the heat flux (**Figure 13**).

The most relevant parameters were, by decreasing order, the support steel gantry, the perimeter thermal insulation and the wall steel fixing elements. It was found that for a reference wall (U = 0.30 W/m²/K), the heat flux values changed from -22% (external surface) to +50% (internal surface) having as reference a wall with a flanking heat loss set to zero, that is, an adiabatic wall perimeter. Notice that, flanking heat losses are relevant not only in laboratory tests or numerical simulations but also in real buildings given the increased steel lateral heat exchange with the adjacent construction.

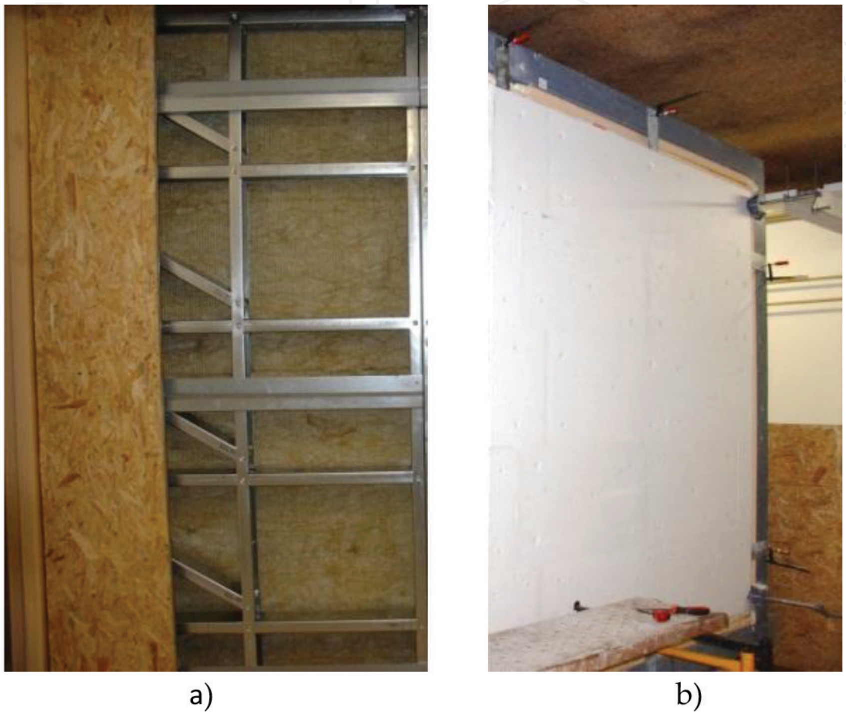


Figure 12. LSF wall tested in a climatic chamber [27]. (a) Inside view of the LSF wall structure. (b) External thermal insulation (EPS).

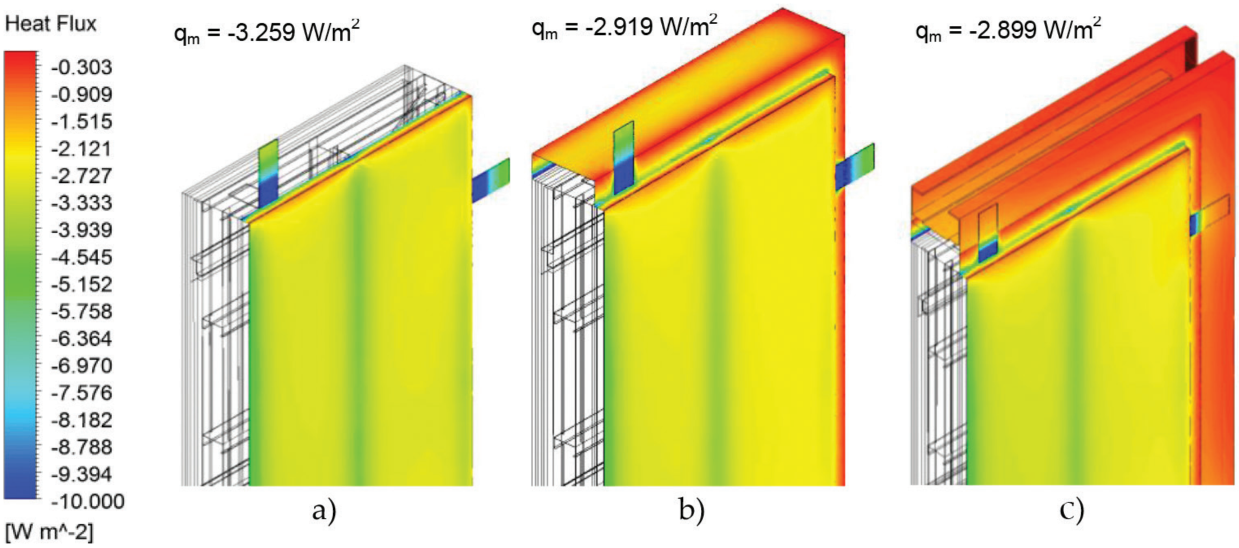


Figure 13. Heat flux predictions on the external surface of the wall for different 3D FEM models [27]. (a) Model B: "L" fixing elements. (b) Model C: "L"+XPS edge insulation. (c) Model D: "L"+XPS + Steel gantry.

4.1.3. EAHE system to increase thermal inertia

In addition to the building envelope (e.g. mitigating thermal bridges), the thermal behaviour and energy efficiency of LSF buildings could also be improved by making use of the huge thermal inertia of the ground. Santos et al. [22] monitored an earth to air heat exchanger (EAHE) system, located in Coimbra (PT), in order to assess its thermal and energy performance. This EAHE system consists of several buried ducts through which outdoor air for building ventilation is forced to flow by means of a fan. **Figure 14a** illustrates the buried pipes during the construction works of this EAHE, as well as the main relevant dimensions. Notice that, the fresh outdoor air is drawn into the EAHE through an inlet tower that contains a particle filter (**Figure 14b**).

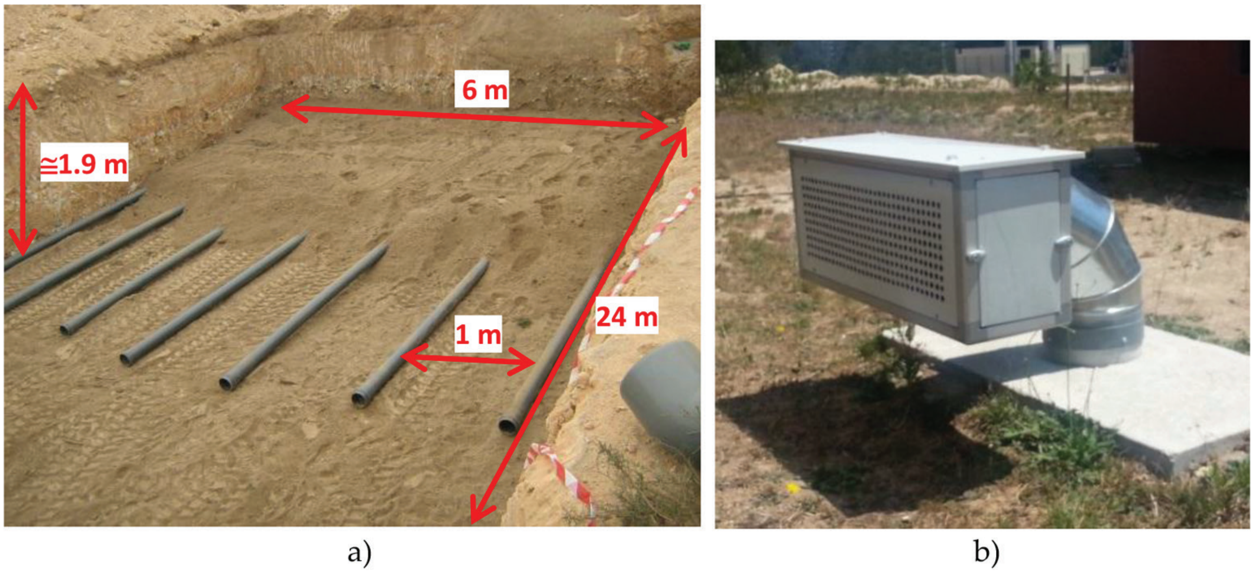


Figure 14. EAHE buried pipes and inlet filter. (a) EAHE buried pipes installation. (b) EAHE inlet filter.

Several parameters such as temperatures of the ground at different deeps, of the inlet and outlet air and the electric energy consumption of the fan have been recorded in different seasons of the year. **Figure 15** illustrates some of these recorded data and also the coefficient of performance (COP) of the EAHE system during November (heating season).

It was concluded that energy performance was higher in cooling mode (summer time), reaching an average COP of 1.7 during September, reaching a peak hourly value of 3.3. It was also observed that the control of the operation of these EAHEs is vital to optimize their energy efficiency, that is, the system should work only when it is useful to preheat (winter) or precool (summer) the air drawn into the building. Moreover, it was also found that the occupancy schedule of the building is another important parameter, that is, the system exhibits a higher heating performance during night-time (e.g. typical occupation schedule of residential buildings) and a higher cooling performance during daytime (e.g. typical occupation schedule of office buildings).

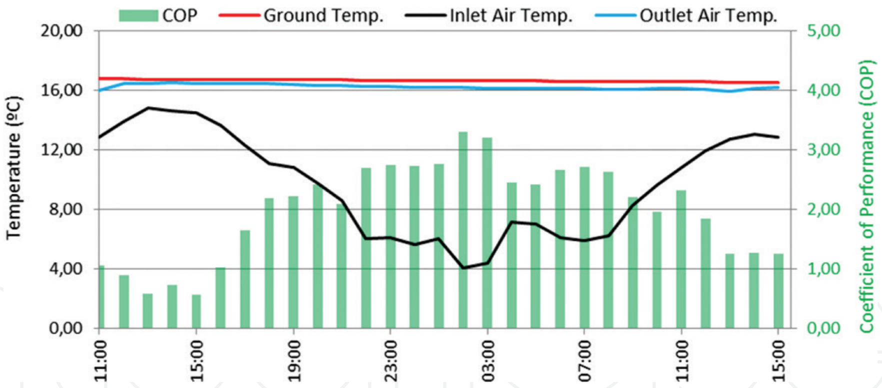


Figure 15. EAHE heating season performance: hourly values [22].

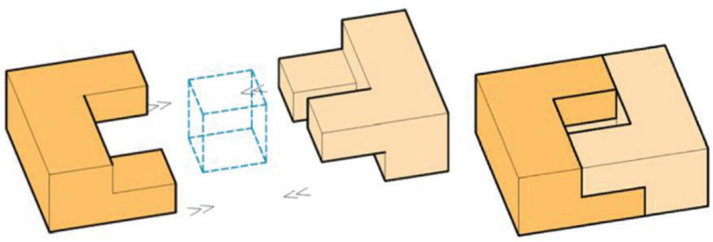
4.2. LSF buildings

4.2.1. "Affordable Houses" Portuguese proposal

The international research project "*Affordable Houses*", involving eight countries (Brazil, Czech Republic, China, India, Poland, Portugal, Romania and Sweden), aimed to develop affordable and innovative housing concepts, which are culturally adapted to each country, using the LSF construction system. Moreover, each country proposal should be feasible, reproducible and exploitable. The total duration of this research project was 1 year, and it was divided into two stages: (1) pre-design stage and (2) design stage. The pre-design stage deliverables were as follows: (1) socio-economic evaluation; (2) traditional housing concept; (3) innovative concept; and (4) follow-up with general planning for 2nd stage. The design stage had two deliverables, namely (1) final design, including the detailed description of the technical solutions, and (2) socio-economic assessment.

The Portuguese proposal, prepared by a multidisciplinary team from the University of Coimbra, makes use of a modular LSF construction system developed by the national research team as illustrated in **Figure 16** and detailed by Murtinho et al. [5].

a)

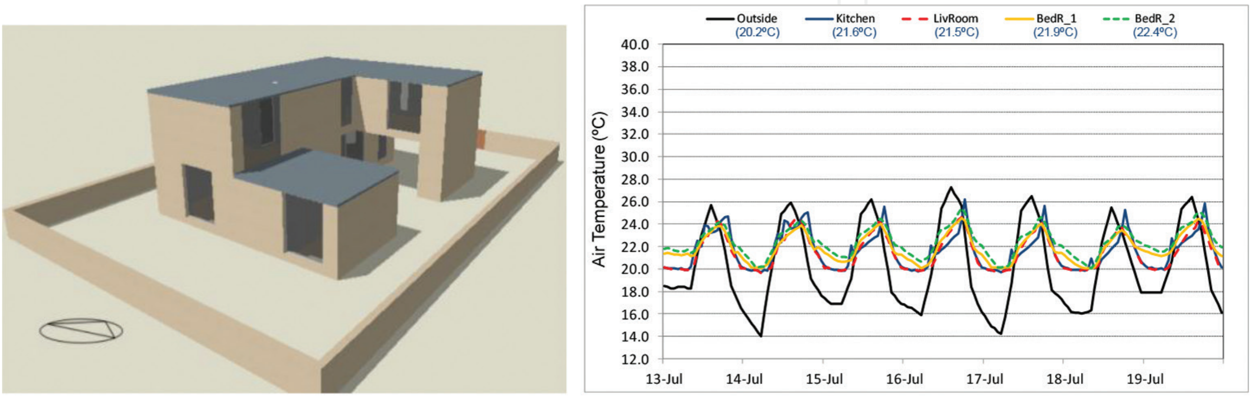


b)

Figure 16. Modular concept for LSF houses [5]. (a) Example of modular typological expansion. (b) Two jointed houses.

http://dx.doi.org/10.5772/66136

The functional, structural and technological performance of the Portuguese proposal was evaluated and described by Santos et al. [6]. The building components and the functional requirements for proposed LSF residential building envelope were also presented, including energy performance, thermal and acoustic insulation, as well as the tools used in the design and performance assessment. The environmental performance of this house was also evaluated based on its carbon emissions. The thermal behaviour and energy efficiency of buildings were evaluated in accordance with the Portuguese regulation, also performing some advanced dynamic simulation using the *DesignBuilder* software as illustrated in **Figure 17**.



a) b)

Figure 17. Modular Portuguese LSF house thermal performance assessment [6]. (a) *DesignBuilder* model. (b) Summer typical week.

4.2.2. Passive thermal performance in Csb climatic regions

Thermal performance of buildings could be assessed in an active mode (i.e. with the space cooling/heating equipment working) or in a passive mode (i.e. with the cooling/heating systems turned off). Santos et al. [28] performed a parametric analysis of the passive thermal performance of LSF residential buildings in Csb climatic regions located in southern European countries. With that purpose, a Portuguese low-rise residential building (**Figure 18**) was monitored in terms of its thermal behaviour, and an advanced dynamic *DesignBuilder* model was assembled (**Figure 18c, d**), calibrated and validated making use of the *in situ* recorded data. The relevance of several parameters (e.g. thermal insulation, ventilation, windows glazing, shading devices and overhangs) on the passive thermal behaviour of this building was evaluated making use of a previously validated model. Moreover, an optimum building envelope and operational control solution were specified, and design guidance was provided for the range of Csb climatic conditions. **Figure 19** illustrates how to use the suggested design guidance regarding two parameters: thermal insulation for roofs, walls and ground floor (**Figure 19a**) and overhangs ratio (**Figure 19b**) for the Genova (IT). The suggested simplified design process is very easy to use. Taking into account the average annual mean temperature for the building location, in this case 16°C, it is only needed to mark this value in the abscissa axis, intercept with the plotted line, and the recommended value is obtained in the ordinated axis.

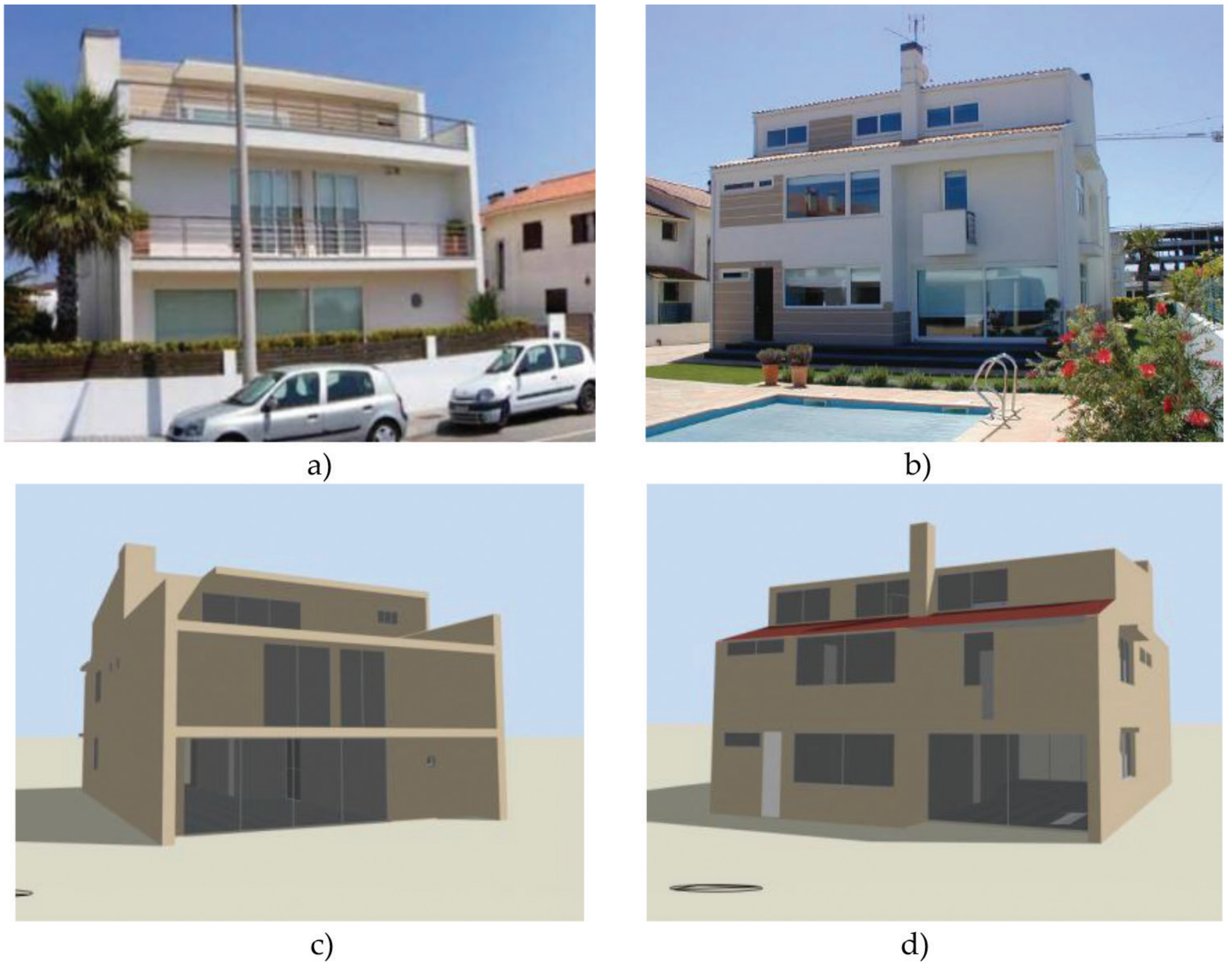


Figure 18. LSF residential building and *DesignBuilder* model [9]. (a) Front view. (b) Rear view. (c) Front view. (d) Rear view.

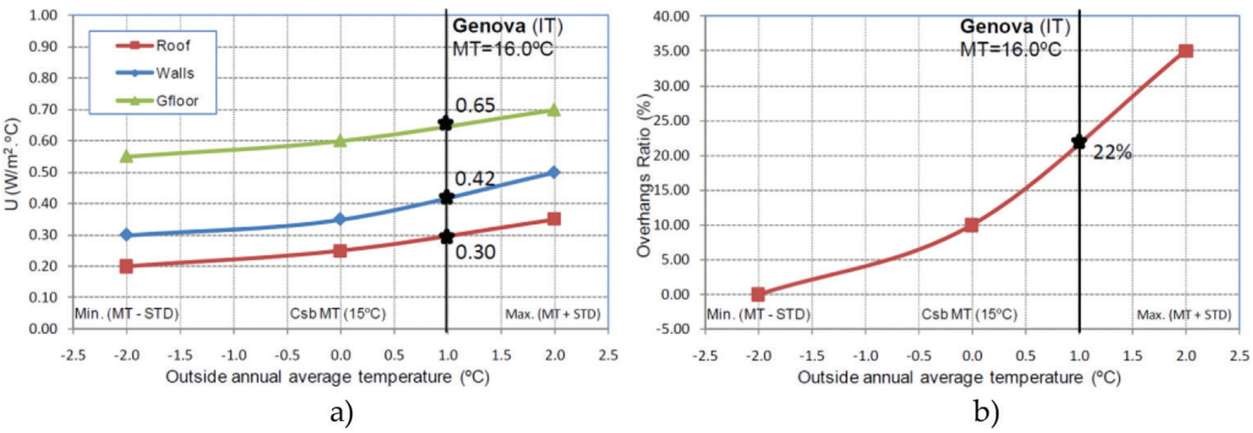
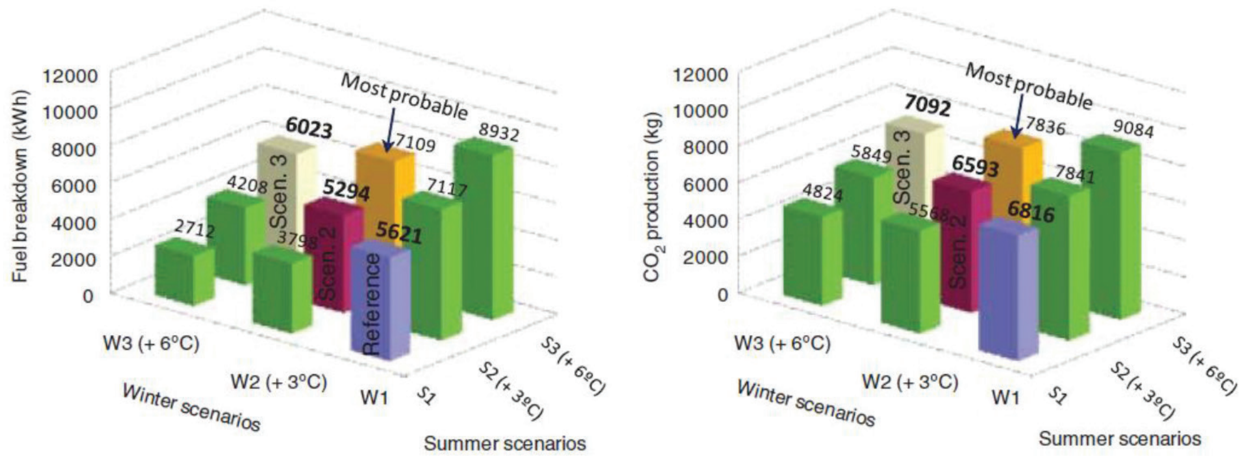


Figure 19. Design values suggested for Genova, Italy [1]. (a) Thermal insulation. (b) Overhangs ratio.

4.2.3. Impact of global warming on the energy efficiency

Obviously, global warming will induce changes on the thermal behaviour and energy efficiency of buildings. Santos et al. [9] assessed the impact of global warming on the energy efficiency of a LSF residential building (**Figure 18a, b**) based on the predictions of Intergovernmental Panel for Climate Change (IPCC) for southern European countries. With that purpose, an advanced dynamic simulation model developed in *DesignBuilder* software was calibrated against normative requirements regarding the thermal behaviour and energy consumption for space heating and cooling [29], and against a sophisticated computational fluid dynamics model (ANSYS CFX). Three climate scenarios were assessed, namely the annual recorded values for Coimbra city in Portugal (Scenario 1), and assuming an average temperature increase of +3°C (Scenario 2) and +6°C (Scenario 3). Besides climate, the energy consumption results for three building occupation schedule scenarios have been compared. Moreover, a set of winter and summer scenario combinations has been performed to predict the annual energy consumption and CO_2 emissions for a real occupation schedule scenario. **Figure 20** illustrates some of the results obtained. As expected, global warming will slightly reduce the energy for space heating but increase cooling energy. For the most probable climate change scenario predicted by IPCC (winter Scenario 2 and summer Scenario 3), an annual building energy consumption increase of 26.5% was projected. Regarding CO_2 production, the most likely increase in emissions was 15.0%.



a) b)

Figure 20. Annual fuel breakdown and CO_2 production for winter and summer climate scenario combinations [9]. (a) Fuel breakdown. (b) CO_2 production.

4.2.4. Multidimensional optimization of PCM drywalls

As previously mentioned, the use of PCMs in LSF buildings could be an efficient way to increase thermal inertia without increasing the mass/weight of the building. However, to optimize the efficiency of the PCMs in buildings is not an easy task since it depends on a lot of factors and they must be assessed in a holistic way [25].

Soares et al. [25] evaluated most of these factors by performing a multidimensional optimization of the incorporation of PCM drywalls in LSF residential buildings in different climates. This optimization was performed using *EnergyPlus* and *GenOpt* tools. **Figure 21** illustrates the model *EnergyPlus*, that is, a single-zone living room of a low-rise LSF residential building.

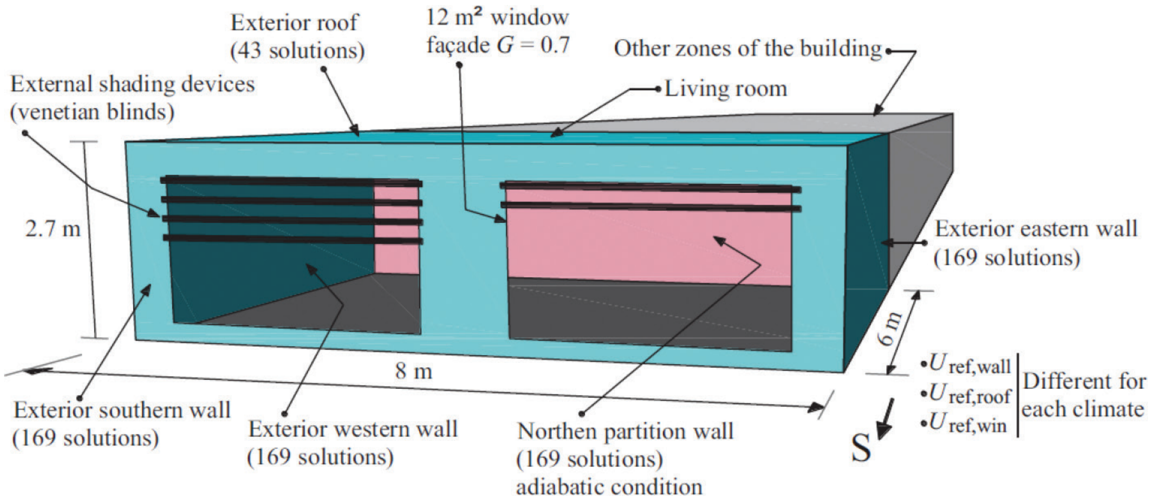


Figure 21. *EnergyPlus* model: single-zone living room of a low-rise LSF residential building [25].

The optimum solution for each climate (Csa-Seville, Csb-Coimbra, Cfa-Milan, Cfb-Paris, Dfa-Bucharest, Dfb-Warsaw, Dfc-Kiruna) was found considering a set of discrete variables in the model, namely the PCM enthalpy-temperature function, the PCM thermal conductivity-temperature variation, solar absorptance coefficient of the inner surfaces, the thickness and location of the PCM drywalls. To better simulate real-life conditions in the model, several parameters are included, mainly those related to the air conditioning setpoints, air infiltration rates, solar gains, internal gains from occupancy, equipment and lighting schedules.

It was concluded that the energy savings related to the use of PCMs in LSF construction were more evident in warmer climates. Given the higher daily external temperature amplitudes, PCM drywalls are particularly suitable for Mediterranean climates, with an expected energy efficiency gain of about 62% for Coimbra location (Csb climate). For the other climates/locations considered were obtained values between 10 and 46% regarding the energy efficiency improvement.

5. Conclusions

In this chapter, the thermal behaviour of LSF elements and energy efficiency of LSF buildings was presented, starting with an overview of LSF construction system including materials, classification, manufacturing and framing methods. The advantages of LSF construction were mentioned, and the two main potential drawbacks (steel originated thermal bridges and low thermal inertia) were addressed including several design rules to enhance the thermal behaviour of LSF elements. Moreover, the major key factors regarding the energy efficiency of LSF buildings were also assessed. Finally, case studies related to thermal and energy performance of LSF elements, components and buildings were presented.

LSF construction system has specific particularities (e.g. high thermal conductivity of steel and low thermal mass) that may have a relevant influence on thermal behaviour and energy efficiency of buildings. Therefore, special attention to design in terms of the mitigation of thermal

http://dx.doi.org/10.5772/66136

bridging and thermal inertia increase is essential to ensure a better thermal performance of LSF elements and an increased energy efficiency of LSF buildings. To illustrate this, several case studies were presented here, exemplifying the specificities of LSF construction system and its relevance in energy efficiency of buildings. Furthermore, in this design process, a holistic approach should be adopted in order to take into account the main energy efficiency key factors, that is, climate, building envelope, occupants behaviour (or human factors) and building systems. Only this way, it is possible to achieve "Energy Efficient Buildings", the title of this book.

Acknowledgements

The author would like to thank the ACIV ("Associação para o Desenvolvimento da Engenharia Civil") and the ISISE (Institute for Sustainability and Innovation in Structural Engineering) for their support.

Abbreviations and nomenclature

2D	two dimensional
3D	three dimensional
CDD	cooling degree-days
CO_2	dioxide carbon
COP	coefficient of performance
EAHE	earth to air heat exchanger
EPBD	energy performance building directive
EPS	expanded polystyrene
ESSAT	early stage sustainability assessment tool
ETICS	external thermal insulation coating system
EU	European Union
GHG	green-house gas
GSHE	ground-source heat exchange
HDD	heating degree-days
HVAC	heating ventilation and air conditioning
IPCC	Intergovernmental Panel for Climate Change
LSF	lightweight steel-framed
OSB	oriented strand board
PCMs	phase change materials
PT	Portugal
RES	renewable energy sources
TB	thermal bridges
TI	thermal inertia
U	thermal transmittance value [W/m^2/K]
UK	United Kingdom
XPS	extruded polystyrene

Author details

Paulo Santos

Address all correspondence to: pfsantos@dec.uc.pt

ISISE, Department of Civil Engineering, University of Coimbra, Coimbra, Portugal

References

[1] Santos P, Simões da Silva L, Ungureanu V. Energy efficiency of light-weight steel-framed buildings. In: 1st ed. European Convention for Constructional Steelwork (ECCS), Technical Committee 14—Sustainability & Eco-Efficiency of Steel Construction, ISBN 978-92-9147-105-8, p. 129; 2012.

[2] European Directive 2010/31/EU. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (EPBD). Brussels, Belgium: Official Journal of the European Union; 2010.

[3] LSK. European lightweight steel-framed construction. Luxemburg: European Lightweight Steel-framed Association (LSK) and Arcelor; 2005.

[4] Murtinho V, Ferreira H, Antonio C, Simoes da Silva L, Gervasio H, Santos P. Architectural concept for multi-storey apartment building with light steel framing. Steel Constr. 2010;3(3):163–8.

[5] Murtinho V, Correia A, Ferreira H, da Silva LS, Gervasio H, Rebelo C, et al. Affordable houses: architectural concepts of a modular steel residential house. In: Cruz P, editor. Proceedings of the 2nd International Conference on Structures and Architecture. London: Taylor & Francis Group; 2010. p. 1325–31.

[6] Santos P, Mateus D, da Silva LS, Rebelo C, Gervasio H, Correia A, et al. Affordable houses (Part II): functional, structural and technological performance. In: Cruz P, editor. Proceedings of the 2nd International Conference on Structures and Architecture. London: Taylor & Francis Group; 2010. p. 1332–40.

[7] Santos P, Martins C, Simões da Silva L. Thermal performance of lightweight steel-framed construction systems. Metall Res Technol. 2014;111(6):329–38.

[8] Santos P, Gervásio H, Silva LS, Lopes AG. Global warming and the thermal performance of light steel residential buildings: parametric study. In: Topping BHV, Neves LFC, Barros RC, editors. Proceedings of the 12th International Conference on Civil, Structural and Environmental Engineering Computing. Stirlingshire: Civil-Comp Press; 2009. p. 1–17.

[9] Santos P, Gervásio H, da Silva LS, Lopesa. G. Influence of climate change on the energy efficiency of light-weight steel residential buildings. Civ Eng Environ Syst. 2011;28:325–52.

[10] SB_Tool. Website "SB_Steel Tool—Software to Evaluated Sustainability of Steel Buildings in Early Stages of Design": www.onesource.pt/sbsteel (last assessed: June 2016).

[11] Santos P, Gervásio H, da Silva LS. A simplified tool to evaluate the sustainability of buildings in steel in early stages of design. Matériaux Tech. 2016;104(103):1–12.

[12] Santos P, Martins R, Gervásio H, Silva LS. Assessment of building operational energy at early stages of design—a monthly quasi-steady-state approach. Energy Build. 2014;79:58–73.

[13] Gervásio H, Santos P, Martins R, Simões da Silva L. A macro-component approach for the assessment of building sustainability in early stages of design. Build Environ. 2014;72:256–70.

[14] Ferreira M. The construction system with lightweight steel structure (in Portuguese). Master Thesis in Civil Engineering, University of Coimbra; 2014.

[15] Veljkovic M, Johansson B. Light steel framing for residential buildings. Thin-Walled Struct. 2006;44(12):1272–9.

[16] Martins C, Santos P, da Silva LS. Lightweight steel-framed thermal bridges mitigation strategies: a parametric study. J Build Phys. 2016;39(4):342–72.

[17] Lawson RM, Ogden RG. Thin-walled structures "Hybrid"light steel panel and modular systems. Thin-Walled Struct. 2008;46:720–30.

[18] ThermaBlok. Website "ThermaBlok—Aerogel Insulation": http://thermablok.com (last assessed: June 2016).

[19] TUD. Website "ThermaChannel—Energy-Efficient Steel Framing": www.thermachannel.com (last assessed: June 2016).

[20] ThermaChannel. Website "ThermaChannel—Energy-Efficient Steel Framing": www.thermachannel.com (last assessed: June 2016).

[21] DOE-EnergyPlus. Website "DOE—EnergyPlus weather data base": www.energyplus.net/weather (last assessed: June 2016).

[22] Santos P, Sousa MA, Costa JJ. Modelling and performance analysis of an earth-to-air heat exchanger. In: Tadeu A, Ural D, Ural O, Abrantes V, editors. Proceedings of the 40th IAHS World Congress on Housing: Sustainable Housing Construction. Coimbra: ITeCons—Instituto de Investigação e Desenvolvimento Tecnológico em Ciências da Construção; 2014. p. 1–10.

[23] DuPont-Energain. Website "DuPont Energain—Thermal mass solution for drywalls": www.dupont.com (last assessed: December 2010).

[24] Soares N, Costa JJ, Gaspar AR, Santos P. Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. Energy Build. 2013;59:82–103.

[25] Soares N, Gaspar AR, Santos P, Costa JJ. Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. Energy Build. 2014;70:411–21.

[26] Köppen-Geiger. Website "Köppen-Geiger climate classification". http://koeppen-geiger.vu-wien.ac.at (last assessed: June 2016).

[27] Santos P, Martins C, da Silva LS, Braganca L. Thermal performance of lightweight steel framed wall: the importance of flanking thermal losses. J Build Phys. 2014;38(1):81–98.

[28] Santos P, Simoes da Silva L, Gervasio H, Gameiro Lopes A. Parametric analysis of the thermal performance of light steel residential buildings in Csb climatic regions. J Build Phys. 2011;35(1):7–53.

[29] EN 15265. Energy performance of buildings—Calculation of energy needs for space heating and cooling using dynamic methods—general criteria and validation procedures. CEN—European Committee for Standardization. Brussels; 2007.

[30] Perfisa-SA. Website "PF Perfisa—Fábrica de Perfis Metálicos SA". www.perfisa.net (last assessed: June 2016).

[31] TreeHugger. Website "TreeHugger—Making Sustainability Sexy": www.treehugger.com (last assessed: June 2016).