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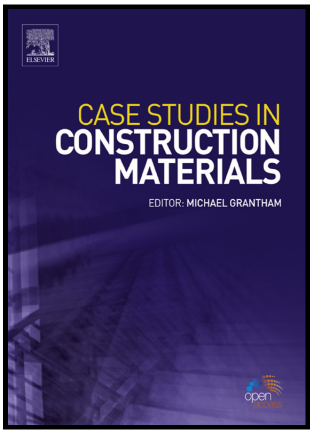

THE ROLE OF SPECIFIC HEAT CAPACITY ON BUILDING ENERGY PERFORMANCE AND THERMAL DISCOMFORT

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THE ROLE OF SPECIFIC HEAT CAPACITY ON BUILDING ENERGY PERFORMANCE AND THERMAL DISCOMFORT.

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Abstract

The key role of the building and construction sector, in terms of sustainability and decarbonization, has led building codes to tighten mandatory requirements related to buildings energy performance. Envelope quality, beyond light efficiency or the renewable energy contribution, is a key factor since the highest percentage of energy consumption is produced by thermal losses through enclosures. Therefore, building codes have significantly increased the mandatory benchmarks for equivalent thermal transmittance. However, the specific heat capacity (SHC) has commonly been overlooked in the discussion. Thus, in order to estimate the impact of such parameter in the energy consumption and thermal comfort of residential and non-residential buildings, a building model has been simulated by means of Transfer Functions Methods and the Finite Difference Methods. A traditional double brick façade has been considered and the SHC of bricks has been varied from 800 to 1,800 kJ/kg K. The thermal behavior of the building has been assessed at several locations in accordance with the Spanish building code. In addition, building orientation has also been shifted from north to south. Although passive strategies have not been considered, the results show significant energy savings (i.e. up to 20 %) and a reduction of thermal discomfort (i.e. up to 20 %), depending on the type of building and its location.

Keywords

Specific heat capacity; Thermal Conductivity; Construction materials; Building envelope; Energy performance

1. Introduction

Criteria for building envelope design have become increasingly complex in order to reduce energy consumption and increase thermal comfort. Moreover, from last decades, due to the role of construction and building sector in terms of environmental impact, the building energy performance has become the center of most ambitious decarbonization policies [1]. For instance, Europe has lately updated Directives 2010/31/UE and 2012/27/UE related to the energy performance of buildings and energy efficiency, respectively, by enacting Directive 2018/844 with the aim of increasing growing rate of nearly zero energy building stock by 2050 [2].

In Spain, the last building code (CTE-DB-HE) came into force in 2019 [3] and is aimed to promote nearly-Zero Energy Buildings by regulating greenhouse gas emissions, energy consumption, energy efficiency and energy generation from renewable sources, in accordance with the four indicators stated by ISO 52000-1 standard [4].

Regardless of the mandatory limits for the use of primary energy and installation of renewable energies, the decarbonization strategy of European Council is clearly based on the reduction of energy demands.

In response to this challenge, national building codes have been tightening building energy performance standards by reducing the maximum thresholds related to the overall thermal transmittance of façades (k_G). For instance, in CTE-DB-HE, the k_G index has been varied from a maximum of 2.1 W m^{-2} K^{-1} to a maximum of 0.8 for W m^{-2} K^{-1} for same building compactness (f_{factor}) and location (i.e. thermal zone).

Thermal transmittance certainly plays a critical role in energy saving by reducing the rate of heat transfer through the building envelope. Under steady-state conditions heat flux through a wall is proportional to k_G and the temperature distribution in the wall (i.e. only spatial and not time dependent) [5]. However, as it has been demonstrated, for the correct evaluation of the effects of temporal variations, it is necessary to know not only the thermal conductivity but also the density and specific heat of each envelope layer and to solve the time-dependent heat equation [6].

At this point, numerical methods are currently implemented in widely used software which eases the assessment of dynamic properties in transient regime. However, neither European directives nor most of the national building codes have paid attention to other parameters but on thermal transmittance. To the best our knowledge, the only exception is Italy which is leading this new approach and has demonstrated that the control of the thermal inertia ensures a lower energy consumption in the building [7-9]. For instance, the Italian building code does establish minimum values for thermal mass (i.e. 230 kg m^{-2}).

In case of Spain, the CTE-DB-HE has ignored any reference point or threshold to guide engineers in order to take advantage of SHC [10,11].

This situation has even led researchers to search for new materials with lower thermal conductivity in order to meet CTE-DB-HE benchmarks [3] while SHC has been commonly missed from discussion.

For instance, latest review articles clearly show how this behavior is missed from discussion when traditional or new eco-materials are tested. For instance, Abu-Jdayil et al. (2019) [12] and Hung Anh and Pásztory (2021) [13] reviewed insulation materials and only two researchers, out of more than 350 references, did explicitly report SHC. Muñoz et al. (2016) [14] and Salleh et al. (2021) [15] similarly analyzed more than 350 studies related to ceramic materials and no reference were highlighted. Same situation did occur regarding geopolymers [16] and cementious materials [17]. However, regarding later cementious material Asadi et al. (2018) [18] certainly recognize that, thermal mass materials enable significant energy consumption reductions in buildings (by 7–22%), although 64% of studies reviewed measured only the k_G when cement-based materials are assessed.

Therefore, the paper aims to highlight the importance of incorporating SHC thresholds in building codes. For this purpose, the variation of thermal discomfort and energy consumption by varying SHC of bricks is assessed.

It must be noted that the effectiveness of an increasing of SHC depends on several parameters such as the buildings' envelope configuration. For instance, in multilayer envelopes several authors have discussed where is better to insert the higher thermal mass layer (e.g. internal, external) [19]. Moreover, the building shape, façades orientation, roof type or window to wall ratio are also parameters which highly influence energy performance and thermal comfort [20-22].

However, in this manuscript the searching for the best configuration is out of the scope. Therefore, it has not been intended to select a particular scenario but to give range of estimations which provides a useful guidance for the policy makers in order to incorporate SHC to building codes.

In addition, the validation of basis calculations (see appendix A) is out of the scope. Several numerical methods are currently available based on the Transfer Functions Methods [23] and the Finite Difference Methods which are implemented in widely used software like EnergyPlus®. This software is the official building simulation program of the United States Department of Energy and several authors agree to trust on the accuracy of the so carried out results [24,25].

2. Methodology

2.1. Building model

It is well known that shape of building, orientation or indoor distribution, among others variables highly influence building energy performance. Since it is unable to consider all potential cases, the analysis has been performed by modelling a simple rectangular space of 91 m^2 (i.e. 15 m x 6.1 m) which corresponds to the average usable floor area, in accordance with Spanish statistics (INE, 2020) [26]. Distance between stories is typically 3 meters and ceiling is 2.2 m height which leads to account for an indoor volume of 200 m^3. This volume is aimed to represent a conventional apartment within a generic building (Figure 1a).

Actually, almost 75 % out of the Spanish's building stock belongs to multi-story buildings (i.e. two or more stories). From this point of view, floor and roof have been modelled as adiabatic surfaces (i.e. heat flow is null) since it is assumed that equal thermal conditions would take place above and under this evaluated volume [27]. Same principle applied for the adjacency definition between occupied spaces. This assumption has been previously applied by previous authors for similar studies [7].

The traditional construction system in Spain, for both new and existing buildings, consists of multilayer façades made up of two bricklayers (i.e. perforated fired clay bricks) covered with plaster mortar and a rock wool insulation between the exterior and internal wall [28] (Figure 1b).

Since the independent variable of the study is the SHC of bricks, these values varied between 800 J kg^{-1} K^{-1} to 1.800 J kg^{-1} K^{-1}, in accordance with the lowest and highest values showed by Balaji et al. (2019) for fired clay bricks [29]. Density and thermal conductivity were taken as constants and corresponding values have been taken from the most typical ones (i.e. 1,700 kg m^{-3} and 0.62 W m^{-1} K^{-1}) [30].

SHC of bricks obviously modify the amount of heat that can be stored in a particular material. Therefore, the amount of heat stored in the overall must take into account the specific heat of each wall layer. Thus, heat capacity (i.e. kJ m^{-2} K^{-1}) has been defined by the addition of the heat capacity of each layer (i.e. calculated by multiplying the density times its thickness times the SHC of the material).

In addition, thermal transmittance of façades (kG) must match the limits showed in CTE-DB-HE [3] which states different limits for k_G by depending on the building location.

As it has been pointed out by several authors, Spain shows all climates described in the Köppen–Geiger Classification by excepting for the tropical ones [31]. Spanish building code divides the territory into five thermal zones with the aim of streamlining the mandatory thermal requirements for envelopes. These thermal zones are mainly defined as a function of the number of cooling and heating degree-days and the solar radiation (Figure 1).

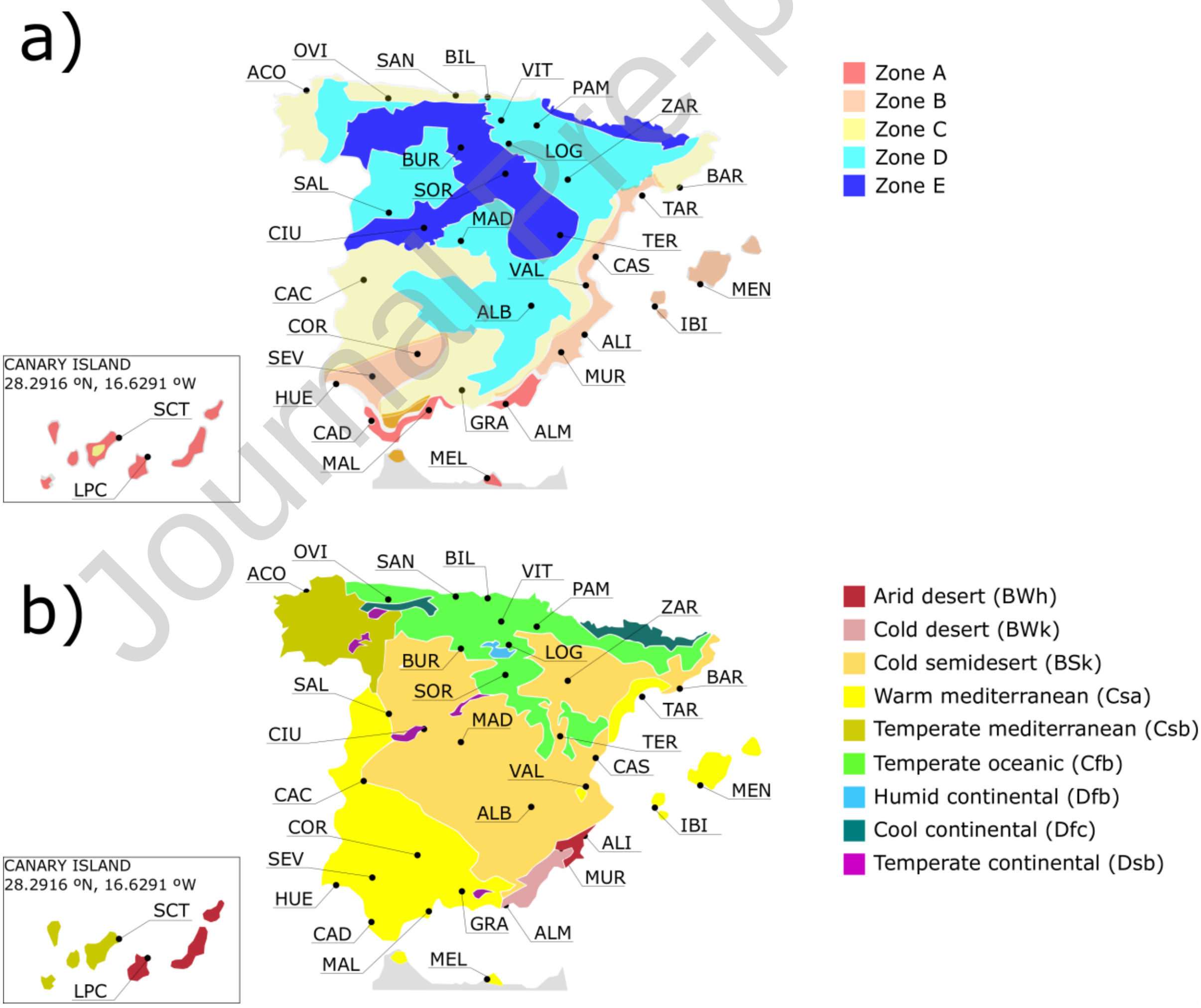

Figure 1. Location of considered cities, in accordance with the (a) CTE-DB-HE [3] and (b) the Köppen-Geiger climate classification [32].

Therefore, since the same wall configuration was used in all models but each thermal zone specifies a maximum k_G value, in this research, the mandatory threshold has been achieved by varying the width of rock wool insulator. It must be noticed, that the variation of insulation thickness slightly modifies the overall thermal capacity of the wall from thermal zone A to E. Nevertheless the biggest impact is produced by the SHC of bricks which leads heat capacity of envelopes to range from 140 to 315 kJ m^{-2} K^{-1}.

Finally, regardless the increase in thickness of rock wool layer, the internal area kept equal for all models while exterior perimeter was obviously increased (Table 1). By this way, all cases show equal indoor volume. Besides, the influence of glassy surfaces (i.e. 20 % in all cases) and f_{factor} (i.e. surface area to volume ratio) were also taken into account and the so calculated k_G complies with CTE-DB-HE in all cases.

Table 1. Width and k_G for each thermal zone, in accordance with CTE-DB-HE.

Thermal zone	A	B	C	D	E
k_G [W m^{-1} K^{-1}]	0.7	0.56	0.49	0.41	0.37
Width of the rock wool insulator [cm]	5	7.5	10	16	20
Width of the entire envelope [cm]	27.8	30.3	32.8	38.8	42.8
Highest wall´s thermal capacity [kJ m^{-2} K^{-1}]	315.7	315.9	316.2	316.8	317.2
Lowest wall´s thermal capacity [kJ m^{-2} K^{-1}]	140.6	140.8	141.1	141.7	142.1

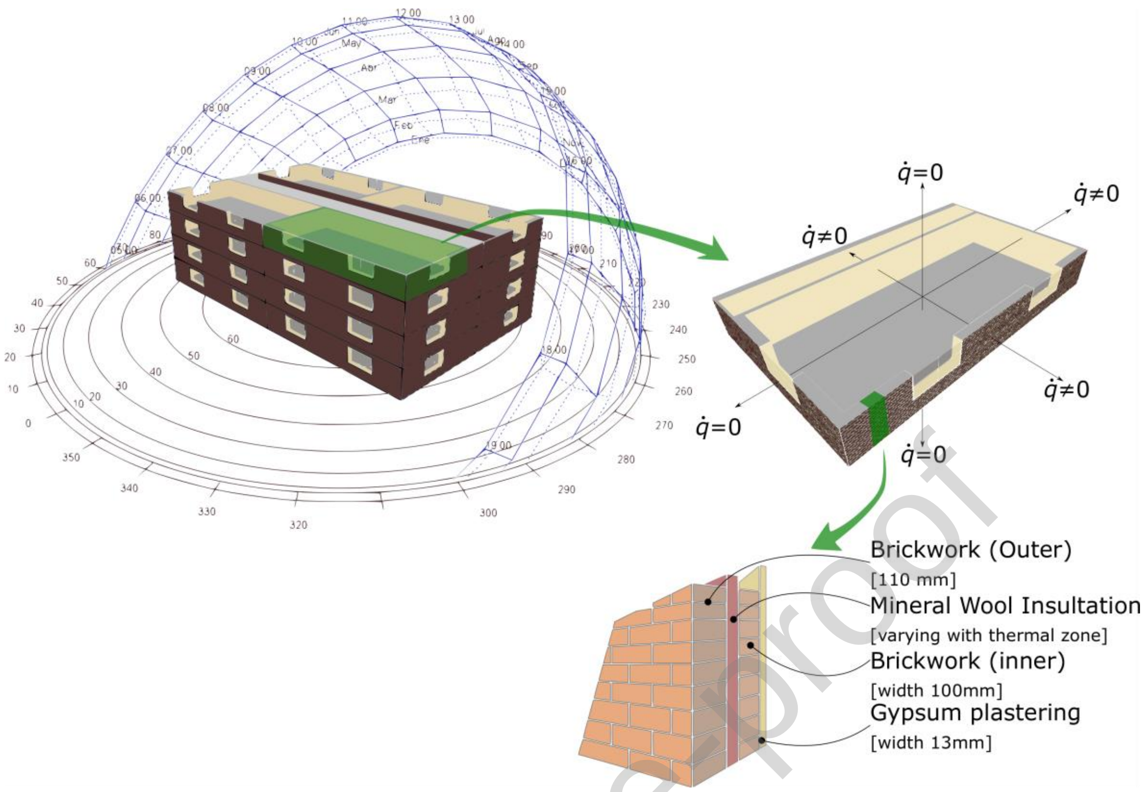

Figure 2. Overall building plant of the analyzed space and envelope cross section.

2.2. Building operation

Regarding the building operation, occupancy schedules and HVAC operating program were varied with the aim of showing the differences between non-residential (NRBs) (Figure 3a) and residential buildings (RBs) (Figure 3b). Although both cases were set at same indoor thermal comfort benchmarks, occupants are not passive participants in buildings and several authors have worldwide highlighted their effect on energy consumption (e.g. accessible enclosures such as windows, lighting control, thermostat set points, electrical appliances, etc.) for both RB [23,33] and NRB [34,35]. Nevertheless, internal gains such as electronic devices (i.e. 13 W m^{-2}, radiant fraction 20 %), lighting systems (i.e. 5 W m^{-2}, radiant fraction 42 %), gas stove for cooking (i.e. 13 W m^{-}

[2], radiant fraction 20 %) have been assumed to work on as it is shown in Figures 2 and 3. Besides, while in both cases other electrical supplies might be permanently switched, 1 W m^{-2} with a radiant fraction of 20 % has been added as permanent internal load. It must be noted that for NRBs, holidays will be closed (Fig. 4b).

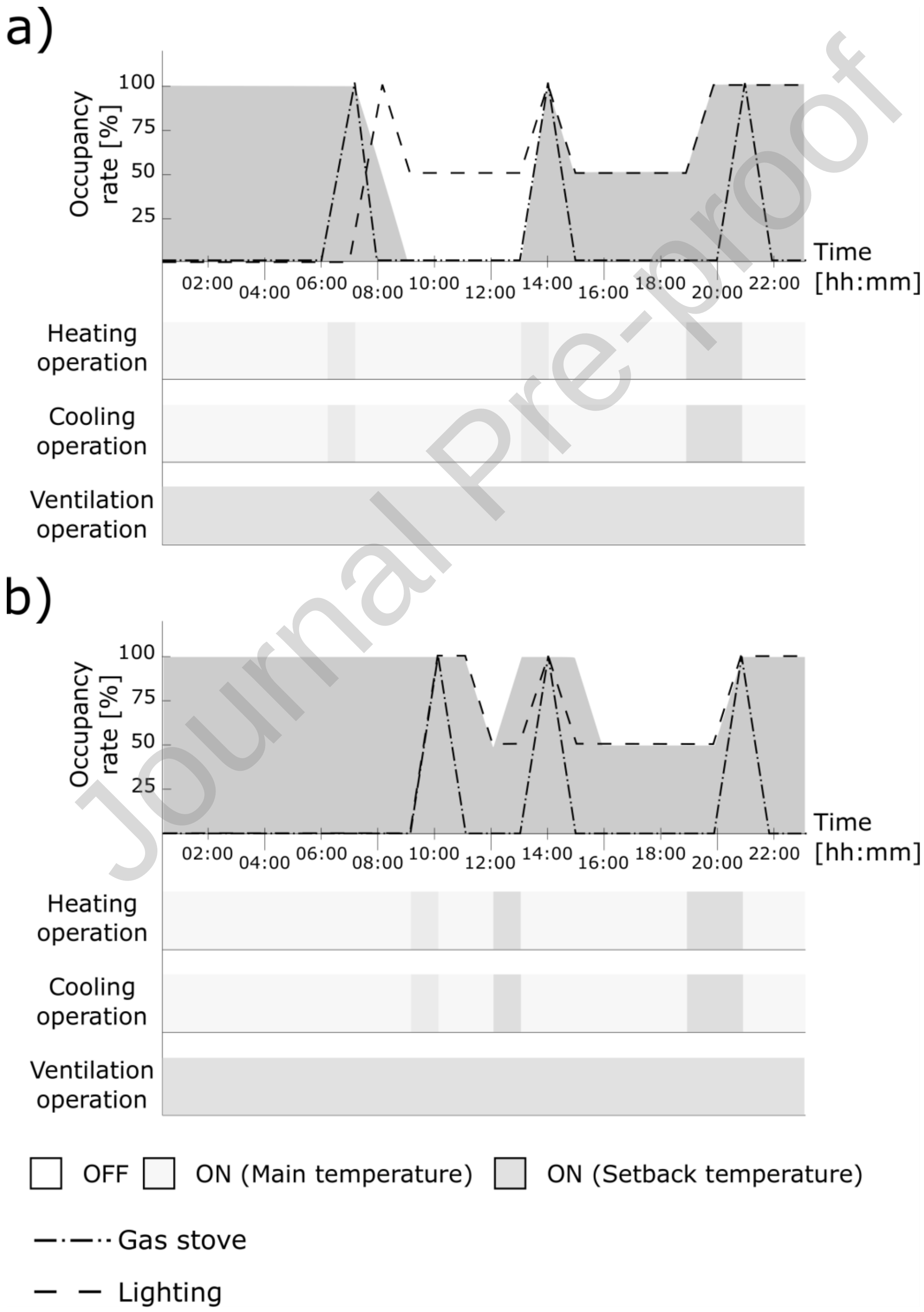

Figure 3. Operational schedules for occupancy and HVAC systems for RBs in labor days (a) and holidays (b).

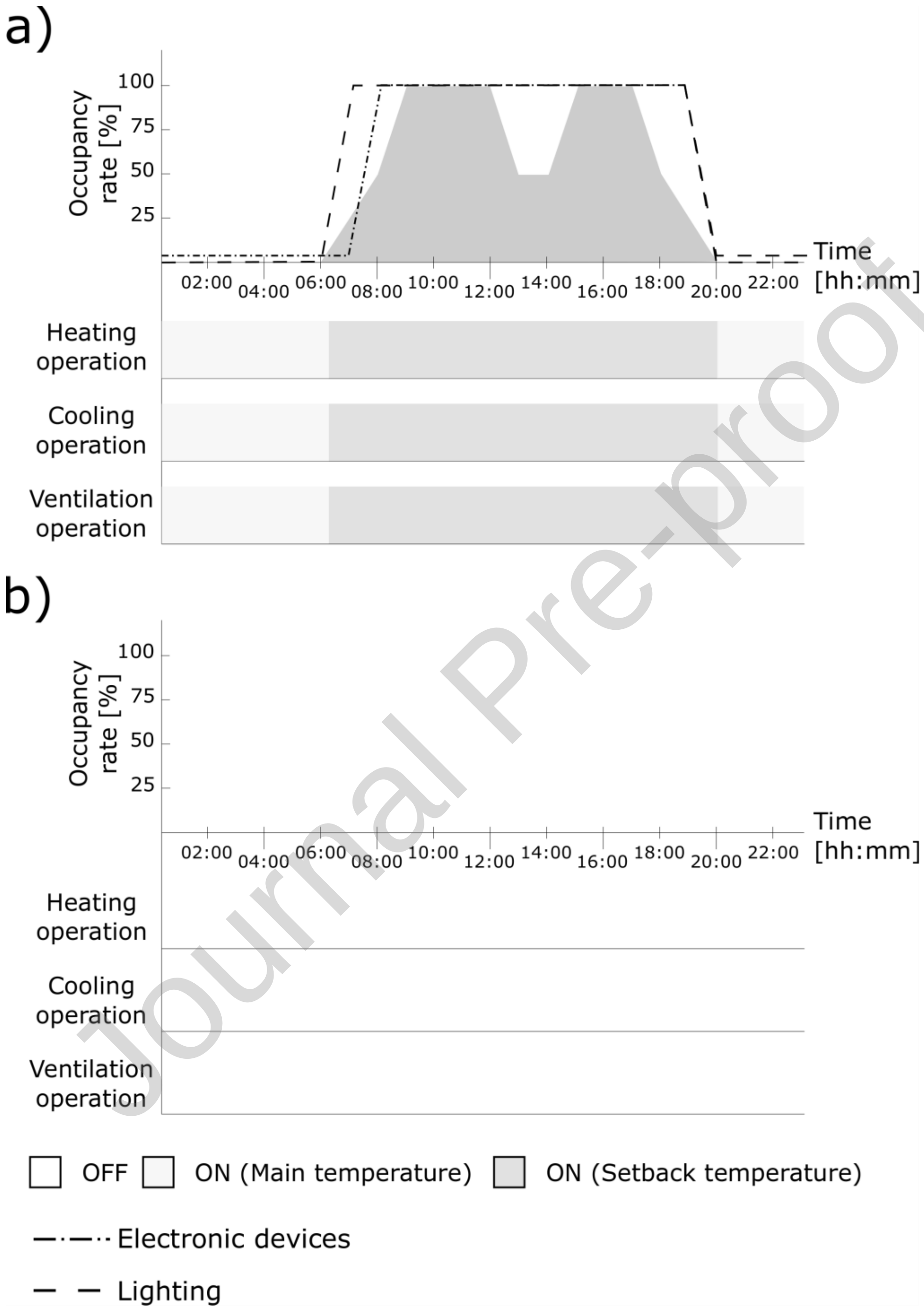

Figure 4. Operational schedules for occupancy and HVAC systems for NRBs in labor days (a) and holidays (b).

Moreover, by depending on the building end use, the standards compliance requires different air quality thresholds which highly influence thermal performance, as well. Therefore, CTE-DB-HS states a permanent ventilation for RBs while for tertiary sector, both the occupancy intensity and the type of activity determine mandatory renovations rates. Thus, for the non-residential scenario, at maximum occupancy (i.e. 40 persons), the renovation is set at 4 times per hour [36] while, in case of RBs (i.e. 5 persons) ventilation is continuously working at 1.0 renovation per hour [37]. In addition these air flows are added to the air provided by infiltrations through envelopes which is set at 0.7 renovation per hour along the day [38].

Regarding heating and cooling operation, main temperatures were set at 22 ºC and 24 ºC, respectively while setback temperatures were set at 15 ºC and 28 ºC for heating and cooling, respectively. It must be noted that main temperatures correspond to the setting of the thermostat during occupancy and setback temperatures defines the limits during non-occupied periods. Some buildings require a low level of heating during unoccupied periods to avoid condensation/frost damage or to prevent the building becoming too cold and to reduce peak heating requirements at startup. Results did not take into account primary energy and only report the final energy demanded at each case and scenario.

Heating and cooling energy data are calculated on an hourly basis over a period of 1 year, using recorded weather data appropriate for each location.

The output reports the overall quantity of heating and cooling energy that would be required to maintain conditions within the building to the assigned comfort zone. Besides, the total time during thermal comfort is not achieved has been calculated in accordance with ASHRAE 55 [39].

Finally it must be noted that building orientation plays a major role in the overall energy performance due to the received solar irradiation. Therefore, all cases have been calculated by rotating the model orientation from the south to the north face.

3. Results and discussion

The reported percentages must be understood as the average variation in energy consumption and thermal discomfort achieved by increasing SHC. In all cases, energy performance is improved by increasing SHC. Similar findings were provided by previous authors which pointed out the importance of SHC for moderate climates of Southern Europe and the Mediterranean area where thermal inertia can work as a stabilizing factor of the thermal dynamics of the whole building system [40].

However, in view of the results, the saving rates derived from cooling demands can be neglected in all scenarios (i.e. RBs and NRBs) and thermal zones (i.e. from A to E) ranging from 0 % to 3.5 % (Figure 5). Results are in agreement with previous authors which showed that the effect depends on climate and is less pronounced in the case of large solar gain and diurnal temperature differences [41]. This low impact can be also explained due to the lack of passive cooling strategies such as free cooling during the summer period or the incorporation of shadings on the windows, among others [42,43]. Conversely, the savings rates related to heating consumption are positively influenced by SHC in all cases (Figure 6), especially for hot and dry climatic zone where the continental climatic effects are dominant, as it has been stated by previous authors [44].

Thus, an average of 10.8 % (std.dev. 3.7 %) can be saved in the case of NRBs while lower savings can be expected in the case of RBs. In spite of the warmest Spanish region (i.e. thermal zones A and B) showed energy savings ranging from 4 % to 7 %, it must be considered that low absolute values (i.e. below 8 kWh m^{-2}) lead to virtually increase the value for carried out percentages. For instance, Canary Islands (i.e. SCT and LPC) shows mild and stable winters which reduce the energy required for heating to zero, regardless of the SHC value chosen or whether the building is intended for RB or NRB.

Despite this conflict of values, the increasing of SHC has been proved to important savings into a low solar radiation and cold climatic context, in accordance with previous authors [45].

Moreover, thermal zones with harsher winters are also unable to take full advantage of SHC. Low occupancy rates and the operational schedule of internal heat sources (i.e. lights, gas stoves and electrical appliances) lead to minimize the thermal buffering effect. Hence, these energy saving rates should be considered as reference thresholds, since the inclusion of passive strategies would obviously lead to higher values. Nevertheless, similar results were showed by previous authors for RBs located in cold winter climates which could save up to 10% of heating demands [46].

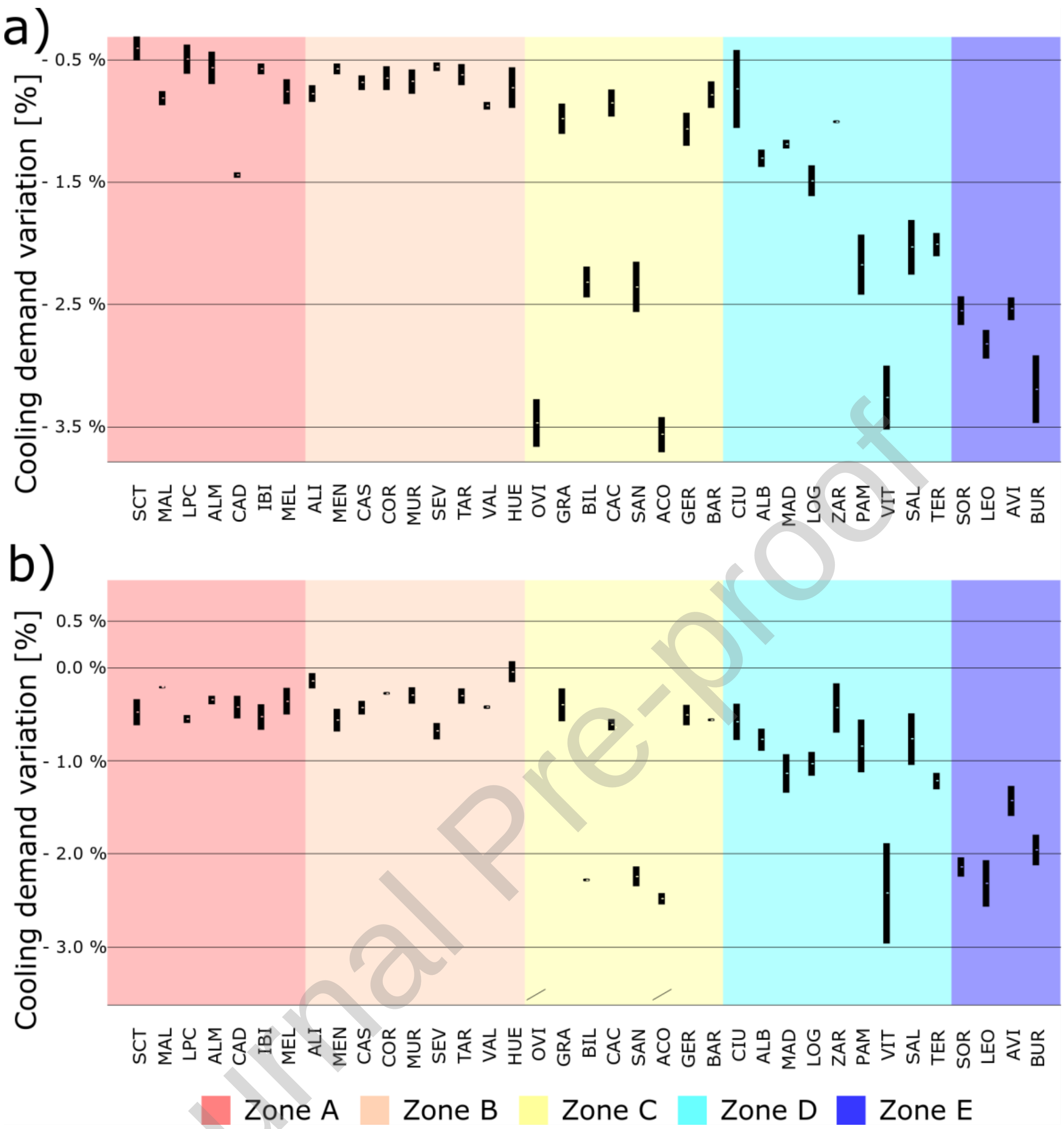

Figure 5. Energy consumption savings rates for cooling in a) NRBs and b) RBs.

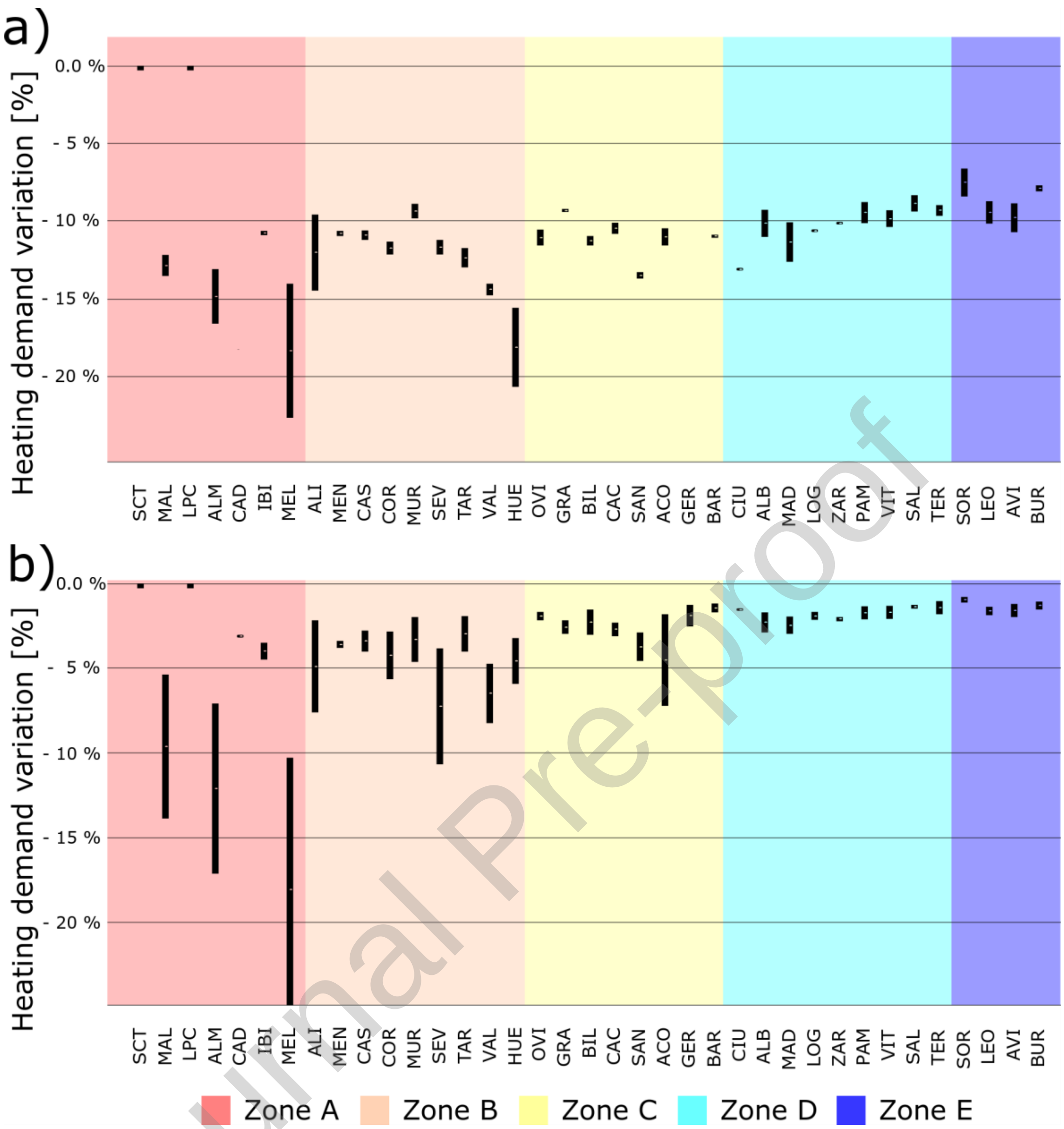

Figure 6. Energy consumption savings rates for heating in a) NRBs and b) RBs.

Thermal discomfort occurs when temperatures do not meet acceptable thermal environmental specifications for occupied spaces. Thus, envelopes with higher SHC incorporate a damping effect on temperature variation which allows HVAC systems to act more efficiently and prevent the temperature from leaving the thermal comfort ranges. Thus, an increase of SHC also reduces thermal discomfort (Figure 7). The effect is especially highlighted in NRBs, located in cold regions (i.e. thermal zones C, D and E), since the internal gains are buffered by envelopes. This stored heat leads to reduce thermal discomfort by an average of 20 % in NRBs, while this rate is highly reduced in those buildings located in warmer regions (i.e. an average of 2.7 %, standard deviation of 3.5). On the other hand, these percentages are highly reduced in the case of RBs and, in some cases, thermal comfort is even worsened by increasing SHC. The problem is related to the occupancy schedule. While NRBs commonly require a constant HVAC operation during opening hours, in case of RBs, the HVAC system commonly operates according to the occupancy schedule.

This lack of continuity, in terms of HVAC operation, implies that higher SHC reduces temperature variation rates which might lead to set operational temperature out of the thermal comfort ranges, since thermal energy is used for varying material´s temperature instead of air temperature. For instance, although temperature variation are damped by increasing SHC, the removal of overheat might be also hindered in some cases, as it is highlighted in Figure 8. These findings are in accordance with previous authors which demonstrated that the effect of SHC is more pronounced when HVAC systems operate in a more continuous way [47].

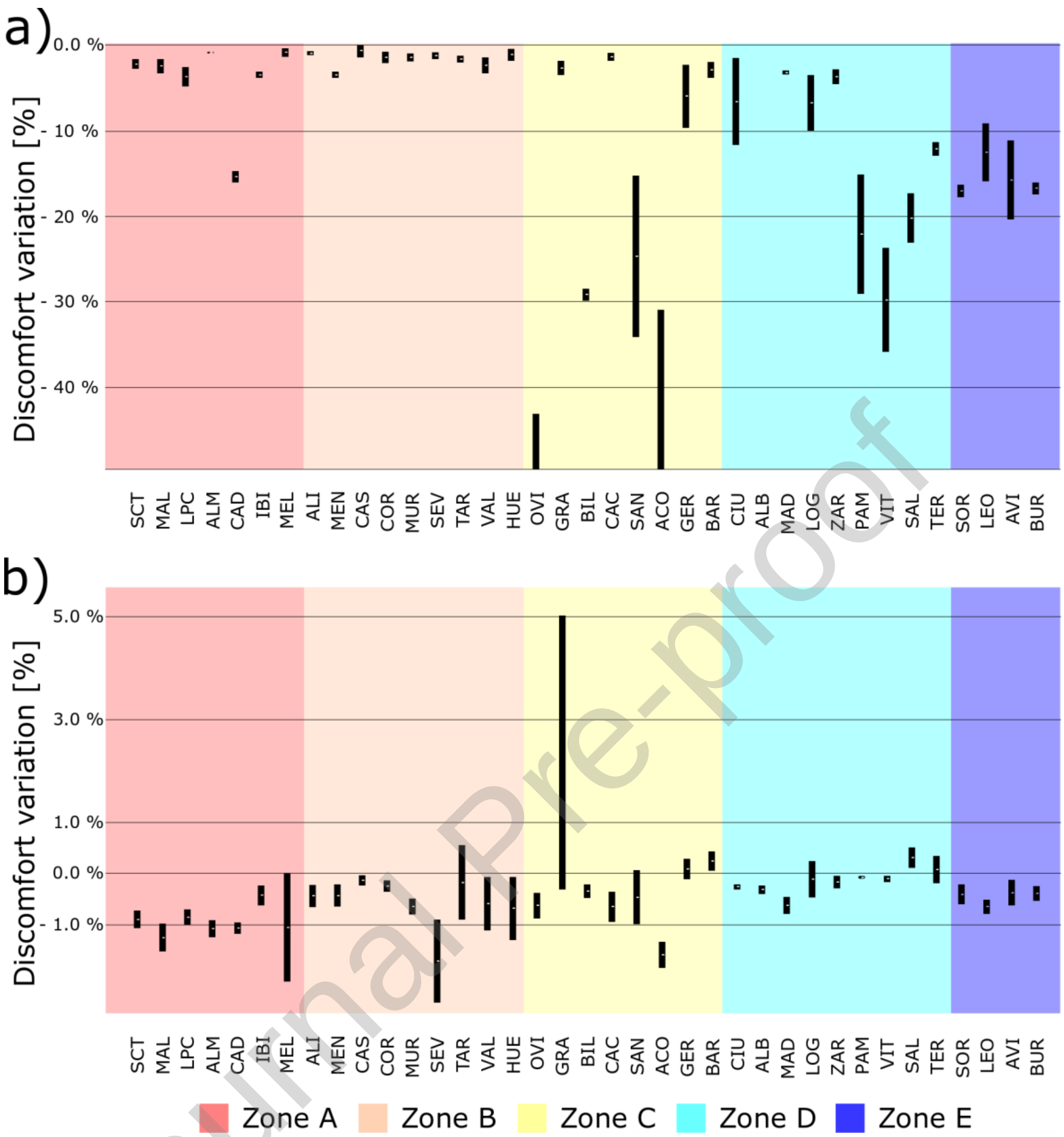

Figure 7. Thermal discomfort variation rates for a) NRBs and b) RBs.

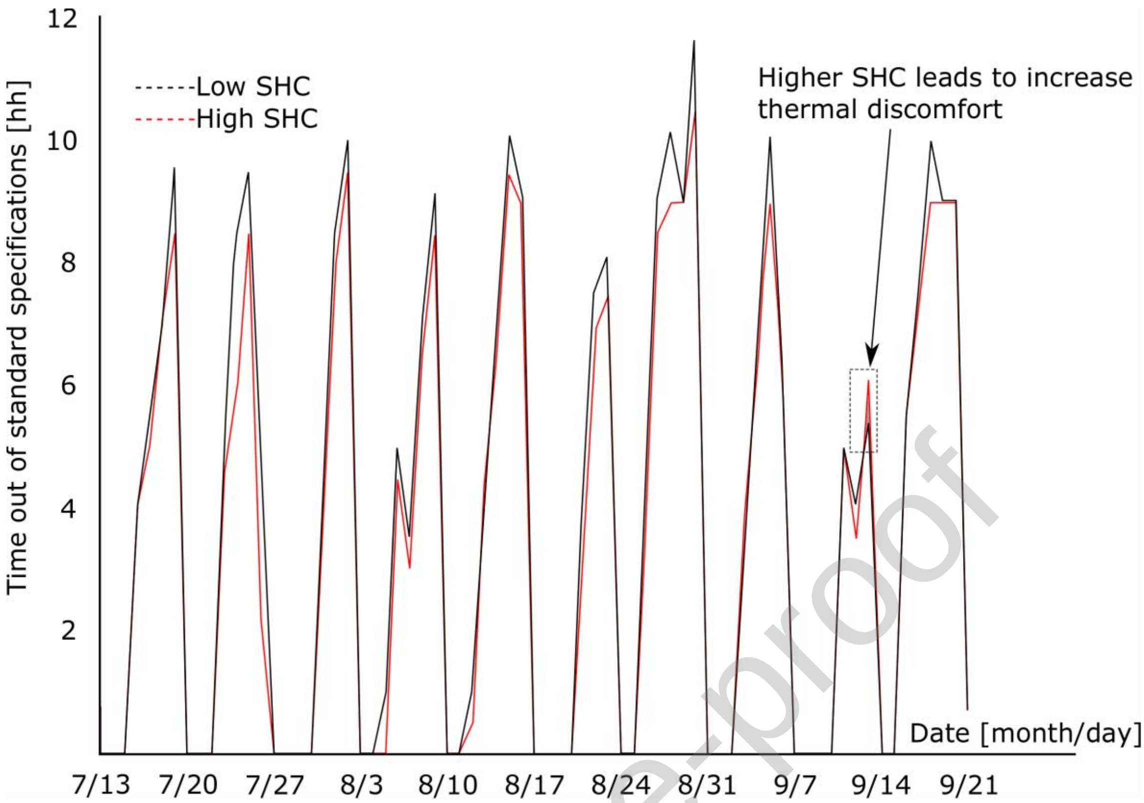

Figure 8. Example of thermal discomfort variation during summer for a NRBs located in SAN.

4. Conclusions

As it has been demonstrated, the role of specific heat capacity cannot be underestimated since it contributes to reducing energy consumption and to improve thermal comfort in all cases, regardless of both location and building type.

In terms of heating demands, thermal capacity was relevant for colder regions (i.e. Spanish thermal zone D and E) where it can work as a stabilizing factor of the thermal dynamics of the whole building system. In case of desert and semi desert climate, these thermal zones (i.e. A, B and C) showed small number of heating degree days which led to increase saving rates when SHC was increased. Internal gains are stored by envelopes and, in some cases, completely avoid annual heating requirements. Related to building type, since the continuous operation of HVAC increases the effect of SHC, NRB show higher savings than RB, for equal thermal zone.

SHC also impacts on cooling demands but the effect is much lower. In this case, saving rates range from 0.5 to 3.5 % for NRBs while RB may reach savings up to 3 %. However, for locations with small diurnal temperature swings, the storage of the heat from the room (i.e. internal loads or solar gains through the windows) can slightly increase energy consumption of cooling system.

High values of SHC result on small indoor temperature variations which has also a positive influence on thermal comfort. The effect is much more significant in case of NRBs which shows more continuous occupation schedule.

Since the calculations did not take into account passive heating and/or cooling strategies (i.e. nighttime ventilation, precooling during off-peak hours, Trombe walls, etc.), the carried out results should be considered as minimums for guiding designers and policy makers.

Finally, it is concluded that building codes must be updated in order to include benchmarks related to SHC which should be influenced by climate and building type.

Added to these conclusions regarding the stated goals, this study has also highlighted the scarcity of available data related to the specific heat capacity of new materials. The incorporation of such thresholds in the building codes would lead researches to report SHC within the assessment of new building and construction materials.

Appendix A

A.1. Conduction through the walls by Conduction Transfer Functions (CTF)

The basic method used in EnergyPlus for conduction transfer function (CTF) calculations is known as the state space method defined by the following linear matrix equations:

$$\frac{d[x]}{dt} = [A][x] + [B][u]$$

$$[y] = [C][x] + [D][u]$$

Where:

x is a vector of n-state variables

u is a vector of inputs

y is the output vector

t is time

A constant coefficient matrix of n x n dimensions.

B constant coefficient matrix of n x p dimensions.

C constant coefficient matrix of m x n dimensions.

D constant coefficient matrix of m x p dimensions.

Enclosures were formed by several layers which were individually defined by four parameters (i.e. thickness, conductivity, density, and specific heat). For these materials, EnergyPlus divides each material layer within a construction into between 6 and 18 nodes for the application of the state-space method. Nodes are also placed at the interface between two layers. These interface nodes consist of half a node of the first layer and half a node of the second layer.

Through the use of matrix algebra, the vector of state variables (x) can be eliminated from the system of equations, and the output vector (y) can be related directly to the input vector (u) and time histories of the input and output vectors.

This formulation can be used to solve the transient heat conduction equation by enforcing a finite difference grid over the various layers in the building element being analyzed. In this case, the state variables are the nodal temperatures, the environmental temperatures (interior and exterior) are the inputs, and the resulting heat fluxes at both surfaces are the outputs. Thus, the state space representation with finite difference variables would take the following form:

$$\frac{d\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix}}{dt} = [A]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [B]\begin{bmatrix} T_i \\ T_o \end{bmatrix}$$

$$\begin{bmatrix} q"_i \\ q"_o \end{bmatrix} = [C]\begin{bmatrix} T_1 \\ \vdots \\ T_n \end{bmatrix} + [D]\begin{bmatrix} T_i \\ T_o \end{bmatrix}$$

where T_1, T_2, ..., T_n are the finite difference nodal temperatures, n is the number of nodes, T_i and To are the interior and exterior environmental temperatures, and $q"_i$ and $q"_o$ are the heat fluxes (desired output).

In contrast to Laplace's method, the so called state space method, avoids searching roots and allows the treatment of multidimensional heat conduction which overcomes the lack of accuracy of Laplace's method due to these issues. See more details in [48,49].

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Highlights

- *"Building codes do not pay attention to the specific heat capacity of building materials"*
- *"Specific heat capacity plays an important role in terms of heat storage and highly impact on building energy consumption"*
- *"Residential and non-residential building have been modelled by varying the specific heat capacity of envelopes"*
- *"Regardless building orientation and location, higher specific heat capacity leads to lower energy consumption"*
- *"By increasing specific heat capacity, thermal discomfort is improved in all cases, in particular for non-residential buildings"*