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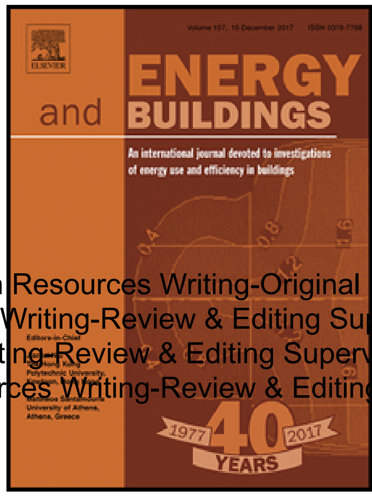

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PII: S0378-7788(19)32373-4
DOI: https://doi.org/10.1016/j.enbuild.2019.109704
Reference: ENB 109704

To appear in: *Energy & Buildings*

Received date: 30 July 2019
Revised date: 27 November 2019
Accepted date: 14 December 2019

Please cite this article as: Rui Oliveira Conceptualization Methodology Formal Analysis Investigation Resources Wr
António Figueiredo Conceptualization Methodology Validation Resources Writing-Review & Editing Supervision ,
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Impact of unoccupied flats on the thermal discomfort and energy demand: case of a multi-residential building, *Energy & Buildings* (2019), doi: https://doi.org/10.1016/j.enbuild.2019.109704

Impact of unoccupied flats on the thermal discomfort and energy demand: case of a multi-residential building

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Abstract. Energy consumption and indoor thermal comfort are two major issues that always come into play in any building retrofit. Furthermore, if the impact of user behaviour and their social activities in buildings must be taken into consideration when defining renovation strategies, the importance of occupancy can also be very important for the performance of the building. This subject is of special relevance in the context of social housing, where the number of unoccupied flats is sometimes quite expressive due to their temporary and intermittent use. A multi-residential social housing neighbourhood was used as a case study to assess the impact of occupancy of different flats on the overall energy savings and indoor thermal comfort of the building. The indoor environment (air temperature and relative humidity), the envelope airtightness (blower door test) of occupied and unoccupied flats and the tenants' habits were assessed during 7 weeks. The exterior weather data was collected from a local weather station. This data was used to calibrate a numerical model created with EnergyPlus software. The model was used for a sensitivity analysis where the importance of occupancy was evaluated. The occupied and unoccupied flats position (under, over and adjacent) within the building was changed, to assess the impact on the indoor thermal comfort of the occupied flats (according to EN 15251). The results confirmed the importance of occupancy as a decrease of the thermal discomfort rate up to 34.3% for the winter period and an increase up to 85.3% in the summer period were found.

Keywords: thermal discomfort, energy demand, occupied and unoccupied flats, internal heat gains, dynamic building simulation.

1. Introduction

Existing building stock mainly from the 1970s, '80s and '90s are the least energy-efficient and represent the largest share of the building stock in Europe and the most potential for energy refurbishment. The energy consumption trend of the built environment in the next 50 years will be mainly ruled by the existing older building stock and their rate of refurbishment and renewal over time. Some predictions point out that, without a significant change of practice, the non-retrofitted building stock is estimated to represent around 80% of the total energy consumption by 2050 [1]. However, new challenges and support programs have emerged across Europe [2–4] focusing on the integration of renewable energy sources into the existing and new building technology.

The massive construction of new buildings and infrastructures has heavily decreased in the last decade, giving priority to the rehabilitation of existing buildings and built heritage. In this scope, social housing complexes have been a target since plays an important role in society, aiming to provide dwellings to low-income families, either for renting or purchasing. This housing typology is unfortunately also associated with low-cost buildings solutions and materials, as well as to poor execution and workmanship. This condition contradicts the fact that energy-efficient constructions require higher construction expenditure to provide reasonable living and comfort conditions [5].

The world's population is becoming increasingly urban, leading to an alarming environmental disorder associated with urban settlements. Thus, one of the major problems, that aggravates this disorder, is related with the increasing buildings energy demand, a consequence of the increasing quality of life standards and human habits [6]. The lifestyle of the occupants of social housing and their educational level could be an obstacle for the acceptance of energy-saving practices or to invest in more efficient systems to provide thermal comfort [7]. This issue is a worthwhile complex challenge, with direct influence on the energy consumption of buildings and on the indoor thermal comfort conditions [8].

The effect of occupant behaviour on buildings energy demand has been a topic of interested among the scientific community. Emery and Kippenhan (2006) [9] conducted a long-term survey (15 years) of energy measurements in residential buildings. Their findings indicate that different lifestyles led to distinctive energy consumptions, even in very similar buildings. Martinaitis et al. (2017) [10] research focuses on the occupant's influence in the energy demand of a residential building, using the building energy model (BEM) software DesignBuilder to simulate different scenarios of occupancy, combined with other input parameters, and comparing the results with the default occupancy schedules, a difference range of 14 to 21% was observed for a two-occupants scenario, while for four-occupants situation the difference never exceeded 5% [10]. In fact, occupant behaviour is pointed as the main driving factor for the buildings energy performance gap. Calì et al. (2016) [11] demonstrated that the real energy consumption of a refurbished building can be 41 to 117% greater than the estimated in the design stage.

According to Haldi and Robinson (2011) [12] besides acknowledging that the occupant behaviour has a significant impact not only in the heating and cooling demand, the internal gains due to lighting and appliances are in cases considerable. Additionally, the authors found that one of the causes is the occupants' adaptations to restore their thermal comfort, for instance through the window opening and operating the shading devices.

In the scope of social housing buildings, some studies has been carried out to evaluate the impact of occupant behaviour on thermal comfort, energy demand and the indoor air quality. Most of these studies focused on the occupants' actions, such as window operation and shading.

As reported by Curado et al. (2015) [13], thermal comfort is highly influenced by the occupation, especially in mild climates context. Their findings were based on a large monitoring campaign in which the performance of 24 social housing buildings was evaluated according to the adaptive model presented in standard EN 15251 [14]. In the scope of this study, results were analysed searching for indoor hygrothermal patterns through clusterization and the importance of users and their behaviour was once again exposed [15].

Guerra-Santin et al. (2018) [16] applied different models of occupant behaviour as input parameters in building simulations, aiming to reduce the uncertainty in the energy consumption. Their findings indicate a difference between the lowest and the highest heating demand of around 34%.

Multi-residential social housing is inevitably linked to the inconstant rate of occupied versus unoccupied flats due to provisional housing solutions, social problems, the constant moving of residents, flats degradation and vandalism problems. Thus, social housing buildings constitute good case studies if one intends to assess the impact of different occupation conditions on the building thermal performance.

In this context, this work aims to assess the impact of different occupation scenarios, considering the thermal comfort and energy demand of a multi-residential social housing building in Aveiro, Portugal. The study provides useful information on the impact of unoccupied flats in mild climates and in the social housing context. Using a real building as case study strengthens the conclusions.

2. Methods

A BEM was created using EnergyPlus (EP) and calibrated resourcing to monitoring data collected in-situ.

An extensive survey was performed to collect all the geometric and constructive data required to build the model. Thermo-hygrometer sensors were used to record the air temperature and relative humidity inside the flats and several Blower Door tests were carried out to assess the airtightness of the flats. The in-situ survey included the envelope characterisation through boreholes and thermal imaging to identify the constitution of the building solutions (material layers and thickness).

The data collected was used for the calibration of the BEM, by using a hybrid evolutionary algorithm to instruct the engine calculation software (EP).The calibration of the BEM was achieved using the hybrid evolutionary algorithm to minimise the deviation of the Root Mean Squared Error (RMSE) between the measured and the simulated indoor air temperature, suiting pre-established uncertain input parameters (design variables). The accuracy of the BEM was assessed by the goodness of fit (GOF) and the Coefficient of Variation of the Root Mean Squared Error (CV RMSE) hourly criteria, according to the methodology proposed in other studies [17,18]. The criteria (or the limit values) were defined by the following standards: (i) American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) guideline 14 [19], (ii) the International Performance Measurement and Verification Protocol (IPMVP) [20] and (iii) the Federal Energy Management Program (FEMP) [21]. The strategy used to calibrate the model consists of achieving the best match between measured and simulated indoor air temperatures, previously tested and validated by the author [17]. The assumption of standardised statistical indexes was proposed by the authors in reference [22] to represent the performance of a model defined in references [22–24].

A sensitivity analysis was carried out, using dynamic simulation resourcing to EP tool for energy demand and thermal comfort assessment. The thermal comfort and energy demand analysis was carried out following the methodology defined by standard EN 15251 [14] and divided in two phases: Phase I – all flats occupied; and Phase II – different of scenarios occupation (see section 6.1).

The methodology is schematically depicted in Figure 1.

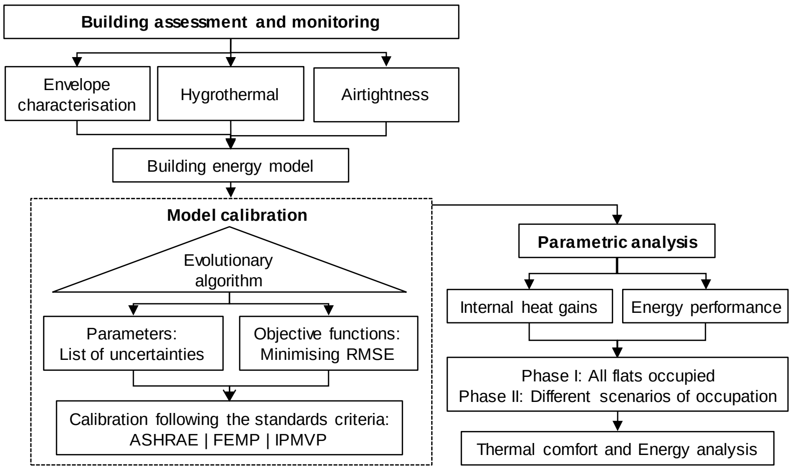


Figure 1. Methodology: monitoring, model calibration and sensitivity analysis.

3. Case study

3.1. Multi-residential social housing neighbourhood: building 31

The case study is located in Aveiro, Portugal and was built in 1991 (Figure 2a). The building under study (nr. 31) (highlighted in Figure 2) is part of a large neighbourhood composed of 788 flat units, distributed in 38 multi-residential buildings.

Figure 2. Case study: a) plan view of the neighbourhood with the identification of the case study; b) exterior front view and c) exterior back view.

The building under study is composed of 4 identical stories. Each storey is composed of 6 flats, including T2 (two rooms) and T3 (three rooms) typologies. Figure 3 shows the floor plan of the storey. The flats are composed by hall, kitchen, living/dining room, balcony (open or closed), bedrooms and bathrooms according to their typology. The stories are disposed symmetrically with a T-shape geometry. The main entrance of the building is west oriented.

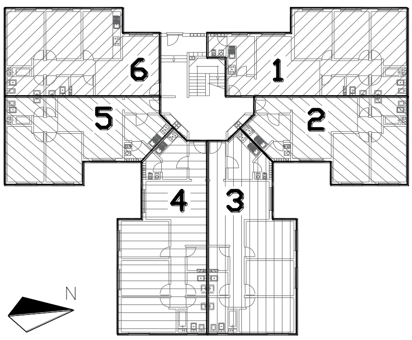


Figure 3. Geometry of the representative floor of building (without scale).

The building has a volume of 5403.6 m^3, a treated floor area of 1604.4 m^2 and an untreated floor area of 209.4 m^2 corresponding to the entrance and staircase, which are isolated from the flats and therefore were not considered as a treated floor area and are not assessed for thermal comfort.

Table 1 presents the building window-to-wall ratio of the conditioned areas. The largest glazed surfaces are west-oriented (24%) and the overall window-to-wall ratio is 17%

Table 1. Opaque and glazing surfaces and window-to-wall ratio.

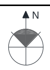
Surfaces type					Total
Opaque (m^2)	151.0	280.9	279.8	265.9	977.5
Glazing (m^2)	20.7	56.0	23.9	65.1	165.7
Window-to-wall ratio (%)	14	20.0	9	24	17

Table 2 presents the geometric characteristics of 6 flats of each storey.

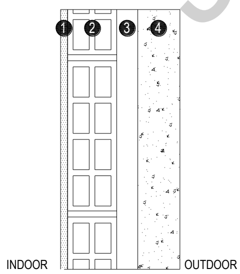
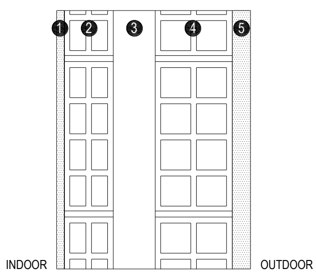
Table 2. Geometric characteristics of the flats.

Flat	Typology	TFA (m^2)	Volume (m^3)	Opaque ext. (m^2)	Glazing (m^2)
1	T3	76.8	192.0	28.2	8.6
2	T2	59.8	149.4	19.7	5.5
3	T3	79.1	197.6	40.87	7.7
4	T3	79.1	197.6	40.87	7.7
5	T2	60.3	150.8	35.25	5.9
6	T3	79.4	198.4	43.67	9.0

TFA: treated floor area

3.2. Envelope characterisation

The construction consists of a mixed system of laminated walls and lightened slabs, which is described in the original design as “optimising time and cost of construction”. A comprehensive in-situ survey was performed for the characterisation of constructive solutions. The façades are composed of prefabricated panels, except the exterior walls of the ground floor, which are constituted by double brick masonry. The prefabricated panels in the zone of the glazing areas incorporate the sill and the roller-shutter box. All the windows are single glazed with a steel frame. The roller-shutter box is located above the window, directly connected to the interior, thus, is a potential area for unintended air infiltration. The horizontal constructive solutions consist of a lightened concrete slab on the ground floor, which supports prefabricated panels; the internal floors and the roof structure are composed by a lightened concrete slab, however, in the upper side of the roof there is a highly ventilated crawl space. The constructive solutions are described in Figure 4.

Prefabricated external wall panels	Double brick masonry
 U_{value} = 1.73 W/(m^2.°C) ① Cement plaster 1.0cm ② Brick masonry 7.0cm ③ Air cavity 3.0cm ④ Prefabricated panel 6.0cm	 U_{value} = 1.19 W/(m^2.°C) ① Cement plaster 1.0cm ② Brick masonry 7.0cm ③ Air cavity 6.0cm ④ Brick masonry 11.0cm
Concrete wall with exterior thermal insulation	Window with roller-shutter box

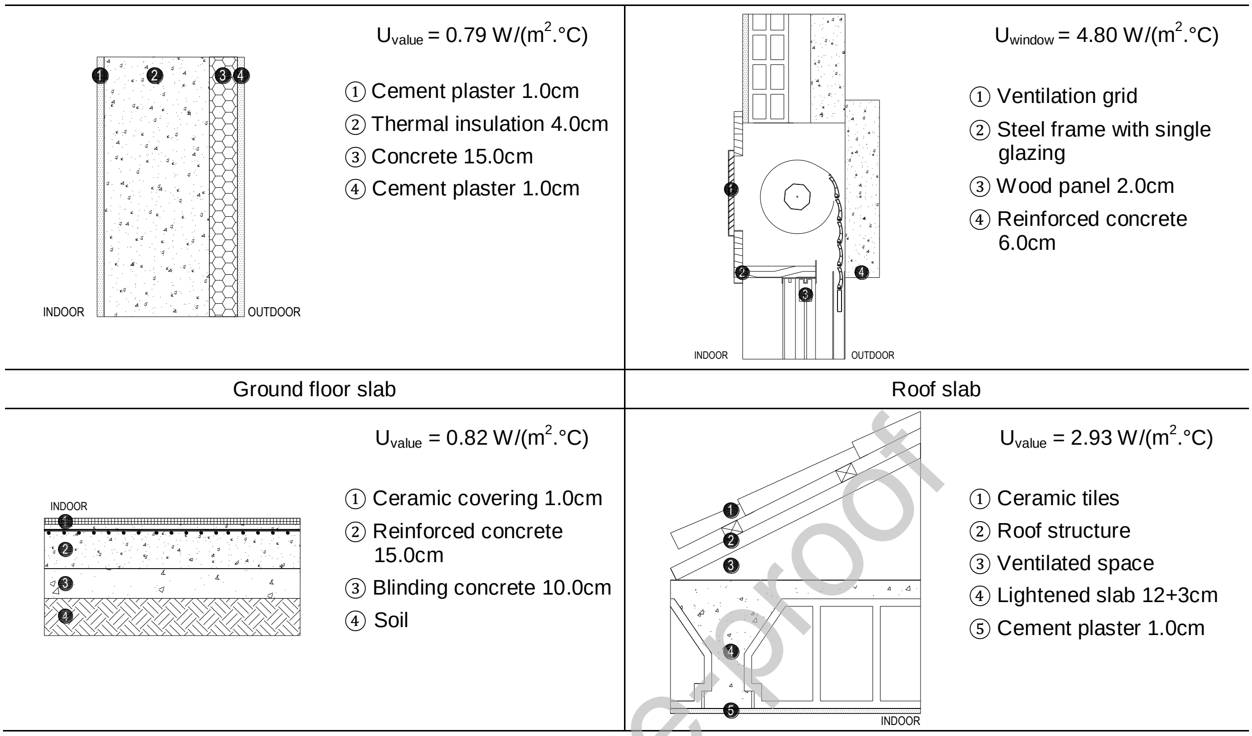


Figure 4. Constructive solutions (without scale).

4. Hygrothermal monitoring and airtightness assessment

The results of the monitoring of the flats are essential to calibrate a numerical model.

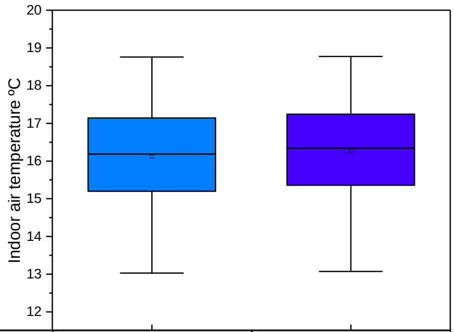
For the monitoring assessment, each flat was divided into two thermal zones (TZ): TZ01, includes the bedrooms, the living room and the toilets; and TZ02, includes the kitchen and the balcony. The thermal zones definition was defined according to the similarity of hygrothermal conditions identified in the preliminary measurements of the flats. The monitoring was carried out in 7 unoccupied flats of the building, located in different floors and with different solar exposure (flats 1 to 6 – see Figure 3).

The sensors were placed in each thermal zone, ensuring a continuous record of the air temperature and relative humidity. The position of the sensors inside the rooms was defined in order to avoid direct sun exposure from the glazed areas in accordance with ISO 7726 [25]. The monitoring acquisition system is logged at 10 minutes intervals and averaged hourly, with a precision of ±0.30 ºC and ±2.0%, and a resolution of 0.01 °C and 0.01%, for temperature and relative humidity, respectively. The thermo-hygrometer sensors were installed in seven unoccupied flats.

The exterior weather data was collected from a local weather station, located 500 m away from the social housing neighbourhood. Air temperature, relative humidity, global horizontal solar radiance and wind speed and direction were registered and collected with a time step of 10 min.

Figure 5 shows the mean air temperature of the two thermal zones of the unoccupied flats during the monitoring period. A similar tendency on both TZ01 and TZ2 can be observed, with a mean air temperature of around 16 ºC. The minimum air temperature was, approximately, 13 ºC and the maximum was 19 ºC.

The monitoring was only carried out during the winter, since this region has a mild summer and thus the biggest concerns are related to underheating. The flats were monitored from the 07 February 2017 to 24 March 2017.



Thermal Zone	TZ1	TZ2
Mean	16.12	16.26
Min	13.03	13.07
Max	18.76	18.77

Figure 5. Mean air temperature monitoring results of TZ01 and TZ02 of unoccupied flats.

The airtightness assessment of flats was performed with a Blower Door apparatus. The tests were conducted with a Retrotec 1000 Blower Door system, following the methodology proposed by EN 13829:2006 [26] and ISO 9972:2006 [27] with a flow precision of ±3.0 %, a maximum flow at 50 Pa of 10.19 m^3/h and a pressure accuracy of ±1 Pa. The flats envelopes were assessed according to EN 13829:2006 [26], using the procedure described as Method 1 [27]. All the openings, in bathrooms and bedrooms, were remaining opened as well as the smoke extractors. All the windows in the flats were closed and all the interior doors were left open during the tests.

The calculated ACH_{50} (air change rate at a pressure difference of 50 Pa) corresponds to the mean value between the pressurisation and the depressurisation test. The seven flats were tested and the mean value attained was 7.50 h^{-1} (see Figure 6). Similar results were already reported by other authors also in social housing context studies [28].

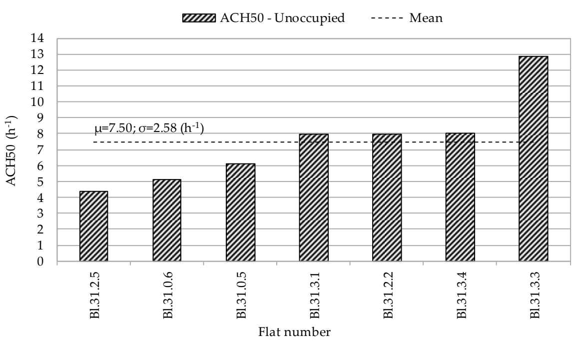


Figure 6. ACH_{50} values, mean and standard deviation of the unoccupied flats.

5. Model calibration

5.1. Local climate data

The exterior climate data was collected from a local weather station and it was used in the BEM for calibration purposes. The data used in the model calibration is shown in Figure 7 and Figure 8. Figure 7 shows the outdoor air temperature and relative humidity for the monitoring period.

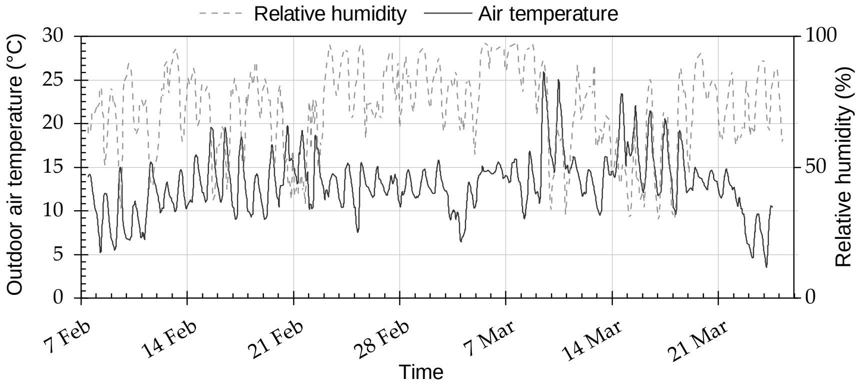


Figure 7. Outdoor air temperature and relative humidity for the monitoring period.

Figure 8 shows the direct and diffuse irradiance converted from the monitored global horizontal solar radiance, using the operational model developed by Cipriano et al. [29] and programmed in CitySim software.

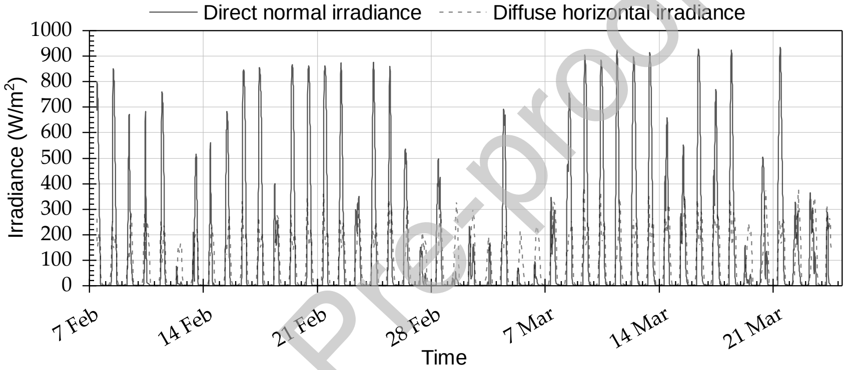


Figure 8. Direct normal and diffuse horizontal irradiance data for the monitoring period.

5.2. Numerical model definition

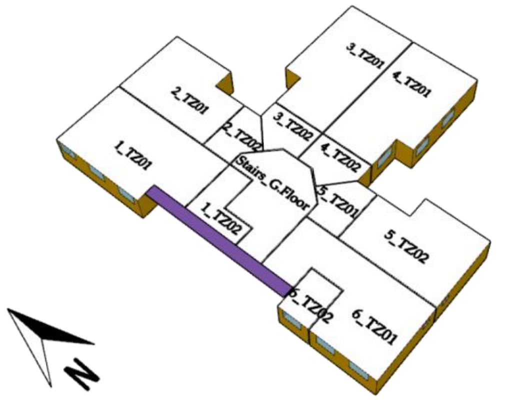
A geometrical model was created in OpenStudio to be simulated in EP software. Figure 9 presents the West and East views of the BEM defined through the SketchUp and OpenStudio plug-in. The exterior building surroundings, namely the presence of constraints and adjacent buildings were included in the BEM as shading surfaces (purple surfaces).

a) b)

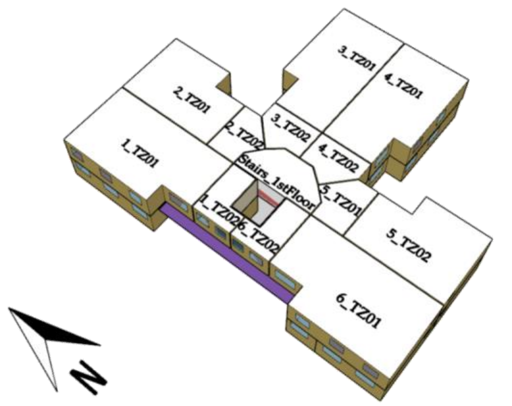
Figure 9. 3D model geometry: a) west view and b) east view.

Based on the building physics defined in the previous sections (3 and 4), a dynamic thermal simulation was performed using the EP software

The BEM was assembled by defining fifty-three thermal zones, corresponding to the main areas, as well as to the main internal partitions. The zoning strategy was also defined according to the temperature asymmetry knowledge of the building (from the monitoring phase - section 4). The ground floor is assembled by the six flats and the common staircase (non-conditioned area) thermal zone, where each flat was divided into two TZ, as described in section 4 (see Figure 10a). The upper floors have similar thermal zones division (see Figure 10b). The roof (above the third elevated floor) is composed of one thermal zone to simulate the open space as ventilated.



a)



b)

Figure 10. Thermal zones division: a) ground floor and b) elevated floors.

During the monitoring campaign, the external shading devices of unoccupied flats were closed. While, for the occupied flats these shading devices, manually controlled by the occupants, were defined with a typical schedule occupants' behaviour use, as depicted in Table 3.

Table 3. Shading device schedules of the flats.

Occupation flat	100% closed	
	Winter	Summer
Unoccupied	all day	all day
Occupied	18:00 to 10:00	22:00 to 08:00 10:00 to 18:00

The internal gains are quantified by the total energy related to human metabolism, lighting and equipment of the occupied flats. In the unoccupied flats, none internal gains were considered. These variables play an important role in the overall thermal behaviour of the building. The European standards [30] for residential buildings use a static norm-based approach for the contribution of internal heat gains, where the standard values are underestimated [31]. According to the Portuguese thermal regulation [32] all the internal gains: occupation, lightning and equipment's, were considered with a constant value of 4 W/m^2.

The continuous development of equipment's and lighting efficiency and the reducing heat losses, internal heat gains might change for residential buildings in the future to give accuracy in BEMs. Furthermore, in social housing, the disparity of internal gains in practice can be itself problematic to decide which internal gains value or schedule is appropriate for use in BEM. Further, the social housing building has not a defined occupancy profile on average due to the lower employment rate and consequently an uncertain use of lightning and appliances [33].

The BEM created for the simulation assumes that internal heat gains are constant over time. In this study the internal heat gains are completely harnessed, considering that all end-use power (heat dissipation, radiant and latent contribute) is transferred into the ambient.

5.3. Definition of the Unknown Parameters

In the model calibration, 36 input parameters (x0 to *x*35) were identified as uncertainties. Consequently, a range was defined for each one, presented in Table 4. Parameters x0 (insulation thickness) was selected as the uncertainty variable to take into to account the thermal bridge's impact and, therefore, their range is rather narrow. Parameters *x*1 to *x*3 are related to the exterior windows U_{value} coefficient, with a range limit (±0.5) of the value given by Portuguese technical information materials - ITE 50 [34]. Parameter *x*4 to *x*5 represent the solar heat gain coefficient (SHGC), estimated by technical manufacture information with a range limit of ±0.5. The air infiltration rate of the roof is defined by the parameter *x*6. Parameter *x*7 to *x*18 (ACH) has a significant impact on the indoor air temperatures, as well as on the space heating or cooling energy demands in buildings. The range defined (0.16 to 0.7 h^{-1}) was based on a Blower Door test carried out with a 50 Pa of pressure difference, combining the rule of thumb ACH50/20, which Sherman [35] attributed to Kronvall and Persily approximation of the air infiltration rate at a normal pressure and exposure conditions. Parameters from *x*19 to *x*35 represent the internal heat gains (W/m^2) of occupied flats. The different occupational habits of the users are a hard task for multi-zone calibration. In particular, the actions of the users can have a strong effect on both ventilation and internal gains, especially in the social housing context. Thus, the maximum value of 4 W/m^2 is defined according to the Portuguese regulation [32] and the lower limit was defined with a value of 2.5 W/m^2 [31].

All uncertainties were considered as continuous variables with the box constraint limits (range) summarised in Table 4.

Table 4. Range of the unknown input parameters.

Parameter id.	Description (units)	Box constraints limits

*x*0	Ground floor insulation thickness (m)	0.035 – 0.045
*x*1 to *x*3 (by window)	Windows: U_{value} (W/m^2.°C)	4.300 – 7.000
*x*4 to *x*5 (by window)	Solar heat gain coefficient (-)	0.650 – 0.880
*x*6	Roof - Air infiltration rate (h^{-1})	0.400 – 0.600
*x*7 to *x*18 (by flat)	Air infiltration rate (h^{-1})	0.160 – 0.700
*x*19 to *x*35 (by flat)	Internal heat gains (W/m^2)	2.500 – 4.000

5.4. Calibration results

A new EP output was programmed using the Energy Management System (EMS) application to calculate the RMSE index. Then, the evolutionary algorithm was used running 10.000 models to minimise a single objective function. RMSE index aimed at finding a trade-off between the input design parameters (defined as variables in Table 4) according to the difference form the monitored and simulated indoor air temperatures. The best id. solution is shown in Table 5.

Table 5. Best model calibrated values for the period under calibration—id. 9541.

Parameter id.	Description (units)	Calibrated values
*x*0	Ground floor insulation thickness (m)	0.045
*x*1 to *x*3 (by window)	Windows: U_{value} (W/m^2·°C)	4.590 – 6.410
*x*4 to *x*5 (by window)	Solar heat gain coefficient (-)	0.650 – 0.800
*x*6	Roof - Air infiltration rate (h^{-1})	0.600
*x*7 to *x*18 (by flat)	Air infiltration rate (h^{-1})	0.220 – 0.700
*x*19 to *x*35 (by flat)	Internal heat gains (W/m^2)	2.500 – 3.530

Figure 11 shows an example of the results with the correlation factor (r2) between the real and simulated results from the best id. attained (id. 9541) for the flat Bl.31.0.6. In an overall analysis of Figure 11, for temperatures between 14 °C and 18 °C, the deviation between simulated results and monitored data reveals a tendency of lower temperatures in the simulated data. Above 20°C of temperature the observed deviation trends for higher temperatures in the simulated data. However, the overall results show good agreement between the two variables, with the cloud of points tending to symmetry.

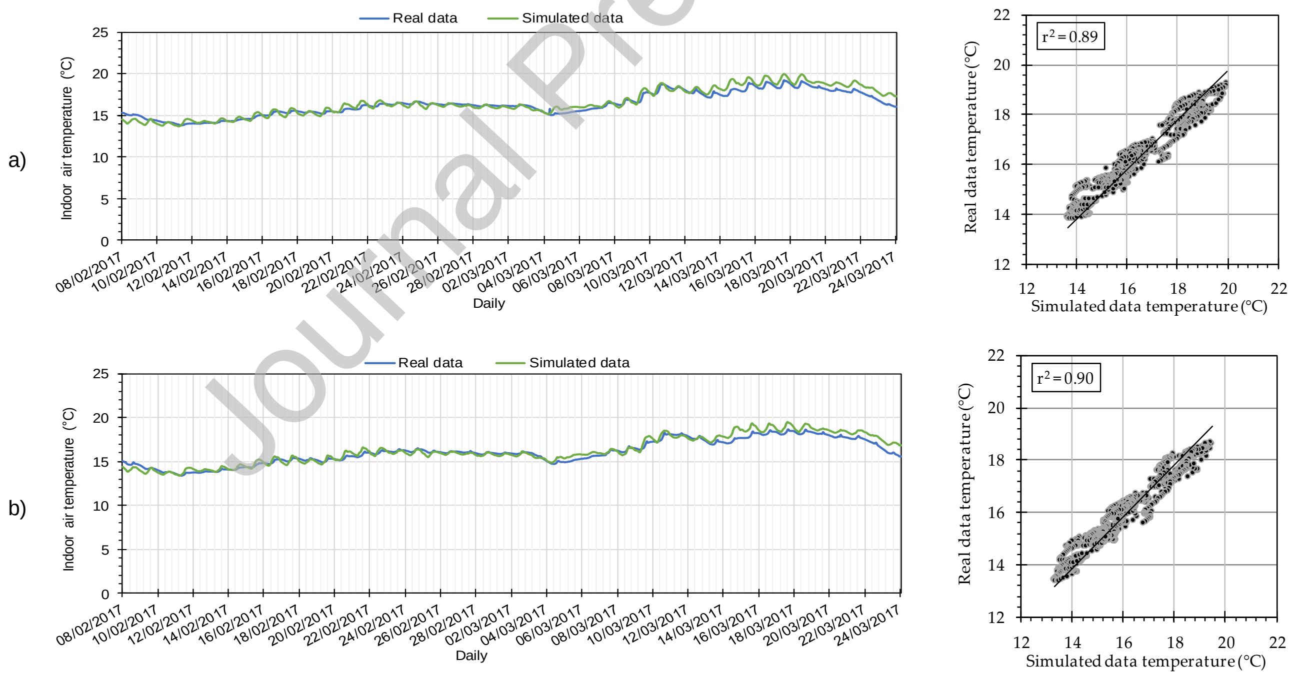


Figure 11. Index and correlation factor of flat Bl.31.0.6: a) TZ01 and b) TZ02.

The validation of the BEM follows the criteria of ASHRAE Guidelines [19], the IPMVP [20] and the FEMP [21] standards, with the attained results and the standard limits presented, as shown in Table 6. The CV RMSE values attained (see Table 6) were always below the limit values imposed by these standards. According to the GOF index, ASHRAE Guidelines recommend a GOF below 11%. In the presented work, the attained GOF is lower than the values imposed. In this study the guidelines identified were verified, meaning that an acceptable agreement between measured and simulated indoor air temperature was achieved. One should stress that the calibration was based on the winter conditions and, thus, a higher uncertainty on the summer results are expected.

Table 6. Acceptance criteria used for building energy model (BEM) calibration—id. 9541.

Flat	Thermal zone	Hourly Criteria (%)	
		CV RMSE*	GOF**
Bl.31.0.5	TZ01	6.03	3.35
	TZ02	3.53	2.81
Bl.31.0.6	TZ01	2.88	2.18
	TZ02	2.64	1.98
Bl.31.2.2	TZ01	12.90	9.25
	TZ02	10.85	7.80
Bl.31.2.5	TZ01	5.26	3.74
	TZ02	5.03	4.07
Bl.31.3.1	TZ01	6.40	5.41
	TZ02	7.35	6.29
Bl.31.3.3	TZ01	6.33	4.66
	TZ02	6.42	4.58
Bl.31.3.4	TZ01	5.41	4.08
	TZ02	5.12	3.90

* ASHRAE Guideline limit – 30; IPMVP limit – 20; FEMP limit – 30.

** ASHRAE Guideline limit – 11%

6. Sensitivity analysis: results and discussion

6.1. Initial assumptions

In the following analysis, the internal gains due to occupancy, lighting and equipment's were the ones obtained during the model calibration procedure (see Table 6). In the unoccupied flats, no internal gains were considered. The air infiltration rate and the internal gains were also defined according to the airtightness assessment.

The standard EN 15251 [14] defines two procedures for comfort assessment: one for buildings with mechanical ventilation; and another for naturally ventilated buildings. The thermal comfort in buildings with natural ventilation, like the ones analysed in this study, is assessed by the indoor operative temperature. The standard EN 15251 [14] also proposes four different categories of comfort, based on the type of construction and the expectation of the occupants. The case study fits on the category III, which refers to an acceptable, moderate comfort level, adjusted for existing buildings and considering the acceptable 'summer' indoor temperatures (cooling season) for buildings without mechanical cooling systems.

In the analysis, two different scenarios were created: a) for comfort assessment, the indoor air temperature was calculated using EP in free-running mode, without active heating and/or cooling systems; and b) for energy efficiency, the annual energy demand was calculated with EP using an ideal heating and cooling HVAC system, operating with temperature set-points of 18°C and 27°C (range defined in Category III of EN 15251 [14]), for winter and summer period, respectively.

In the first phase of the study (Phase I – section 6.2), the thermal discomfort and the energy performance of the building were evaluated assuming all flats occupied. The results were used to select the target flats of the building for the sensitivity analysis. In section 6.3 (Phase II), several different scenarios with progressive unoccupied neighbouring flats were considered. Then, these scenarios were compared with the reference one – all neighbouring flats occupied. In Figure 12 an example of this methodology is detailed, using flat #3 as a target.

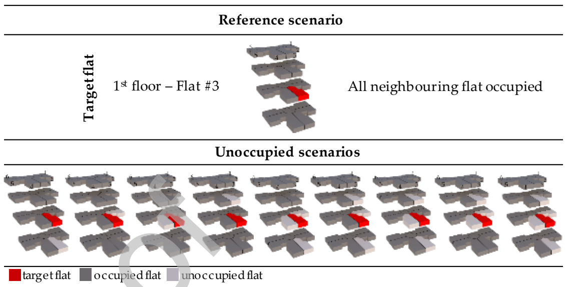


Figure 12. Example of target flat #3 sensitivity analysis.

6.2. Phase I: whole building occupied

Phase I dynamic simulation assumes all flats occupied, as described in section 6.1., showing the performance of the building with total occupancy and presenting the values for thermal discomfort and energy demand.

In a global analysis, the thermal discomfort of flats presented values up to 33.4% for the winter period and up to 10% for the summer period, except in three cases, for which the results are lower (see Table 7). The thermal of discomfort in winter period was always superior to the summer period, confirming that the most important concern is related to the heating demand. At the same floor, flat #4 presented the lowest thermal discomfort rate for the winter period, while flat #2 presented the highest.

Regarding the energy balance, the cooling demand presents similar magnitude, when compared with the heating demand. This would not be expected for this type of flats. However, this result is explained by the large number of windows without shading devices, which lead to high solar gains.

Table 7. Thermal discomfort rate and energy demand of occupied flats.

Floor	Flat#	Thermal discomfort rate (%)		Energy demand (kWh/m^2.y)	
		Winter	Summer	Heating	Cooling
Ground	1	53.2	4.7	21.3	13.7
	2	56.3	26.7	24.3	22.0
	3	43.4	7.6	17.3	15.1
	4	33.4	12.4	11.6	16.9
	5	49.6	25.2	22.6	22.8
	6	50.5	5.7	20.8	14.0
First	1	52.0	20.5	21.9	18.5
	2	62.0	35.3	29.1	28.8
	3	49.5	5.9	22.1	15.0

	4	35.4	16.3	13.6	19.4
	5	49.5	33.6	24.2	27.1
	6	49.5	18.1	22.6	18.9
Second	1	57.4	27.9	26.3	24.4
	2	62.4	37.3	33.7	33.0
	3	57.0	11.5	27.1	17.5
	4	37.8	27.4	15.6	23.6
	5	52.6	40.0	25.8	32.3
	6	53.4	29.3	25.1	24.9
Third	1	63.7	28.2	38.2	30.8
	2	65.1	36.3	43.4	39.4
	3	65.1	18.6	41.7	25.8
	4	49.4	29.0	27.6	1.5
	5	59.1	40.6	36.0	39.4
	6	60.8	33.1	35.5	34.1

The results of the first floor were analysed in order to define the target flats for Phase II (detailed and discussed in section 6.3). This floor presents favourable conditions for this analysis, as both, the effect of the ground floor slab and roof are not relevant. Figure 13 and Figure 14 synthesize the main results.

Figure 13 shows the thermal discomfort rate of the flats and the effect of solar radiation exposure can be clearly identified. Flat #2 presents the highest thermal of discomfort rate, with lower solar heat gains in the winter period, while in the other flats a similar trend was observed, with approximately 50% of discomfort. The West-oriented flats are mostly influenced by deciduous trees, since this façade is shaded, reducing the effect of solar radiation. In the summer period, flats #2 and #5 show the highest thermal discomfort rate and flat #3 presents the most comfortable conditions.

In general, the current conditions of the flats show a significant thermal discomfort rate during the entire year, which underlines the importance of this study. The effect of air permeability (*ACH*) and internal heat gains (*qi*) do not have a significant impact on the results, as shown in Figure 13 and Figure 14.

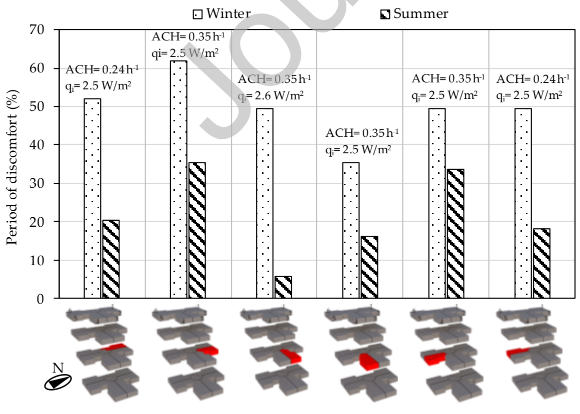


Figure 13. Thermal discomfort rate of the flats of the first floor.

Figure 14 shows the heating and cooling energy demand of the flats on the first floor. Flats #2 and #5 present the maximum energy demand both for heating and cooling. On the other hand, the other flats present similar results for the heating demand while for cooling a lower demand was observed for the case of flat #3.

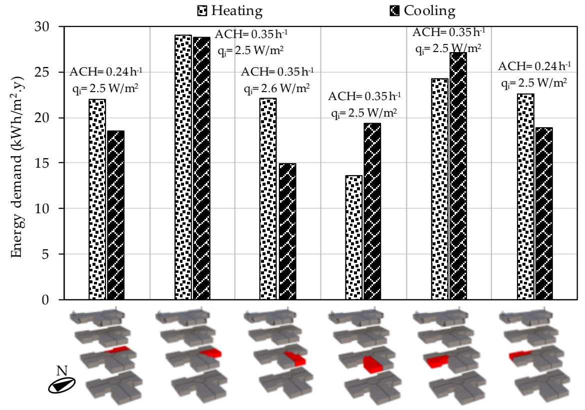


Figure 14. Heating and cooling demand of the flats of the first floor.

Regarding the selection of the target flats for Phase II, flats #3 and #6 were selected, taking into account the different comfort performance, energy demand and the orientation. Flats #2 and #5 present higher thermal discomfort and energy demand. However, these cases were not selected, choosing the flats with an intermediate behaviour, with different orientation and potential for solar gains.

In Figure 15 and Figure 16, the thermal of discomfort and the energy demand results are presented, as a function of the storey height of the target flats.

Figure 15 shows the influence of the floor height in the thermal discomfort of flat #3. The discomfort rate ranged between 43.4% and 65.1% in the winter period, while, in the summer period, it ranged from 5.9% to 18.6%. An increasing trend can be identified in the results as the thermal discomfort and the energy demand, both increase from the ground floor to the third floor, in the winter period. Regarding the summer period, the ground floor shows higher thermal discomfort in comparison with the first floor. This behaviour can be explained by the higher internal heat gains on the ground floor. A similar result is observed for the cooling demand.

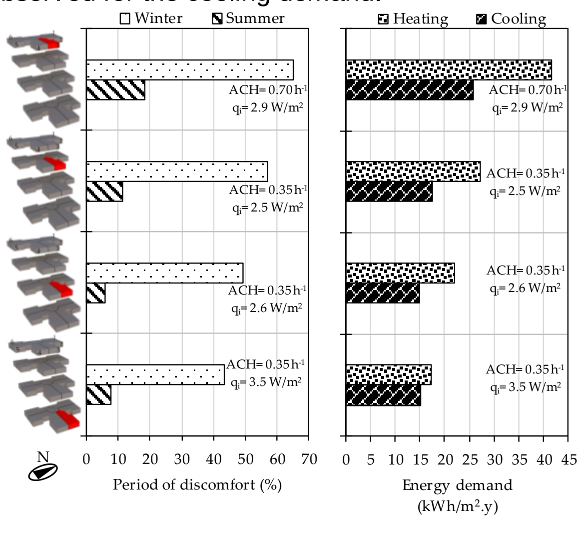


Figure 15. Thermal discomfort and energy demand of flat #3 at different floor height.

Figure 16 shows the influence of the floor height in the thermal discomfort and the energy demand of flat #6. The discomfort rate ranged between 49.5% and 60.8% in the winter period, while, in the summer period, it was from 5.7% to 33.1%. The same tendency found for flat #3 was also observed for flat #6, with higher thermal discomfort and energy demand in the upper floors for both seasons. However, in the winter period, flat #6 presents a similar thermal discomfort rate of the ground floor, the first and the second floor. The ground floor reveals a slightly higher thermal discomfort rate in comparison with the first floor. This behaviour is linked to the infiltration rate, which is higher at the ground floor, in accordance with the results of the Blower Door tests. This behaviour is explained by a higher air infiltration rate on the ground floor. The internal heat gains do not have a significant influence over the results.

Comparing the two target flats, it can be observed a lower thermal discomfort rate in flat #3 in the summer period due to its orientation minimising the solar gains.

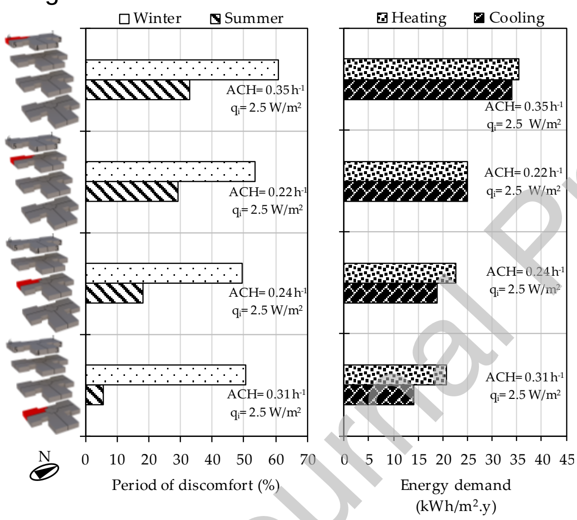


Figure 16. Thermal discomfort and heating and cooling demand of flat #6 at different floor height.

6.3. Phase II: unoccupied scenarios

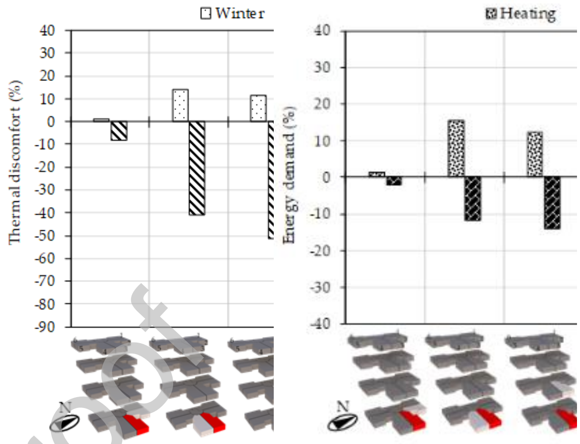
To understand the impact of occupancy of neighbouring flats, different scenarios were created and simulated. The results of this analysis were analysed according to the scheme described above in Figure 12.

The comparison between the reference scenario (all flats occupied) and the unoccupied scenarios included the evaluation of thermal discomfort and energy demand for winter and summer period. Thus, the negative values mean that thermal discomfort or energy demand was reduced in relation to the reference scenario. Hence, the positive values mean an increase of thermal discomfort or energy demand.

Finally, one must stress that the focus of this analysis was the winter period. In fact, in the Portuguese social housing context, peoples' concerns are typically related to underheating rather than overheating issues.

6.1.1. Target flat #3 assessment

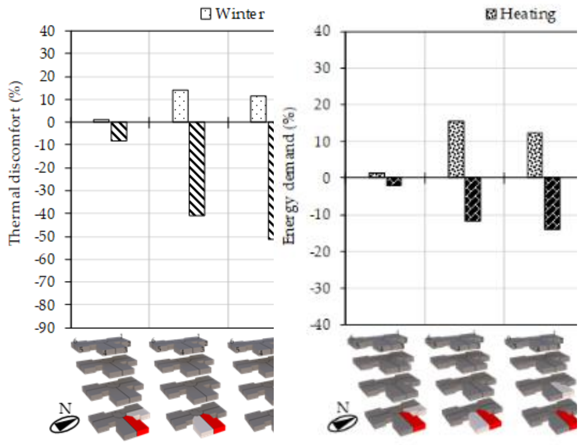
In



a) b)

Figure 17 to Figure 21 show the results of the simulated scenarios are presented, considering flat #3 as the target. The following assumptions can be highlighted:

- Occupancy of neighbouring flats has a significant impact on both thermal discomfort and energy demand;
- In the summer period, unoccupied flats have a positive effect on the thermal discomfort and energy demand of the target flat;
- On the other hand, in the winter period, the higher effect over the thermal discomfort and energy demand were observed when the rate of occupancy decreases.



a) b)

Figure 17a shows the results of the thermal discomfort of target flat #3. A relevant increase of thermal discomfort in the last two scenarios (right side) when compared to the other scenarios is notorious. As previously stated, the increase of unoccupied flats has a negative effect on the thermal discomfort in the winter period, while improving the summer performance. For the last scenario – all neighbouring flats unoccupied – the relative influence is higher in the summer period, with a maximum reduction of more than 80%, while in the winter period this value is just around 25%. However, one must stress that these results are highly influenced by the absolute value of the discomfort rate, which is very low in the summer period. So, in fact, the 80% reduction corresponds only to a decrease in the discomfort rate from 7.6 to 1.3%. A similar tendency can be observed in the energy demand (see

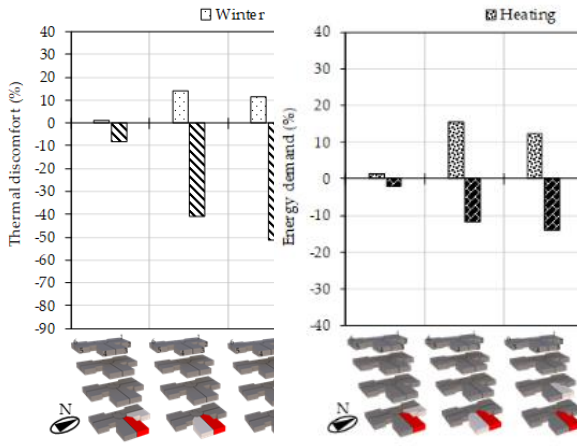


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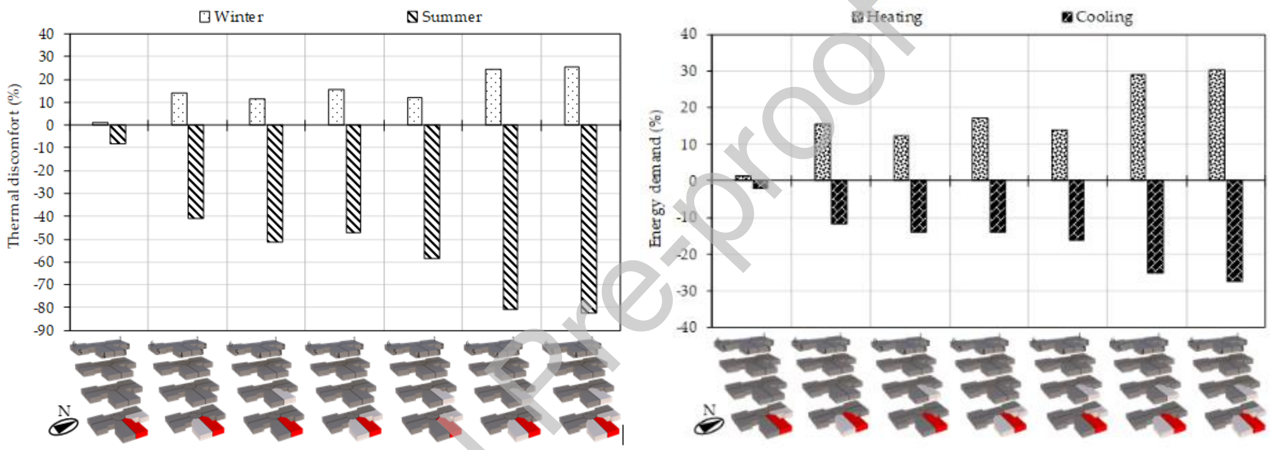
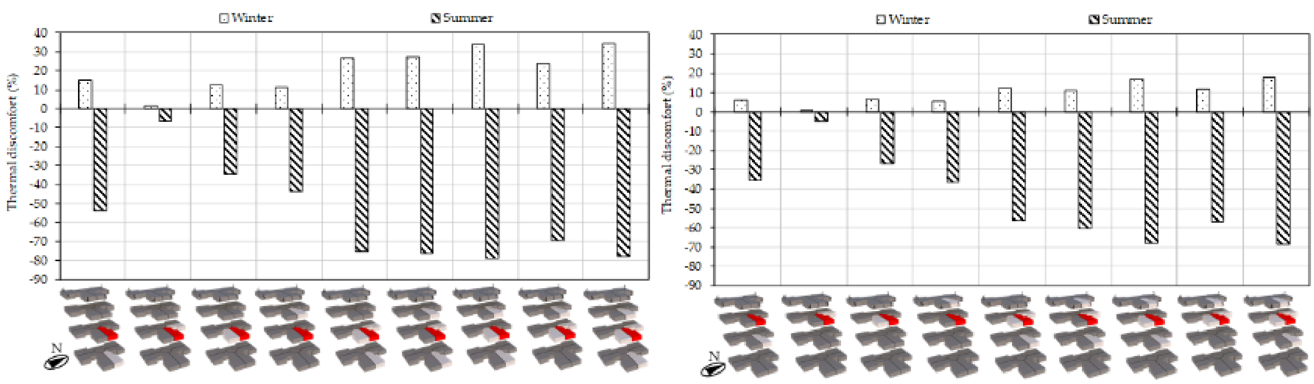
Figure 17b).



a) b)

Figure 17. Target flat #3 in ground floor: a) thermal discomfort; b) heating and cooling demand.

The results of the scenarios with the target flat at the 1st and 2nd floor are simultaneously analysed, since they have similar boundary conditions (see Figure 18a and Figure 18b). Despite these similarities, Figure 18a shows a higher thermal discomfort when the target flat is on the 1st floor, in comparison to Figure 18b (target flat on the 2nd floor). In the former, the maximum discomfort rate was 34.3%, while in the latter was only 17.7%.



a) b)

Figure 18. Thermal discomfort of target flat #3: a) 1st floor; and b) 2nd floor.

Figure 19 shows the results of the energy demand at the 1st and 2nd floor. As expected, the heating demand when the target flat is at 1st floor was greater. On the other hand, a lower cooling demand was observed.

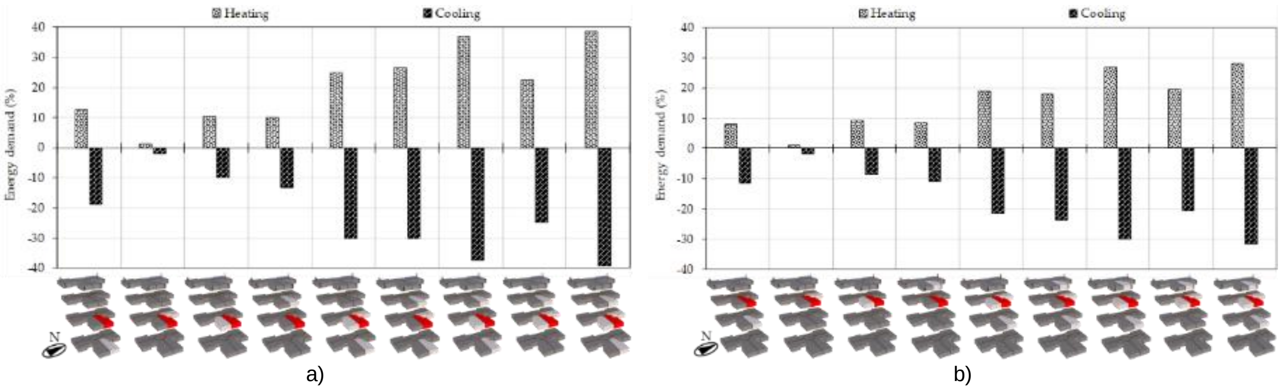


Figure 19. Heating and cooling demand of target flat #3: a) 1st floor; and b) 2nd floor.

Figure 20a shows the discomfort rate when the target flat is on the 3rd floor (top floor). The effect of occupancy is now significantly reduced, when compared to the previous scenarios. In the winter period, the decrease in the thermal discomfort rate is always below 10%.

On the other hand, the effect of occupancy in the energy demand (see Figure 20b) is slightly higher, with an increase of up to 15% in the winter period.

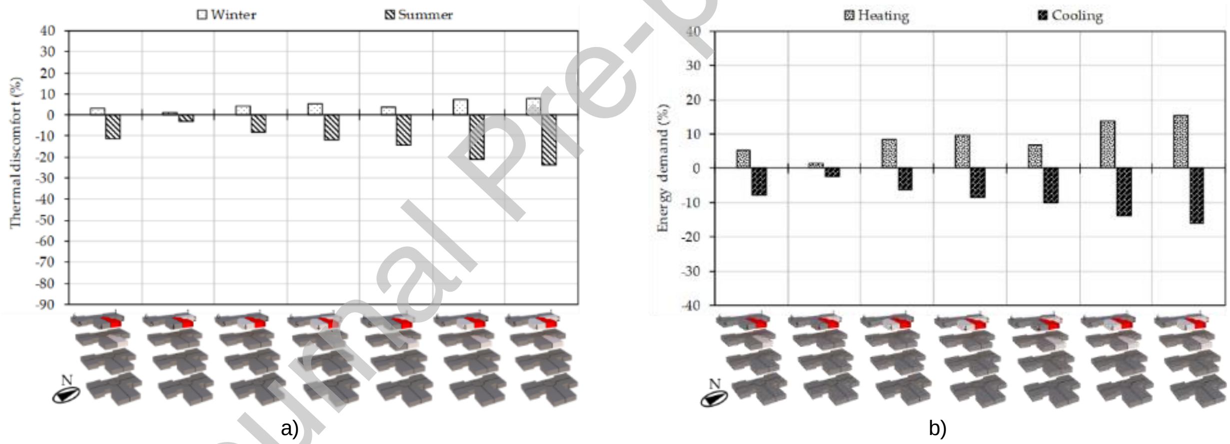
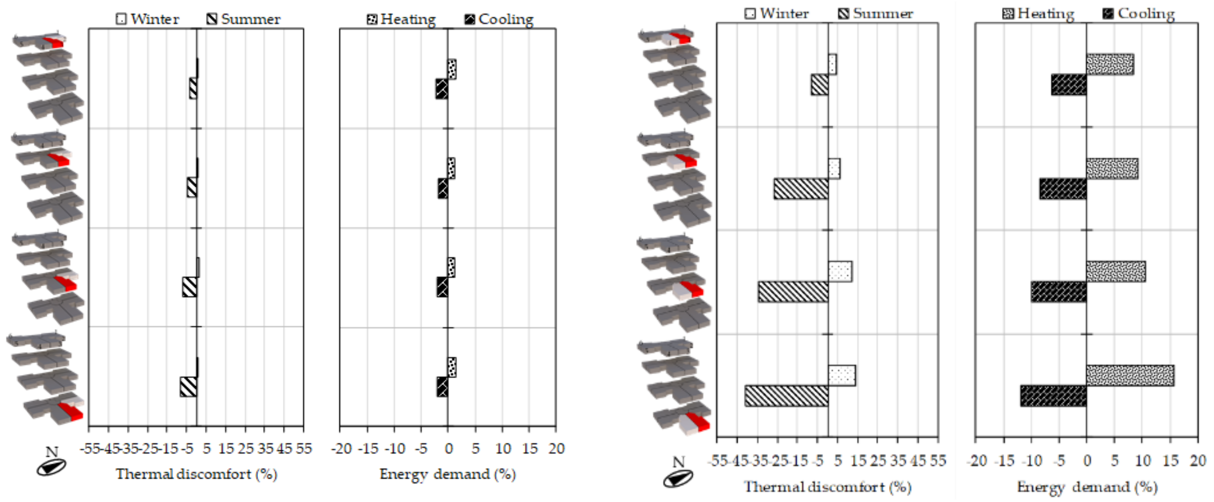


Figure 20. Target flat #3 in 3rd floor: a) thermal discomfort; b) heating and cooling demand.

In Figure 21a and Figure 21b, the effect of the floor height was evaluated. The thermal discomfort and the energy demand were compared taking as the base case an identical scenario, with similar glazing area, treated floor area and occupancy boundary conditions. The results show that the effect of occupancy was identical, regardless of the height of the target flat.

Figure 21a shows that, in both winter and summer period, the effect of occupancy was more relevant for the lower floors. The same trend can be observed in the energy demand analysis (see Figure 20b).



a) b)

Figure 21. Thermal discomfort and heating and cooling demand for the target flat #3 at different floors: a) unoccupied flat #2; b) unoccupied flat #4.

6.1.2. Target flat #6 assessment

In Figure 22 to Figure 26 the results of the simulated scenarios are presented, considering flat #6 as the target.

The following assumptions can be highlighted:

- Occupancy of neighbouring flats has a significant impact on both thermal discomfort and energy demand;
- For the summer period, unoccupied flats have a positive effect on the thermal discomfort and energy demand of the target flat;
- For the winter period, a slight increase in thermal discomfort and energy demand was observed, when only one neighbouring flat was unoccupied.

The effect of occupancy in the thermal discomfort rate and cooling demand was positive for the summer period, but the opposite situation occurred in the winter period (see Figure 22). The highest reduction of thermal discomfort rate occurred when two neighbouring flats were defined as unoccupied, while the minimum effect was when only flat #5 was unoccupied. A similar trend was observed for the heating demand analysis. However, in the winter period, the differences amongst scenarios are more expressive, with an increase of the heating demand of up to 20%.

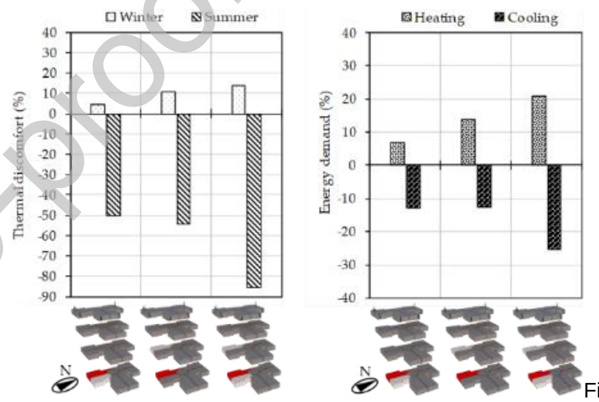
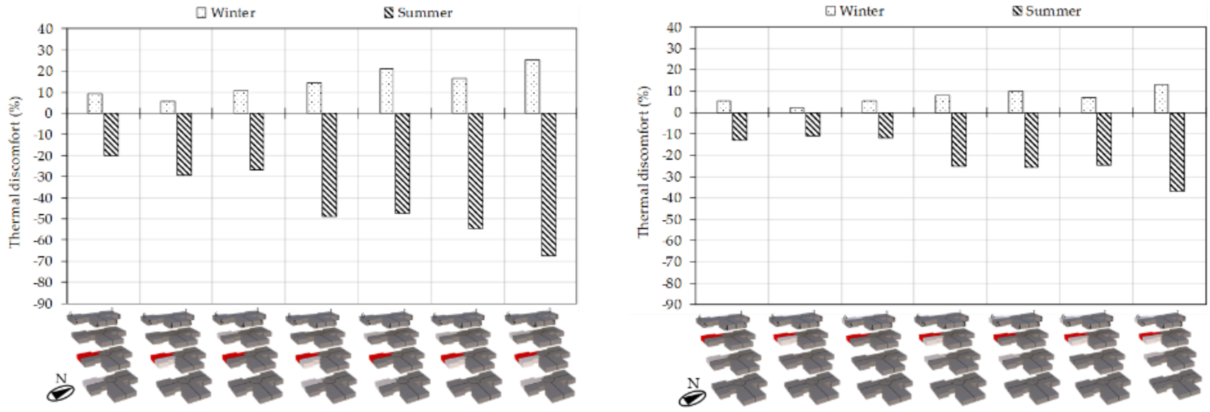


Figure 22. Thermal discomfort rate and heating and cooling demand for target flat #6 at the ground floor.

As explained in section 6.3.1, the scenarios with the target flat at the 1st and on the 2nd floor are analysed simultaneously (see Figure 23). As shown in section 6.3.1, two scenarios arise with significant effect: a) above and below flats unoccupied; b) all neighbouring flats unoccupied. In these scenarios, the increase in thermal discomfort in winter period was above 10% when the target flat is on the 1st floor. When the target flat is on the 2nd floor, the effect was less obvious.

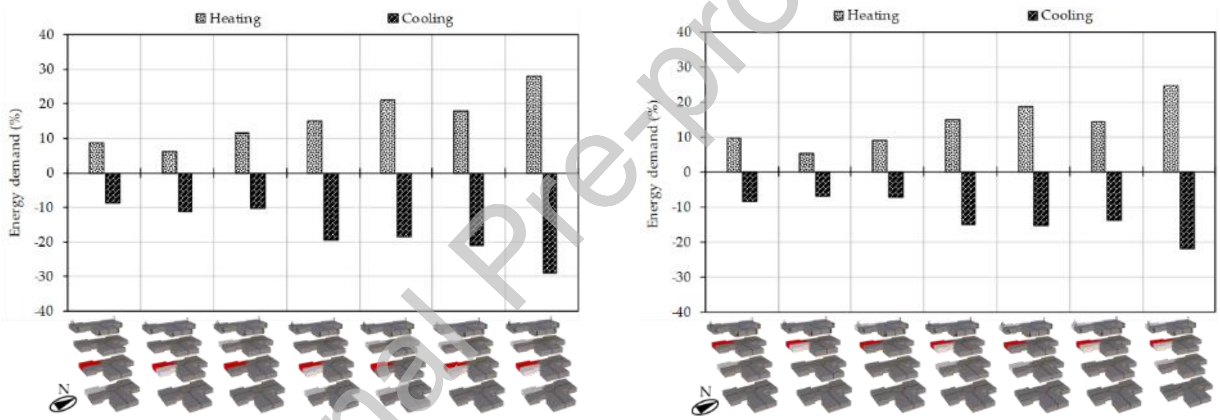
The scenarios with only one neighbouring unoccupied flat proved to be less important (i.e. above 10%). These results confirmed that the effect of occupancy (unoccupied) in the upper and/or lower neighbouring flats was higher, when compared with flats on the same floor.



a) b)

Figure 23. Thermal discomfort for target flat #6: a) 1st floor; and b) 2nd floor.

Figure 24a and Figure 24b show the results of the energy demand analysis for the 1st and 2nd floor, respectively. In these cases, no significant differences were found between floors, since similar heating and cooling demand were attained.



a) b)

Figure 24. Heating and cooling demand of target flat #6: a) 1st floor; and b) 2nd floor.

The results for the scenarios with the target flat on the 3rd floor are depicted in Figure 25. Similar thermal discomfort rate was observed for the winter period, when compared to the reference scenario, resulting in a maximum relative difference of 5.1% when all neighbouring flats are unoccupied and a minimum of 1.9% for the scenario when only flat #5 was unoccupied. The scenario with all neighbouring flats unoccupied shows an increase of the heating demand of 11.2%, while this value decreased to 4.1% when only flat #5 is unoccupied.
Generally, one can state by the comparison to the previous cases that the effect of occupancy is less important when the target flat is on the 3rd floor.

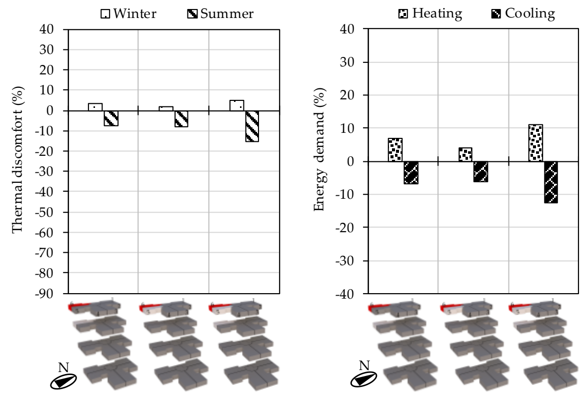


Figure 25. Thermal discomfort and heating and cooling demand for target flat #6 at the 3rd floor.

In Figure 26 the effect of the floor height was evaluated for the scenario with just flat #5 unoccupied. No significant differences can be identified in the increase of thermal discomfort rate for the winter period, indicating that the effect of height was not relevant. However, for the summer period, a distinct situation can be observed as the effect of occupancy is much more pronounced for the scenarios with the target flat located on the lower floors levels. A similar trend can be identified in the analysis of energy demand.

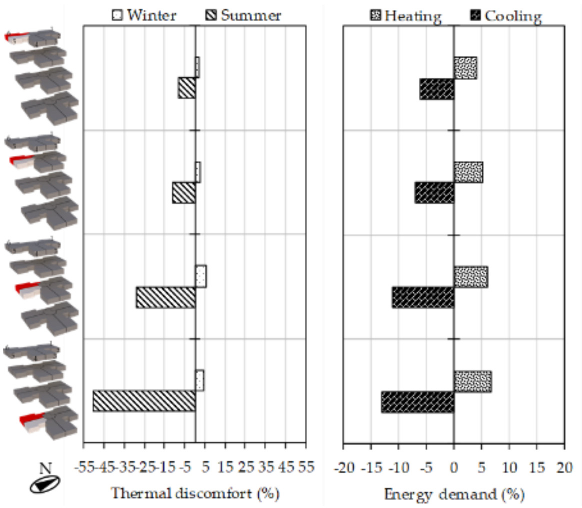


Figure 26. Thermal discomfort and heating and cooling demand for the target flat #6 on different floors.

7. Conclusions

This work focused on the sensitivity analysis of different occupation scenarios of a multi-residential social housing building and their impact over thermal comfort and energy demand of target flats with different occupation neighbouring conditions, using dynamic simulation software as a calculation engine. An evolutionary algorithm was used to calibrate the building energy model resorting to the monitoring data of indoor hygrothermal sensors and Blower Door testing to assess airtightness. Regarding the calibration process, the differences between real data and simulated results were minimised and the attained results have allowed concluding that the building energy model is calibrated according to the standards ASHRAE guideline 14 [19], IPMVP [20] and FEMP [21].

The main goal of this research work is to contribute to the knowledge related to the impact of different occupation scenarios of multi-residential buildings on the thermal comfort and energy demand of flats. This goal was accomplished with the performed work by means of a thorough sensitivity analysis carried out with a comprehensible structure.

The following conclusions can be stated:

- A progressive inoccupation of the building flats have an important impact in both thermal comfort and energy demand;
- In this case, the thermal discomfort rate varied 34.3% in the winter period and in 85.3% in the summer. The heating demand could increase up to 38.5% and the cooling demand could decrease up to 39.2%;
- The relative position of the unoccupied flats within the building is also an important factor;

This work revealed that the flat occupancy status in a multi-residential building can have a significant impact in some case scenarios and constitutes a key issue when exploiting/assessing the energy savings and improving indoor thermal comfort, giving some insights that may help understand the actions and decision making of authorities in social housing buildings. Furthermore, the study provides additional information and key findings that can guide authorities responsible for managing social building stock. From social housing point view, new insights in respect to maintenance and refurbishment measures are risen, for example, the improvement of the internal envelope of flats to avoid undesired heat losses to unoccupied neighbouring flats, reducing the effect of the unoccupied status of buildings.

Acknowledging that building fabric, typology and geometry and climatic context are features that are not generalised and particular to each case study, the proposed method in the scope of this paper can be followed and adapted for further applications for different typologies and climates.

AUTHOR STATEMENT

Manuscript title: Impact of unoccupied flats on the thermal discomfort and energy demand: case of a multi-residential building

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication before its appearance in the Energy and Buildings journal.

In following, a detailed description of authors' contributions to the published work were defined according the CRediT (Contributor Roles Taxonomy).

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Writing-Original Draft Preparation: R.O.

Writing-Review & Editing: R.A., A.F. and R.V.

Visualization: R.O.

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Conflict of Interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript