Building parameter influence on overheating and undercooling risks in the Mediterranean social housing stock of southern Spain

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Abstract. In recent years, there has been a notable rise in temperatures, along with an escalation of heatwaves as a consequence of global warming. This phenomenon conspicuously impacts summer and winter, leading to modifications in the building energy balance, such as higher overheating risks, increased cooling energy consumption or decreased heating demand. Consequently, evaluating the risks associated with overheating and undercooling discomfort in the existing stock becomes of great significance, prior to the implementation of retrofit strategies. In this line, a parameterized and validated building stock simulation model has been constructed, defined from the most representative building archetype, allowing the evaluation of overheating and undercooling risks in the existing social housing stock in southern Spain. To do so, monitored data from a case study and extensive information of a public building database have been considered. The most influential parameters on adaptive overheating and undercooling discomfort have been defined through sensitivity analysis. The study highlights the importance of window configuration and air-related parameters on overheating and undercooling, being also worth noting the relevance of ventilation schedules, even more than ventilation rates. These findings are crucial for defining energy retrofit solutions aimed at minimizing the effects of global warming, while taking into consideration undercooling conditions.

1 Introduction

One of Europe's key objectives to reach a low-carbon economy by 2050 is to improve energy efficiency of existing buildings, enhancing their adaptability to global warming [1]. In the Mediterranean area, where climate change will have more sensitive repercussions, global warming is mainly expected to rise cooling energy consumption, while reducing thermal comfort, deriving in more frequent episodes of indoor overheating [2]. In order to improve buildings energy performance and indoor environment quality, it is generally accepted that the existing stock must undergone an intensive retrofit process. Yet, special care must be focused on the social housing stock due to its high vulnerability and their users' low resources

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[3]. Moreover, thermal comfort becomes even more significant that energy consumption in the building energy balance assessment due to the lack of cooling and heating systems or their limited use as a consequence of users' economic constraints [4]. Therefore, it is important to propose specific energy retrofit strategies that target the building parameters with the highest impact on thermal comfort, assessing the buildings' annual performance, during both summer and winter periods, through the analysis of overheating and undercooling risks.

The most influential design parameters on the buildings' performance have been analyzed in similar works, mainly through sensitivity analysis techniques. For instance, Machard et al. (2023) [5] analyse the influence of several parameters on the thermal performance of Parisian buildings through the Morris and Sobol sensitivity methods. These authors conclude that thermal mass, albedo, emissivity, window-to-wall ratio, ventilation and solar control strategies play a crucial role on indoor overheating. Carpino et al. (2022) [6] conduct a Standardized Rank Regression Coefficients (SRRC) analysis on an Italian public housing complex, determining that the efficiency of cooling energy systems is one of the most influential parameters on annual energy demand in the Mediterranean area. Facundo Bre et al. (2016) [7] present a sensitivity analysis to obtain the most critical parameters on the thermal and energy behaviour of a single-family house in Argentina. These authors found out that the type of external walls, infiltration rate and solar azimuth were of the utmost importance. Figueiredo et al. (2016) [8] discovered that thermal inertia or external shading protection systems, highly influence thermal discomfort and energy performance of Portuguese houses in the Aveiro region, analysing a detached two storey building.

Yet, all of these findings have been reported at the single-building level, through the analysis of a specific case study. Thus, there is a clear research gap on providing similar results at the stock level, i.e. while considering extensive building characterization data and building-archetype simulation models. Thus, the main aim of this research is to provide a general view, from the stock level, of the most influential variables on both overheating and undercooling risks considering the social housing buildings of southern Spain (Mediterranean climate). To do so, a parameterized and validated building stock model has been constructed through the definition of building archetypes, using on-site measurements and extensive building characterization data from a public database. These results may be noticeably useful during the decision-making process for retrofitting the existing stock towards the mitigation of climate change, while taking into consideration undercooling discomfort during winter.

2 Methodology

Fig. 1. shows the workflow implemented in this research, which includes the use of building simulation software (EnergyPlus and jEPlus), numeric parameterization through programming code (EP macro and Python scripts) and statistical techniques. The tasks developed are described in the following subsections.

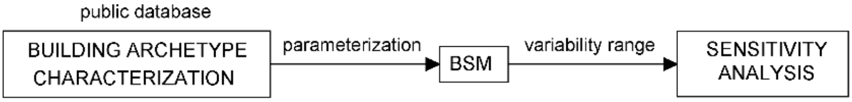


Fig. 1. Scheme of the workflow followed.

2.1 Stage 1. Building archetype characterization

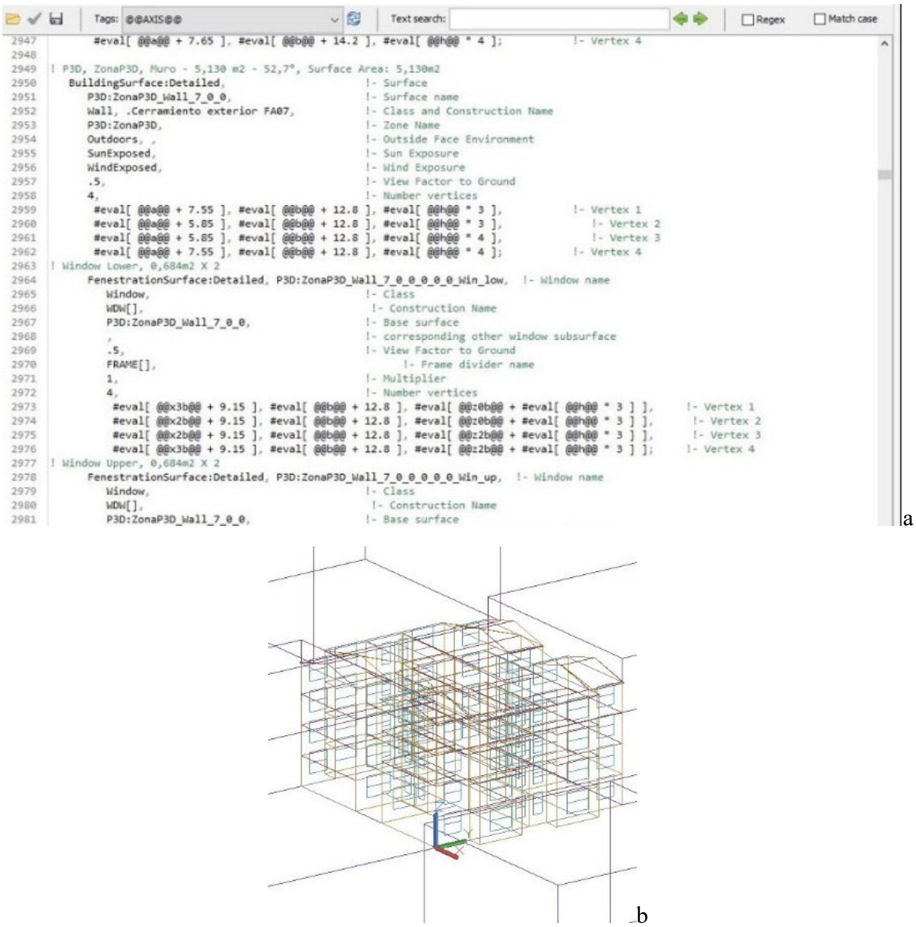
A public building database provided by the Andalusian Agency for Housing and Retrofitting (AVRA in Spanish) [9] was statistically analysed to conduct a building characterisation of the existing public social housing stock of southern Spain (Csa Mediterranean climate [10]). This database contains information on 39.486 social dwellings, including: cadastral reference, address location, building height, dwelling typology (single-family or multi-family building), number of dwellings, year of construction, total built area, average dwelling built area, climatic zone according to the Spanish Building Technical Code [11], architectonic typology (H-block, linear block, tower or irregular), urban typology (isolated, terraced, L-shape, U-shape, collective closed blocks), envelope definition, thermal installations and energy cooling and heating demand. This database was assessed in previous works and, after compiling and rearranging it, a statistical analysis was carried out to obtain the main variability ranges that define the most representative building archetypes [12]. The presented research focused on the most representative social building typology in southern Spain: the H-block (47.2 % of existing buildings), whose variability ranges (the most representative building configurations) are shown in Table 1.

Table 1. Variability ranges of the H-block building in southern Spain.

Building variable	**AVRA database**
Construction year	1970-2050
Urban configuration	Isolated, Terraced, Corner
Orientation (º)	0 to 90 each 15
Floor area (m^2) / Floor height (m)	70 to 115 / 2.5 to 3
WWR (%) / Number of floors	10 to 30 / 3 to 5
Roof and facade solar absorptance	0.3 to 0.9
Roof / Facade / Floor / Window U-value (W/m^2K)	1.2 to 2.4 / 1.2 to 2.5 / 3.0 to 7.0 / 5.50 to 5.70
Roof / Facade / Floor / Partition thickness (m)	0.25 to 0.4 / 0.10 to 0.35 / 0.15 to 0.30 / 0.07 to 0.12
Type of window glass / frame	Single / Aluminum
Infiltration rate (ACH)	0.30 to 1.00
People density ($people/m^2$)	0.01 to 0.15

2.2 Stage 2. Construction of building stock models

Considering the morphology, constructive and physical characteristics defined during the building archetype characterization, a building stock model (BSM) was developed through the open access EnergyPlus and jEPlus simulation tools. Firstly, a representative real H-block building was selected as case study, being monitored during a long-term period (summer, mid-season and winter). A building energy model (BEM) of the case study was constructed considering the single-building level and, later, the simulation model was properly calibrated and validated through Bayesian techniques [3]. After this, a parameterization process was conducted through EnergyPlus macro and programming code to allow the implementation of the variability ranges defined in stage 1 (Fig. 2). This approach makes it possible to simulate different representative cases, automatically running the simulations and significantly reducing manual variation settings, since different configurations (geometry, orientation, envelope properties…), can be easily modified in the parameterized model.



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     #eval[ @@a@@ + 7.65 ], #eval[ @@b@@ + 14.2 ], #eval[ @@h@@ * 4 ];          !- Vertex 4

! P3D, ZonaP3D, Muro - 5,130 m2 - 52,7°, Surface Area: 5,130m2
  BuildingSurface:Detailed,                         !- Surface
    P3D:ZonaP3D_Wall_7_0_0,                         !- Surface name
    Wall, .Cerramiento exterior FA07,               !- Class and Construction Name
    P3D:ZonaP3D,                                    !- Zone Name
    Outdoors, ,                                     !- Outside Face Environment
    SunExposed,                                     !- Sun Exposure
    WindExposed,                                    !- Wind Exposure
    .5,                                             !- View Factor to Ground
    4,                                              !- Number vertices
     #eval[ @@a@@ + 7.55 ], #eval[ @@b@@ + 12.8 ], #eval[ @@h@@ * 3 ],          !- Vertex 1
     #eval[ @@a@@ + 5.85 ], #eval[ @@b@@ + 12.8 ], #eval[ @@h@@ * 3 ],             !- Vertex 2
     #eval[ @@a@@ + 5.85 ], #eval[ @@b@@ + 12.8 ], #eval[ @@h@@ * 4 ],             !- Vertex 3
     #eval[ @@a@@ + 7.55 ], #eval[ @@b@@ + 12.8 ], #eval[ @@h@@ * 4 ];          !- Vertex 4
! Window Lower, 0,684m2 X 2
    FenestrationSurface:Detailed, P3D:ZonaP3D_Wall_7_0_0_0_0_0_Win_low,  !- Window name
      Window,                                       !- Class
      WDW[],                                         !- Construction Name
      P3D:ZonaP3D_Wall_7_0_0,                       !- Base surface
      ,                                             !- corresponding other window subsurface
      .5,                                           !- View Factor to Ground
      FRAME[],                                            !- Frame divider name
      1,                                            !- Multiplier
      4,                                            !- Number vertices
       #eval[ @@x3b@@ + 9.15 ], #eval[ @@b@@ + 12.8 ], #eval[ @@z0b@@ + #eval[ @@h@@ * 3 ] ],      !- Vertex 1
       #eval[ @@x2b@@ + 9.15 ], #eval[ @@b@@ + 12.8 ], #eval[ @@z0b@@ + #eval[ @@h@@ * 3 ] ],       !- Vertex 2
       #eval[ @@x2b@@ + 9.15 ], #eval[ @@b@@ + 12.8 ], #eval[ @@z2b@@ + #eval[ @@h@@ * 3 ] ],       !- Vertex 3
       #eval[ @@x3b@@ + 9.15 ], #eval[ @@b@@ + 12.8 ], #eval[ @@z2b@@ + #eval[ @@h@@ * 3 ] ];      !- Vertex 4
! Window Upper, 0,684m2 X 2
    FenestrationSurface:Detailed, P3D:ZonaP3D_Wall_7_0_0_0_0_0_Win_up,  !- Window name
      Window,                                       !- Class
      WDW[],                                         !- Construction Name
      P3D:ZonaP3D_Wall_7_0_0,                       !- Base surface
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Fig. 2. (a) Example of programming code in EnergyPlus; (b) 3D of the parameterized H-block model.

2.3 Stage 3. Sensitivity analysis

Once the BSM was successfully parameterized, a sensitivity analysis was conducted to determine the variables with the higher influence on thermal comfort. To do so, the SRRC sensitivity method was applied, a global sensitivity analysis based on the ordinary least square [13], which allows to determine the influence of group action by modifying several variables simultaneously. This method is a rank transformation approach where impact coefficients that result from a regression analysis are defined. The SRRC presents data after undergoing a standardization process to allow the comparison of variables that are measured in different units. Thus, all variables are comparable since they are ranged from -1 to +1, which respectively represents a direct and indirect parameter-output relationship. As proven by Allam et. al (2020) [14], the SRRC method has been extensively used in building performance analysis. The objective parameters considered in the sensitivity analysis are: annual percentage of hours that lead to overheating (summer) and undercooling (winter) risks, which are determined according to the adaptive thermal comfort model in EN 16798-1:2019 [15] (Equations 1 and 2), using a Python code implemented in EnergyPlus. This standard establishes an adaptive comfort temperature ($T_{comfort}$) derived from the running average dry bulb outdoor temperature for today (T_{out}) and previous 1 to 7 days (T_{out1} to T_{out7}). This sets a comfort band of +3°C and -4°C, which defines both the upper and lower limits. This band considers a maximum of 10% predicted percentage of dissatisfied, setting a ±0.5 predicted mean vote. Finally, to determine the percentage of overheating and undercooling hours, calculations were made to obtain the percentage of hours surpassing and falling below the upper and lower comfort limits, respectively. For the sensitivity analysis, the variability ranges specified in Table 2 were considered.

$$T_{comfort} = 0.33\times T_{out} + 18.8 \quad (1)$$

$$T_{out}=(T_{out1}+0.8\times T_{out2}+0.6\times T_{out3}+0.5\times T_{out4}+0.4\times T_{out5}+0.3\times T_{out6}+0.2\times T_{out7})/3.8 \quad (2)$$

Table 2. Variability ranges of the H-block in southern Spain considered in the sensitivity analysis.

Building variable	Variability range
Urban configuration	Isolated, Terraced, Corner
Orientation (º)	0 to 90 each 15
Floor area (m^2) / Floor height (m)	70 to 115 / 2.5 to 3
WWR (%) / Number of floors	10 to 30 / 3 to 5
Roof and facade solar absorptance [sa]	0.3 to 0.9
Roof / Facade / Floor / Window U-value (W/m^{2}K)	0.2 to 2.4 / 0.24 to 2.5 / 3.0 to 7.0 / 1.40 to 5.70
Roof / Facade / Floor / Partition thickness [t] (m)	0.25 to 0.4 / 0.10 to 0.35 / 0.15 to 0.30 / 0.07 to 0.12
Type of window [WDW] glass / frame	Single, Double / Aluminum, Aluminum with thermal bridge break, PVC
Infiltration / Natural ventilation / Mechanical ventilation rate (ACH)	0.30 to 1.00 / 1 to 5 / 6 to 10
Natural ventilation [NV] / Mechanical ventilaton [MV] schedule [Sche]	8:00-9:00 (summer and winter), 8:00-9:00 (summer) & 14:00-15:00 (winter), 22:00-8:00 (summer) & 8:00-9:00 (winter), 22:00-8:00 (summer) & 14:00-15:00 (winter) / Off, Night-time, Always ON
External solar protections schedule	OFF, 50% opened all year, optimized according to solar radiation in summer and winter
People density (people/m^2)	0.01 to 0.15

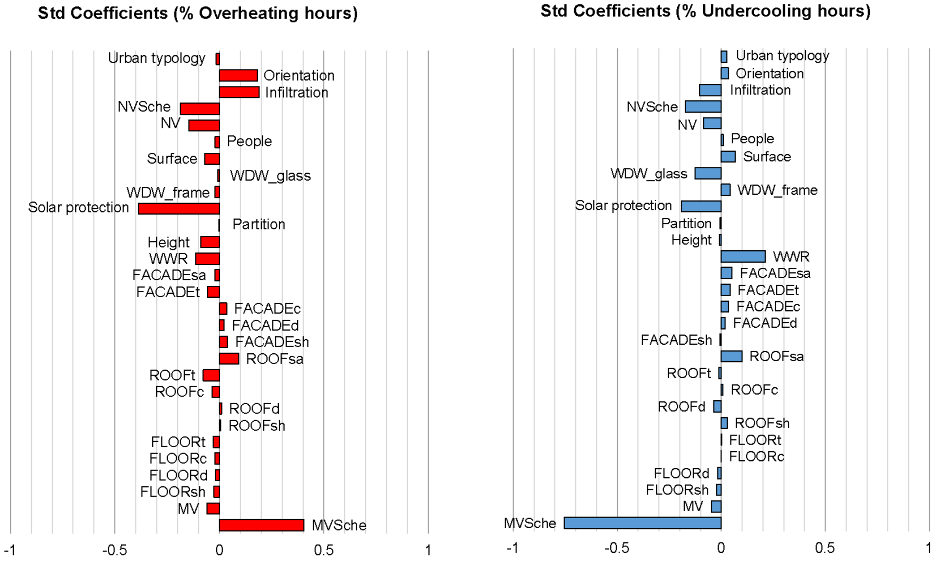
3 Results and discussion

Figure 3 depicts the outcomes from the SRRC sensitivity analysis conducted on the validated BSM, examining the impact of several building parameters on the annual overheating percentage (red color) and undercooling discomfort (in blue) hours. To achieve this, 3400 simulations were executed, ensuring a population size surpassing the generally accepted threshold of ≥ 10 Latin hypercube sampling per parameterized variable (considering 31 parameterized variables).

Regarding overheating risks, the most influential variables on discomfort are as follows: mechanical ventilation schedule, external solar protections, natural ventilation schedule, infiltration, building orientation, window-to-wall ratio and natural and mechanical ventilation rates. Similarly to Machard et. al (2023) [5], window-to-wall ratio, ventilation and solar control systems, are among the most influential variables on thermal performance. Yet, the order of importance varies from the results obtained, probably given the climate differences (Paris vs. southern Spain). Also, as pointed by Figueiredo et al. (2016) [8], external shading protections highly influence discomfort, highlighting the importance of windows.

Conversely, the variables with the lowest impacts include partition wall configuration and roof density and specific heat. Similarly, when analyzing the variables with the higher impact on undercooling risks, mechanical ventilation schedule holds the top one, being followed by window-to-wall ratio, external solar protections, natural ventilation schedule, window glass type, infiltration and natural ventilation rates. In contrast, several envelope characteristics, such as façade and roof specific heat or roof conductivity, floor conductivity and thickness, are among the variables with the lowest impact. This is interesting when compared to the results of Facundo Bre et al. (2016) [7], who identified external walls as a critical parameter for building thermal performance in Argentina, proving again the significance of the climate.

Therefore, it is worth noting that in southern Spain, while the performance of the building's envelope holds paramount importance in terms of energy balance, parameters related to window configuration and air-exchange variables assume greater significance under the Mediterranean climate conditions. Thus, retrofit strategies should focused on these aspects, in order to optimize the improvement of building thermal and energy performance. Likewise, operational issues are of the utmost importance, being necessary to define adequate ventilation and window operation schedules according to each seasonal period, appropriately transferring this knowledge to the ultimate users.


Std Coefficients (% Overheating hours)

Std Coefficients (% Undercooling hours)

Fig. 3. SRRC results for the % of overheating (red) and undercooling (blue) discomfort hours. Abbreviations are defined in brackets in Table 2 (c, d and sh refer to conductivity, density and specific heat, which are related to the U-values).

4 Conclusions

The most critical variables on overheating and undercooling risks in the social housing stock of southern Spain have been obtained through parameterized BSM. The main findings are:

- When analyzing several building design parameters, the most influential variables on overheating and undercooling discomfort are window configuration and ventilation-related variables, highlighting the significance of ventilation schedules over ventilation rates, and the importance of window operation for guaranteeing thermal comfort.
- The proposal of retrofit strategies to improve energy efficiency and thermal comfort should consider the most critical variables on both overheating and undercooling risks, in order to implement the solutions with the highest impacts on the building' energy balance, while considering other aspects, such as users' economic capacities or public programs.
- Parameterized and validated BSM facilitate to thoroughly assess buildings' performance and the potential of retrofit solutions, simultaneously simulating different building archetypes through the modification of key parameterized variables (orientation, window-to-wall ratio, geometry, envelope properties, operational aspects, etc.). Thus, it offers great opportunities in contrast to the single-building level, reducing computation time and manual input configuration, as well as, providing general results at the stock level.

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