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Passive Discomfort Index as an alternative to Predicted Mean Vote and Predicted Percentage of Dissatisfied to assess occupant's thermal discomfort in dwellings

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Abstract

Besides energy poverty, a certain tolerance to discomfort justifies Portugal's low heating energy consumption. Once Portuguese buildings stock, previous to 1990, has a weak energy performance, it is crucial to reflect on how to make renovations with more assertive benefits (besides energy), such as those related to the health and comfort of occupants. Hence, we have studied a single house in the TRNSYS dynamic simulation tool. We performed a sensitivity analysis by simulating the same building in three locations based on Portuguese climatic winter zones: I1 – Santarém, I2 – Santa Maria da Feira, and I3 – Guarda, for two ranges of wall insulation thickness, in free float. Considering Fanger's Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) as the Passive Discomfort Index IDP, results suggest that lowering 20 mm on the insulation thickness does not substantially impact occupants' discomfort in winter. As the variations between scenarios considering PPD > 15%, PMV < -1, or IDP (T_{air} < 18 ºC) are very similar, IDP could be an alternative to PMV/PPD for assessing thermal discomfort in dwellings.

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
Building Energy Simulation (BES)
Directorate-General for Geology and Energy (DGEG)
Energy Performance Certificates (EPCs)
Energy Performance of Buildings Directive Directive (EPBD)
National Civil Engineering Laboratory (LNEC)
Nearly Zero Energy Buildings (NZEBs)

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Passive Discomfort Index (IDP)
Predicted Mean Vote (PMV)
Predicted Percentage of Dissatisfied (PPD)

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Keywords: Dwellings; IDP; PMV/PPD; Thermal Discomfort; TRNSYS

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1. Introduction

The Energy Performance of Buildings Directive Directive (EPBD) [1] establishes improvements to existing buildings' comfort conditions and energy performance, bringing them closer to buildings with almost zero energy needs, Nearly Zero Energy Buildings (NZEBs). There are three winter climatic zones in mainland Portugal, I1, I2, and I3, with severity increasing from I1 to I3 [2]. Based on ISO 13790:2008 [3], the adopted methodology to estimate building heating and cooling needs considers only two seasons: winter (heating) and summer (cooling), assuming that people continuously heat or cool their homes throughout the seasons, which is not valid for Portuguese families [4].

Furthermore, there is a clear difference between the theoretical energy consumption resulting from the seasonal calculation and the actual one, lower the latter. Occupants' perception strongly influences their behavior and represents an important variable affecting buildings' energy performance [5]. The characteristics of the users differ widely from one profile of inhabitant to another, due not only to varied lifestyles but also to reasons related to geography, culture, behavior, and socioeconomic status [6]. Occupant's adaptive actions strongly affect the indoor environment, leading to significant discrepancies between the actual and predicted indoor environment [7]. Energy poverty and tolerance to discomfort are some reasons for Portugal's low heating energy consumption [8]. When the topic is energy efficiency and the reduction of final energy for heating, the conclusion is that energy consumption is already so low that the concern should be minimizing people's winter discomfort [4].

Thermal comfort is a crucial factor determining the health of the occupants living in dwellings [9]. However, perceived comfort is a complex interaction of several variables, and it took pioneering laboratory and field research in the '70s. Per-Ole Fanger provided the theoretical description of such interaction leading to the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) method. In the sense of PMV/PPD, occupants achieve thermal neutrality when the heat generated by human metabolism dissipates, maintaining the body's thermal equilibrium with the surroundings. It is necessary to define environmental parameters like air temperature, mean radiant temperature, air velocity, partial vapor pressure, and individual-related input parameters like metabolic rate and clothing insulation [10].

Researchers have widely studied thermal comfort since the middle of the twentieth century. From Fanger's model based on the neutral thermal state and the development of the PMV/PPD indexes to the adaptive approach based on buildings that operate with natural ventilation, several studies set detailed conditions with strengths and limitations. Magalhães and de Freitas proposed a methodology to quantify a passive discomfort index, *Índice de Desconforto Passivo* (IDP), from Portuguese, by calculating the temperatures outside the comfort range within the building based on the Portuguese reality of free-floating temperature or intermittent heating [4].

The main objectives of this study are to perform a dynamic multizone simulation for a single-family building in three Portuguese geographical locations, varying the thickness of the thermal insulation of the exterior walls and calculating PMV, PPD, and IDP. The final goal is to check if IDP can be an alternative to Fanger's PMV/PPD indexes to evaluate occupants' discomfort in winter.

With PMV/PPD, it is necessary to consider a lot of parameters, some of them with an inevitable subjectivity like metabolic rate and clothing insulation. On the contrary, IDP is more accessible as it considers the discomfort hours outside the comfort range.

This paper is structured as follows. Section 1 introduces the problem and provides a literature review about retrofitting strategies and thermal comfort assessment. Section 2 presents the adopted methodology, and Section 3 highlights meaningful discussions about results. Finally, Section 4 presents the conclusions.

2. Methodology

2.1. Thermal comfort

Fanger considered one's skin temperature and sweat secretion as the base for human thermal comfort. With these two factors balanced, Fanger thought occupants to be comfortable within a narrow range of acceptability. PMV is an index that aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale. There is thermal equilibrium when an occupant's internal heat production is the same as its heat loss. The levels of physical activity, clothing insulation, and the thermal environment parameters influence the heat balance of an occupant. For instance, the thermal sensation is generally perceived as better when individuals can control the indoor temperature. The PMV scale is as follows: 0 is neutral; +3 translates as too hot, while -3 translates as too cold – Table 1.

Table 1. Sensation scale of PMV index.

Scale	Categories
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral (comfort)
-1	Slightly cool
-2	Cool
-3	Cold

The PPD establishes a quantitative prediction of the percentage of thermally dissatisfied occupants. PPD essentially gives the percentage of people predicted to experience local discomfort. The main factors causing lack of comfort are unwanted cooling or heating of an occupant's body. Using both indices, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 [11] establishes requirements for suitable thermal environments. It defines an acceptable environment as "an environment that a substantial majority of the occupants would find thermally acceptable". The remaining percentage of people can experience 10% dissatisfaction based on whole-body discomfort and 10% dissatisfaction based on local or partial body discomfort.

Bienvenido-Huertas & Rubio-Bellido conducted a study from the international to the specific comfort models, concluding that ASHRAE 55-2017 [11] and EN 16798-1:2019 [12] are the two most used. Researchers in Australia, Chile, India, and Romania developed other models for particular building types or climate conditions. Many research studies at different levels of resolution have presented the potential of adaptive thermal comfort models better to understand the occupants' adaptability [13].

Moreover, while analyzing the indoor thermal comfort in a residential building using PMV/PPD, Choi et al. concluded that it is necessary to apply the accurate value of the clothing insulation to control the thermal environment comfortably. Future developments are needed to define a real-time clothing insulation prediction model [14]. Hassan et al. used two data collection methodologies in their study. They have performed a survey to obtain the residents' responses to their environment. In the meantime, based on an indoor physical measurement, the indoor climates have been described and analyzed in terms of air temperature, mean radiant temperature, relative humidity, and air velocity. Finally, with the characterization of the clothing insulation, they evaluated the comfort temperature, PMV/PMD, and determined the comfort temperature band [15].

Maiti evaluated the effect of the indoor thermal environment on occupants' response and thermal comfort using PMV/PPD, concluding that those indexes might be insufficient [16]. The problem is that heat balance is insufficient for human thermal comfort, so the Fanger thermal comfort equation and its evaluation indicators might have limitations. According to Becker & Paciuk, the assumption of a proportional relationship between thermal response and thermal load might be inadequate, with thermal comfort achieved at substantially lower loads than predicted by the model. Survey results also show that symmetrical responses in the negative and positive directions of the scale do not represent similar comfort levels [17]. Studies have shown that the actual thermal sensation of the test subjects is significantly higher than the PMV through the thermal comfort survey of winter and summer dwellings, pointing out that there is a lack of equations [18].

Magalhães et al. studied the influence of insulation on the passive discomfort index of historical residential buildings. According to their findings, the current Energy Performance Certificates (EPCs) methodology might not be the best for evaluating thermal performance in a moderate climate with a low heating practice [19]. They have concluded that high insulation thicknesses may not always have the high expected benefit. Furthermore, Cavaleiro Barbosa et al. studied school buildings and realized that the roof insulation thickness was essential until 5 cm of mineral wool. Still, additional investment in substantial insulation thicknesses did not significantly reduce thermal discomfort [20].

Ensuring thermal comfort is often one of the main objectives of architects and engineers. So far, this success has depended on personal experience and the applicability of standard estimation methods. It is a challenging task to predict PMV and PPD in advance. With the emergence of Building Energy Simulation (BES) tools, guesswork should not be the rule.

2.2. Building energy simulation with TRNSYS

Using TRNSYS software, Hebbal et al. studied how to improve underground buildings' thermal comfort and energy efficiency compared to aboveground facilities in hot and arid climates based on yearly energy consumption. The results revealed that an underground structure considerably decreases cooling energy demand during summer [21]. Calise et al. proposed a novel approach to calculate the energy and economic savings due to heat metering and thermostatic valves in dwellings. They have studied four different typologies of buildings, including their geometrical and thermophysical properties, and have first modeled them in Sketchup and subsequently linked them to the TRNSYS environment [22]. Valdiserri et al. analyzed several parameters, including PMV, and PPD indices under different inlet air temperatures, to identify the best design conditions for energy efficiency and thermal comfort improvement. They found that supplying neutral air was the best option [23]. With a TRNSYS simulation model of energy consumption and energy efficiency, Adam et al. analyzed the influence of the Heating, Ventilation, and Air Conditioning (HVAC) system on thermal comfort through the values of PMV and PPD [24]. Yu et al. used TRNSYS software to simulate the air-conditioning system of the actual and a new control scheme. They found that the new method's PMV and PPD indices were better than the original [25].

Achieving thermal comfort within a space is an intrinsically unwieldy task. Thermal environments can change over time, and proposed limits cannot always be reached, especially with climate change and unpredictable weather patterns. However, TRNSYS can provide PMV and PPD indices based on environmental and personal inputs with a weather file respecting the local climate.

This paper aims to analyze people's discomfort in temperatures below 18 °C [2]. Hence, we have considered Fanger's PMV/PPD indexes and IDP, a passive discomfort index proposed by S. A. Magalhães and V. P. de Freitas [4], representing the number of hours during occupation time with temperatures lower than 18 °C. According to Fanger, people feel discomfort when PPD is higher than 15 %. If PMV is lower than -1, it means that people feel cold. To compare IDP, $PPD > 15\ \%$, $PMV > 1$, and $PMV < -1$, they are all expressed in the percentage of hours of discomfort in the occupied hours of the winter season (2702 hours). We have used the Sketchup plugin and TRNSYS 16 to model the building and perform all the simulations.

2.3. Case study

Thermal discomfort depends on indoor temperature and relative humidity. However, the Portuguese scheme for energy certification of buildings does not refer to relative humidity. Hence, we used the temperature criterion to assess indoor thermal discomfort in this study. We selected a two-floor single-family house (Fig. 1) from the '90s with a concrete structure, masonry walls, and double glazing windows for the case study complying with the legal requirements of Ordinance No. 379-A/2015 [26].

Fig. 1. Plan blueprints of the building under investigation.

Using Sketchup, we have done a 3D simulation model design (Fig. 2).

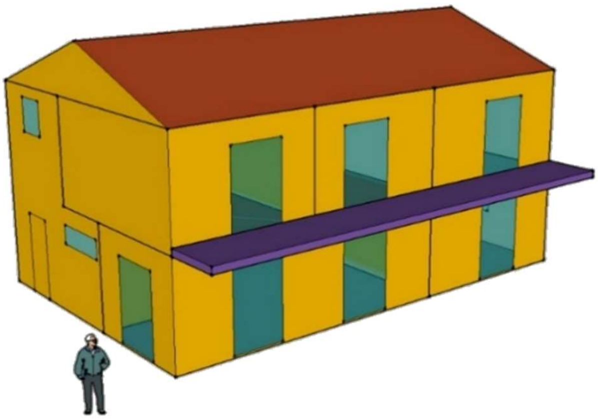

Fig. 2. 3D model of the building developed in Sketchup.

According to the solar orientation and the schedules, we have decided to create eight thermal (Fig. 3).

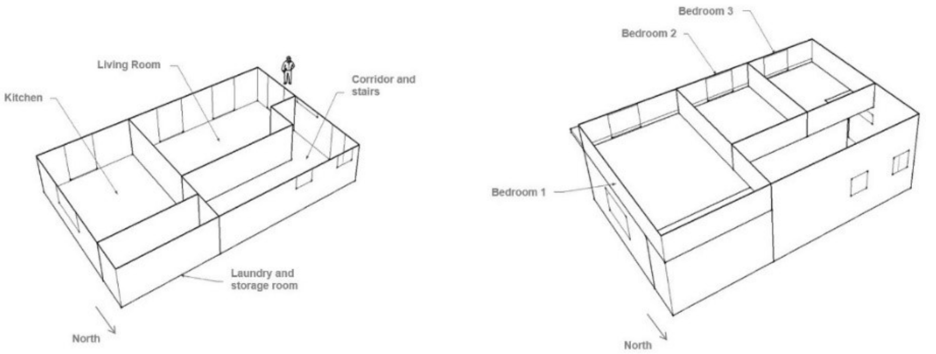

Fig. 3. Thermal zones.

ITE 50 [27], published by National Civil Engineering Laboratory (LNEC) and Order N.º 15793-K/2013 [28], were the basis for the building solutions. The physical properties of the layers are shown in Table 2.

Table 2. Physical properties of the layers.

Layer	Thickness [m]	Thermal Resistance [(m^2.°C)/W]	Thermal Conductivity [W/(m.°C)]	Density [kg/m^3]
Air	$\geq$ 0.03 m	0.18		
Wood	0.024		0.18	650
Brick	0.11	0.27	0.41	1272
Plaster	0.015		1.30	1900
Reinforced concrete			2.00	2350
Wall Ceramic Tile	0.01		1.30	2300
Portuguese roof tile	0.05		0.60	1500
Expanded polystyrene	0.2		0.038	15
Mineral rock wool	0.10/0.12		0.040	21
Voided slab	0.18	0.18	1.00	1583

Table 3 shows the physical properties of the adopted building solutions.

Table 3. Thicknesses of each layer.

Building elements layers (from inside to outside)						
Convective Heat Transfer Coefficient of Wall [W/(m^2.°C)]: Inside/Outside/Ground = 3.05/17.78/0.001 Solar Absorptance[-] of: External Door - Inside/Outside = 0.6/0.6; All other building elements - Inside/Outside = 0.4/0.4						
External Roof						
Scenarios	Layer	Portuguese roof tile				
All	Thickness [m]	0.05				
Internal Floor						
Scenarios	Layer	Plaster	Voided slab	Wall Ceramic Tile		
All	Thickness [m]	0.015	0.18	0.01		
2nd floor internal ceiling						
Scenarios	Layer	Plaster	Voided slab	Mineral rock wool		
scn1, scn2, scn4, scn5	Thickness [m]	0.015	0.18	0.10		
scn3, scn6				0.12		
External Wall						
Scenarios	Layer	Plaster	Brick	AIR	Brick	Expanded polystyrene
scn1, scn6	Thickness [m]	0.015	0.11	-	0.11	0.05
scn2						0.06
scn3						0.08
scn4						0.03
scn5						0.04
External Door						
Scenarios	Layer	Wood				
All	Thickness [m]	0.024				
Internal Wall						
Scenarios	Layer	Plaster	Brick	Brick	Plaster	
All	Thickness [m]	0.015	0.06	0.05	0.015	
Ground Floor						
Scenarios	Layer	Wall Ceramic Tile	Reinforced concrete	Plaster		
All	Thickness [m]	0.01	0.2	0.015		

We have considered free float conditions due to the Portuguese families' low heating practice [8]. Afterward, we studied six scenarios based on the geographic location and the insulation thickness of the exterior walls. To analyze the impact of the thermal insulation thickness on occupant's comfort, we have decided to split the simulations as follows: first with the legal requirements for the insulation level of the masonry walls (scenarios 1, 2, and 3) and then with lower insulation thicknesses (scenarios 4, 5, and 6) as shown in Table 4.

Table 4. Simulation scenarios.

Scenario	Building location	External insulation thickness of masonry walls [mm]
scn1	I1 - Santarém	50
scn2	I2 - Santa Maria da Feira	60
scn3	I3 - Guarda	80
scn4	I1 - Santarém	30
scn5	I2 - Santa Maria da Feira	40
scn6	I3 - Guarda	60

Table 5 (opaque elements) and 6 (fenestration) describe the final physical properties.

Table 5. Physical properties of the opaque elements.

Building Elements	scn 1 U [W/(m^2.°C)]	scn 2 U [W/(m^2.°C)]	scn 3 U [W/(m^2.°C)]	scn 4 U [W/(m^2.°C)]	scn 5 U [W/(m^2.°C)]	scn 6 U [W/(m^2.°C)]
External Roof	3.947	3.947	3.947	3.947	3.947	3.947
2nd floor internal ceiling	0.349	0.349	0.297	0.349	0.349	0.297
Internal Floor	2.708	2.708	2.708	2.708	2.708	2.708
External Wall	0.488	0.433	0.352	0.657	0.560	0.488
Internal Wall	2.160	2.160	2.160	2.160	2.160	2.160
External Door	3.301	3.301	3.301	3.301	3.301	3.301
Ground Floor	3.457	3.457	3.457	3.457	3.457	3.457

Table 6. Physical properties of the fenestration.

Fenestration

Convective Heat Transfer Coefficient of Wall [W/(m^2.°C)]:
Inside/Outside = 3.05/17.78
Solar Absorptance of the frame [-] = 0.6

	U [W/(m^2.°C)]	DR [W/(m^2.°C)]	SGHC [-]
External Window	2.65	0.64	0.5

Regarding the climatic data used for the simulations, we used the database provided by Directorate-General for Geology and Energy (DGEG) [29]. For PMV/PPD, we had to define environmental and individual-related parameters previously, contrasting with the no need to do it for IDP.

Fig. 4 shows the flowchart of the BES with TRNSYS.

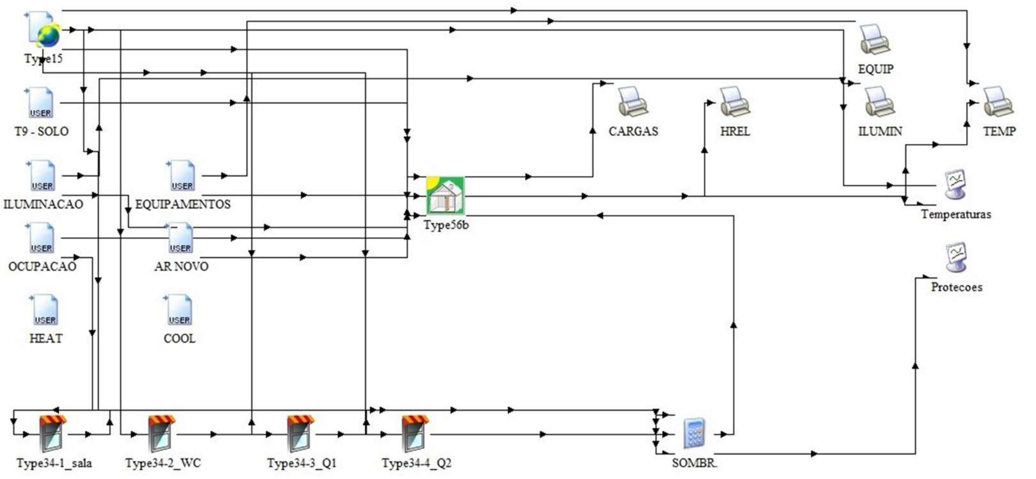

Fig. 4. Flowchart of the BES with TRNSYS.

3. Results and discussion

Results from dynamic simulations have shown that Bedroom 3 (which faces south and west orientations) is where people's discomfort is higher, so the analysis will focus on this space – Table 7.

The percentage of hours of discomfort considering PPD > 15% is accordingly to the severity of the winter climatic zones of Portugal. In I1, 56% (scenario 1) and 57% (scenario 4). In I2, there is an increase in the percentage of discomfort hours – 73% (scenario 2) and 74% (scenario 5). Finally, in the most severe zone, I3, 89% (scenario 3 and scenario 6) is where the percentage of discomfort hours is higher - 89% (scenario 3 and scenario 6).

For PMV < -1, the percentage of hours feeling cold follows the same pattern of PPD > 15%. In I1, 42% (scenario 1) and 43% (scenario 4). In I2, 62% (scenario 2) and 63% (scenario 5) and, in I3, 81% (scenario 3 and scenario 6).

Considering IDP and the percentage of hours with $T_{air} < 18$ °C, the values are very similar to PMV < -1 and also increases from I1 to I3. In I1, 43% (scenario 1) and 44% (scenario 4). In I2, 63% (scenario 2) and 64% (scenario 5) and, in I3, 82% (scenario 3 and scenario 6).

The slight variations of thermal discomfort considering PPD > 15%, PMV < -1, or IDP ($T_{air} < 18$ ºC) suggest that higher insulation thicknesses do not seem to significantly impact occupants' comfort improvement, resulting in financial and resources waste:

- In I1 – Santarém, less 20 mm of the insulation thickness means an increase of discomfort of 2.2% (PPD > 15%), 1.6% (PMV < -1) and 2.4% (IDP);
- In I2 – Santa Maria da Feira, less 20 mm of the insulation thickness means an increase of discomfort of 1.1% (PPD > 15%), 1.5% (PMV < -1) and 2.5% (IDP);
- In I3 – Guarda, less 20 mm of the insulation thickness means an increase of discomfort of 0.2% (PPD > 15%), 0.3% (PMV < -1) and 0.4% (IDP).

Moreover, the variation between scenarios considering PPD > 15%, PMV < -1 or IDP ($T_{air} < 18$ ºC) is very similar. Hence, IDP could be an excellent approach to thoroughly assessing thermal discomfort.

Table 7. PPD > 15%, PMV < -1 and IDP for Bedroom 3 in each location.

Location	I1 - Santarém		I2 - Santa Maria da Feira		I3 - Guarda	
Scenario	1	4	2	5	3	6
External insulation thickness of masonry walls [mm]	50	30	60	40	80	60
PPD > 15%						
% of hours of discomfort	56%	57%	73%	74%	89%	89%
Variation between scenarios	2.2%		1.1%		0.2%	
PMV < -1						
% of hours feeling cold	42%	43%	62%	63%	81%	81%
Variation between scenarios	1.6%		1.5%		0.3%	
IDP						
% of hours with $T_{air} < 18$ ºC	43%	44%	63%	64%	82%	82%
Variation between scenarios	2.4%		1.5%		0.4%	

4. Conclusions

Energy efficiency in residential buildings is crucial in controlling carbon emissions. The profile of occupants has a significant influence on energy consumption in dwellings. There is a difference between the theoretical energy consumption and the one that occurs in Portuguese houses due to energy poverty and cultural reasons. In Portugal, energy consumption for heating is already so low that the concern should minimize occupants' discomfort. Using TRNSYS 16, we have performed a dynamic multizone simulation for a single-family building in three Portuguese geographical locations, varying the thickness of the thermal insulation of the exterior walls. Compared with IDP, for PMV/PPD, we had to consider additional parameters, some of which have subjectivity, like metabolic rate and clothing insulation. Defining complex parameters to assess thermal comfort in dwellings may not be the way to move forward, negatively influencing architects and engineers to change from an exclusive energy point of view and evaluate occupants' thermal discomfort in dwellings.

We evaluated the thermal discomfort variation reducing the masonry walls' insulation thickness with Fanger's, PMV/PPD, and IDP. The results suggest that lowering 20 mm on the insulation thickness does not substantially impact occupants' discomfort in winter. As the variations between scenarios considering PPD > 15%, PMV < -1, or IDP ($T_{air} < 18$ ºC) are very similar, IDP could be an excellent approach to assess thermal discomfort in dwellings.

Further research, based on calibrated models matched with temperature monitoring of the buildings, should be followed to achieve more generalized results.

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