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Mutual Influence of External Wall Thermal Transmittance, Thermal Inertia, and Room Orientation on Office Thermal Comfort and Energy Demand

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Abstract: Upgrades in building energy efficiency codes led to differences between buildings designed according to outdated codes and those with most recent requirements. In this context, our study investigates the influence of external wall thermal transmittance, thermal inertia, and orientation on energy demand (heating, cooling) and occupant thermal comfort. Simulation models of an office building were designed, varying (i) the thermal transmittance values (0.20 and 0.60 W/(m^{2}K)), (ii) the room orientation (four cardinal directions), and (iii) the wall thermal inertia (approximately 60 kJ/(m^{2}K) for low and 340 kJ/(m^{2}K) for high thermal inertia. The energy demand for heating and cooling seasons was calculated for Ljubljana using EnergyPlus 9.0.0 software. The reduction of the external wall thermal transmittance value from 0.6 W/(m^{2}K) to 0.2 W/(m^{2}K) contributes to significant energy savings (63% for heating and 37% for cooling). Thermal inertia showed considerable potential for energy savings, especially in the cooling season (20% and 13%, depending on the external wall insulation level). In addition, the orientation proved to have a notable impact on heating and cooling demand, however not as pronounced as thermal inertia (up to 7% total energy demand). Comparison of the thermal comfort results showed that when internal air temperatures are identically controlled in all the rooms (i.e., internal air temperature is not an influencing factor), the external wall thermal transmittance, thermal inertia, and room orientation show negligible influence on the average occupant thermal comfort. The simultaneous achievement of thermally comfortable conditions in the working environment and low energy use can only be achieved by simultaneously considering the *U*-value and thermal inertia.

Keywords: office building; thermal comfort; energy demand; thermal inertia; orientation

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1. Introduction

The building sector stakeholders are becoming increasingly aware of the importance of holistic building design. Occupant thermal comfort and building energy demand are some of the most important performance aspects affecting buildings' sustainability [1–6]. Reducing energy demand is crucial from the environmental point of view [7], and thermal comfort influences the psychophysical abilities of building users [8–12]. Both factors are strongly linked to the economic and social aspects of building sustainability as reducing energy demand lowers the operating costs and increasing occupant thermal comfort leads to better health and, consequentially, higher productivity of users [1,13–16]. From this perspective, office buildings are an important part of the built environment as a large part of the population spends a huge amount of time in them. They can be considered crucial elements for a functional society, as they represent working environments where various activities take place.

The building fund of office buildings in Europe consists of buildings from different periods. Approximately 38% of buildings in Europe were built before 1960, 45% in 1961–1991, and 17% in the 1991–2010 period [17]. Non-residential buildings represent a quarter of the European building stock; of that, office buildings represent 23% of floor area. They account for 26% of the total energy use in non-residential buildings and over 50% in combination with wholesale and retail buildings [17].

In the past, building technology and legislation regarding building efficiency have changed, and buildings in general have become more energy efficient. For the reduction of transmission heat loss through the building envelope (non-transparent and transparent part), the maximal allowed thermal transmittance (max *U*-value) is regulated (besides annual heating and cooling energy requirements and primary energy).

Upgrading energy efficiency building codes led to a steep reduction of max *U*-values across Europe [18]. In Slovenia, the max *U*-values for building assemblies have changed several times in the past 20 years [19]. For example, from 2002 to 2008, the max *U*-value for external walls was 0.60 $W/(m^2K)$; from 2008–2022, 0.28 $W/(m^2K)$ and 0.18 $W/(m^2K)$ from 2022 onwards. These gradual legislative and technological changes over the past 20 years have resulted in notable differences between relatively new buildings. In the case of Slovenia, a building construction that fulfils energy efficiency requirements from the 2002–2008 period exerts a three times higher external wall *U*-value compared to a building construction that fulfils legislation adopted in 2022. Similar situations occur in all countries that implemented gradual energy efficiency measures over the past decades. Considering that the lifespan of buildings can be well over 50 years, building owners of relatively new buildings can face a dilemma regarding the economic viability of improving the thermal properties of the building envelope. In simple terms, what are the benefits of adding a thermal insulation layer to the building envelope?

The positive impact of reducing heating and cooling demands due to the increased envelope thermal resistance is straightforward and well-understood [20]. In existing design practice, there is less emphasis on understanding the *U*-factor and its impact on occupant thermal comfort. Studies on the effect of thermal insulation have shown that an optimally designed thermal envelope, regardless of the climate, has a beneficial effect on the heat balance of the human body [21]. Additionally, the positive impact of high-efficiency buildings on workers' productivity and reduced absenteeism in the workplace was demonstrated [22]. Recent cost-benefit analyses have shown that the cost to the employer, the building owner, and society of poor indoor environmental quality is much higher than the cost of the energy used by the same building [23]. That is why any improvement towards increasing indoor environmental quality is reasonable and justified. As thermal comfort can significantly influence the productivity of occupants, it can be an additional motivation factor for reducing building envelope thermal transmittance values. It is, therefore, of interest to evaluate if differences in thermal transmittance values, due to changes in building energy efficiency codes, lead to differences in occupant thermal comfort.

However, energy demand and occupant comfort in office buildings are influenced not only by the envelope's *U*-value but also by many factors in constant interactions [5]. One of the important factors is thermal inertia (often referred to as "thermal mass"), which describes the influence of thermal energy storage and release processes due to the transient state of the environment in building design [24]. The research on thermal inertia and its impact on the energy demand and thermal comfort of buildings has gained wide attention. The contribution of thermal inertia to energy demand and thermal comfort is difficult to evaluate accurately. The extreme values of impact on energy demand range from +10% to −80% [24]. The impact of thermal inertia depends on various factors that must be considered in parallel when designing studies and evaluating research results [25]. In the summer, office buildings are prone to overheating due to high internal heat gains of occupants and equipment combined with gains from solar radiation [26]. Studies have shown that high thermal inertia (in combination with other measures, e.g., shading, night-time ventilation) provides energy and thermal comfort benefits in cooling seasons and hot Mediterranean climates [27–29]. Verbai et al. [30] studied the effect of room's orientation, glazed area, and thermal mass on the heating energy demands in a Continental climate.

Using the outdoor temperature and solar intensity data of the reference day, the operative temperature variation in rooms with different thermal mass, different glazing areas, and different orientations of the glazed area was analysed. The differences between the heating energy demands can reach even 11% depending on the orientation, glazed area, and thermal mass of the room.

The degree of thermal inertia also plays a role, as buildings with "medium" inertia can show favourable energy demand compared to those with "low" and "high" inertia [31]. Thermal inertia in office buildings is related to the heating, ventilation, and air conditioning (HVAC) system sizing and electrical grid stability due to the reduction and/or time shift of system peak loads [32–35]. The building orientation and thermal mass distribution can also influence cooling loads and indoor air temperature stability [36]. Considering only thermal comfort, thermal inertia can be used as a tool for improving occupant thermal comfort in office buildings; however, some form of HVAC system is needed to fully satisfy the occupants' thermal needs during the occupied hours [37]. A comprehensive study of 200,000 field and laboratory measurements published by Dawe et al. [38] reports that internal air temperature is the primary influencing factor for occupant thermal comfort in mechanically conditioned offices. This indicates that when the air temperature is sufficiently controlled, the envelope design and internal surface temperatures could influence the occupant thermal comfort minimally.

In order to address the complexity of interactions influencing building energy use and occupant thermal comfort, our study aims to investigate the implications of improving the external wall *U*-value for a theoretical office building. Besides *U*-value, thermal inertia and orientation were also investigated. The impact of each parameter on heating and cooling energy demand is predictable and well understood when evaluated individually. However, their mutual influence on energy demand and, especially, on thermal comfort is not straightforward and worth evaluation. Therefore, the research question of our study is as follows: What is the mutual influence of external wall U-value, thermal inertia, and office room orientation on thermal comfort and the energy demand for heating and cooling?

A simulation model depicting an office building floor was designed. A total of thirty-two simulation alternatives were analysed, with thermal transmittance values varying according to the national requirements (0.20 and 0.60 W/(m^2K)); room orientation (four cardinal directions) and wall thermal inertia (approximate 60 kJ/(m^2K) for low and 340 kJ/(m^2K) for high thermal inertia). Energy demand for the heating and cooling seasons was calculated for the continental climate of Ljubljana (Koppen climate classification: Cfb) using the EnergyPlus software [39]. The thermal comfort was evaluated using the mean radiant temperature (*Tmr*), predicted mean vote (*PMV*), and predicted percentage dissatisfied (*PPD*) metrics. The simulated thermal comfort results were compared with the data of in situ measurements from the ASHRAE Global Thermal Comfort Database [40].

In the context of the study topicality, the study objectives are: (i) to determine the mutual influence of external wall *U*-value, thermal inertia, and office room orientation on the selected parameters of thermal comfort (*Tmr*, *PPD*, *PMV*); (ii) to determine the mutual influence of external wall *U*-value, thermal inertia, and room orientation on the energy demand for heating and cooling; (ii) to evaluate which combination of the observed parameters has the most pronounced influence on thermal comfort and energy demand. The results could assist policymakers, engineers, or owners of relatively new office buildings regarding decisions for or against improving the external envelopes' *U*-value while simultaneously evaluating thermal inertia and orientation. The relevance of the research area with the findings of the paper will be to assist all researchers who are directly and indirectly involved in the process of building construction and who are striving to improve the situation.

2. Materials and Methods

The simulation models were designed to present the mutual influence of the external wall *U*-value, thermal inertia, and orientation on the occupant thermal comfort and energy demand. As many factors influence both energy demand and thermal comfort, the models were designed to exclude as many influencing factors as possible, so that the obtained results reflect the impact of the external wall design and orientation.

The energy simulation software EnergyPlus 9.0.0 [39] was used to analyse the thermal comfort and energy demand of the simulation models. EnergyPlus is a whole-building simulation tool, which enables to calculate unsteady state energy demand based on climate data and a predefined calculation step. The calculations were carried out for a one-year time period. The geometry and basic simulation data were prepared through Sketchup 5.0.1 [41] and OpenStudio 3.2.1 [42]. The input for simulation data regarding the thermal comfort metrics and the output variables were prepared in EP launch 2.14c [43]. The calculated results were available in the CSV file format and were additionally organized in a suitable spreadsheet format. A total of 8 simulation alternatives were designed and based on the thermal transmittance values, they can be divided into two groups, Models 06 and Models 02. The external wall U-value is 0.6 W/(m^{2}K) for the first group and 0.2 W/(m^{2}K) for the second, in accordance with the Slovenian national requirements from 2002 and 2010. The four simulation models in each group differ in the thermal inertia design and distinct temperature setpoints for thermal comfort and energy demand analysis (detailed explanation in Section 2.1). The results were evaluated for the south, north, east, and west office rooms, aggregating in 32 observed entities. The simulation model design framework is presented in Figure 1.

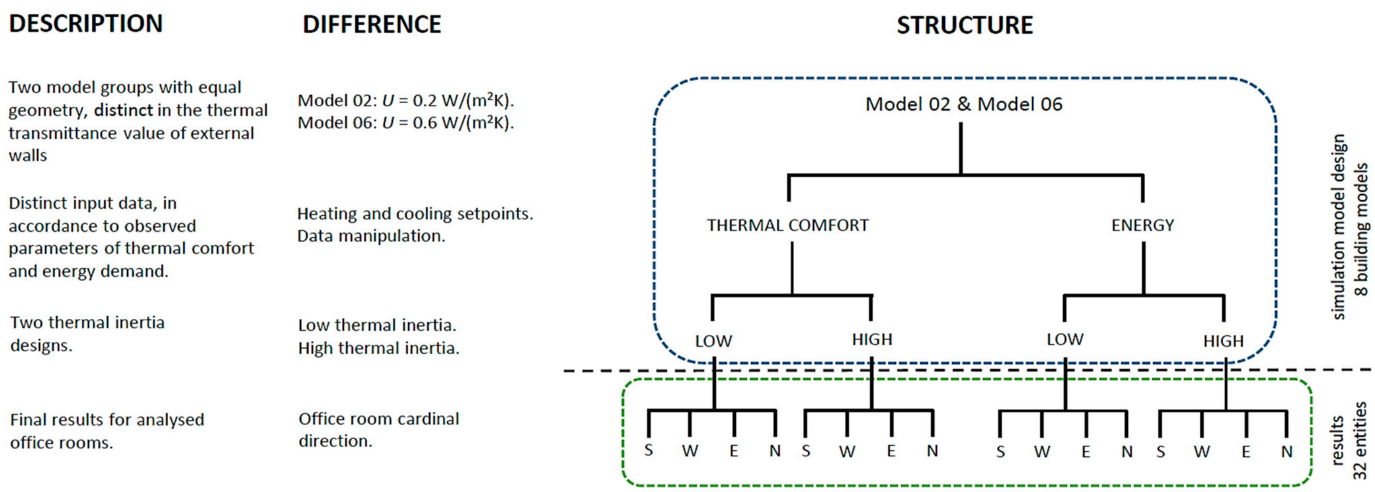

Figure 1. Simulation model design framework.

2.1. Simulation Models

2.1.1. Geometry and Materials

The simulation model emulates an interim office floor with a floor plan of 16 × 16 m and a height of 3.2 m. The floor plan is divided into 4 × 4 m office rooms, which face different orientations. The simulation model is presented in Figure 2. Only office cells facing the cardinal directions are analysed. Each office cell represents a separate thermal zone with the following characteristics: A_u = 16 m^2, V_e = 51.2 m^3. The external walls in the office cells have a window to wall ratio (WWR) of 30%, which is approximately twice the minimum value based on the Slovenian requirements for workplace safety [44]. The assembly compositions and their thermal transmittance values are presented in Table 1. The wall assembly is designed as an external thermal insulating composite system (ETICS).

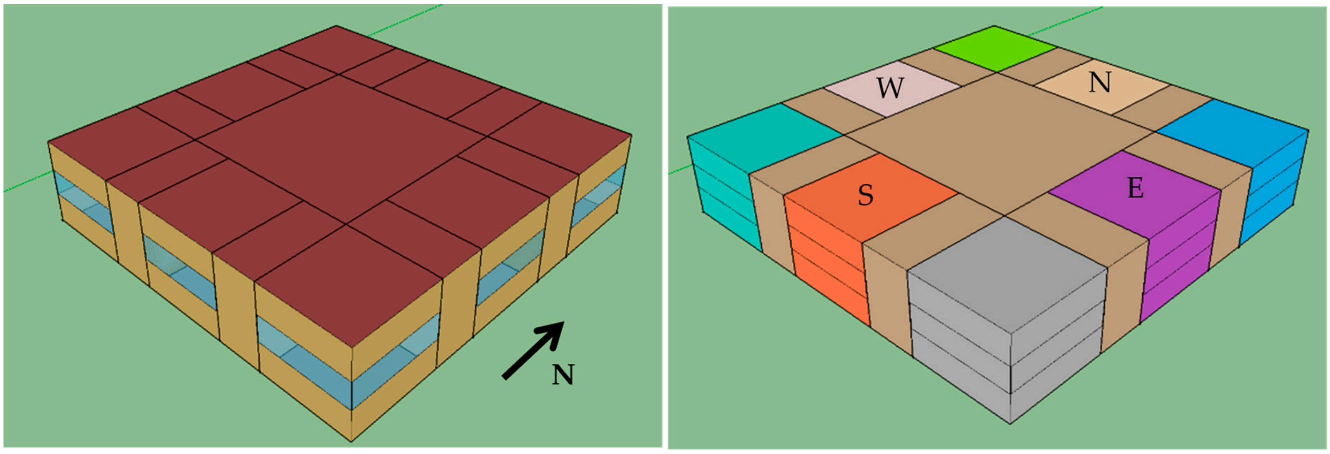

Figure 2. Visual presentation of the interim office floor simulation model and the analysed office cells facing the cardinal directions.

The celling and floor assemblies are identical in all model alternatives. The low thermal inertia external wall represents a filigree structure wall with flexible core thermal insulation. An important simplification in the low thermal inertia design is the omission of the load bearing elements. The design of the external wall with high thermal inertia represents a reinforced concrete wall with external thermal insulation boards. The external wall designs were chosen in order to represent the thermal inertia extremes, achieved with typical building materials. The internal walls were designed based on the external wall thermal inertia design. For the high thermal inertia design, the internal walls consist of a 15 cm thick reinforced concrete wall, and for the low thermal mass design, a simple hollow gypsum board wall partition.

Corresponding window designs were also chosen for Models 06 and Models 02. The windows for the two model groups differ in the thermal properties. For Models 06, a double pane glazing was used, whereas a triple pane glazing system was applied in Models 02 (Table 2).

2.1.2. Input and Output Data

As the aim is to investigate how the thermal inertia of external walls effect thermal comfort and energy demand (heating, cooling), the model was designed specifically for this purpose. The celling and floor assemblies are set to adiabatic boundary conditions, so only the external walls are exposed to the outside environment (outside boundary condition). The internal air temperature was controlled with an active HVAC system using the ideal air loads model. The relevant input data for the simulation models are presented in Table 3.

The simulation models to calculate energy demand for heating and cooling and thermal comfort differ in the internal air temperature setpoints (Tables 4 and 5). In the thermal comfort models, the air temperature is fixed at a single value, which changes depending on the external air temperature (season). In this way, the impact of internal air fluctuations is excluded and the differences in the thermal comfort results between the models can be attributed to the observed influencing factors: external wall *U*-value, thermal inertia, and room orientation. For the thermal comfort analysis, the Fanger thermal comfort model was used with its predicted mean vote (*PMV*) and predicted percentage dissatisfied (*PPD*) metrics [45]. Other relevant parameters for thermal comfort are presented in Table 6. To calculate energy demand, the single setpoint temperature is not suitable, as the simulation model would exert a constant heating and cooling load in order to control the internal air temperature. Therefore, the internal air temperature ranges are set for heating and cooling, which is the usual procedure for building energy simulation.

Table 1. Building assemblies and relevant physical properties of materials and assemblies.

	Material	λ (W/(mK))	ρ (kg/m^3)	c (J/(kgK))	Thickness (cm)	U-Value * (W/(m))	Assembly Thermal Capacity (kJ/(m^{2}K))
Floor/Ceiling						1.46	111.6
	Lightweight concrete	0.53	1280	840	10.0		
	Ceiling air space resistance	R = 0.18 m^{2}K/W					
	Acoustic tile	0.06	368	590	1.9		
Low thermal inertia models							
Internal wall						2.58	33.1
	gypsum board	0.16	800	1090	1.9		
	Wall air space resistance	R = 0.15 m^{2}K/W					
	gypsum board	0.16	800	1090	1.9		
External wall—Model 02						0.20	61.5
outside	outside plaster	0.8	1500	1000	0.5		
	stone wool board	0.035	100	830	7		
	gypsum fibre board	0.25	1300	1100	1.6		
	stone wool slabs	0.035	36	830	10		
	gypsum board	0.25	680	960	2.5		
	inside plaster	0.39	1100	1090	0.5		
External wall—Model 06						0.60	54.2
outside	outside plaster	0.8	1500	1000	0.5		
	gypsum fibre board	0.25	1300	1100	1.6		
	stone wool slabs	0.035	36	830	5.2		
	gypsum board	0.25	680	960	2.5		
	inside plaster	0.39	1100	1090	0.5		
High thermal inertia models							
Internal wall						16.67	316.8
	Reinforced concrete	2.5	2400	880	15		
External wall—Model 02						0.20	344.4
outside	outside plaster	0.8	1500	1000	0.5		
	stone wool board	0.035	100	830	17		
	Reinforced concrete	2.5	2400	880	15		
	inside plaster	0.39	1100	1090	0.5		
External wall—Model 06						0.60	334.9
outside	outside plaster	0.8	1500	1000	0.5		
	stone wool board	0.035	100	830	5.5		
	Reinforced concrete	2.5	2400	880	15		
	inside plaster	0.39	1100	1090	0.5		

* U-value is calculated without internal and external heat transfer coefficients.

Table 2. Thermal properties of window elements.

	Frame Conductance (W/(m^{2}K))	Glazing *U*-Factor (W/(m^{2}K))	*SHGC* (/)
Models 02	1.0	1.05	0.409
Models 06	1.7	1.86	0.439

Table 3. EnergyPlus model input data.

Input	Value	Unit	Description	Reference
Climate	/	/	Ljubljana, Slovenia (Koppen climate classification: Cfb)	/
Timesteps per hour	1	/	The simulation outputs are calculated hourly.	/
Occupancy	2	Persons per office	The average number of occupants is 1.52 as the occupancy depends on the office work occupancy schedule in accordance with EN 15232	/
Ventilation	34	(m^3/h) × person	The ventilation rate depends on office work occupancy schedule in accordance with EN 15232	Standard 189.1: 2009 [46]
Infiltration	0.816	(m^3/h) × exterior surface area	The infiltration rate depends on the infiltration schedule, which assumes 25% infiltration during occupied hours.	Standard 189.1: 2009 [46]
Occupation load/ activity	120	W	Office activity	ISO 8996:2021 [47]
Lighting load	10.66	W/m^2	The final lighting load depends on the office building lighting schedule.	Standard 189.1: 2009 [46]
Electric equipment load	6.9	W/m^2	The final electric equipment load depends on the office building equipment schedule, which assumes a reduced load during unoccupied hours.	Standard 189.1: 2009 [46]
WWR	30	%	/	/
Shading control Venetian blinds (for all orientations except the north one, where no shading devices are used)	130	W	Solar radiation exceeds 130 W on the window surface. Type of slat angle control: Block Solar Beam.	EN 15232-1:2018 [48]
HVAC system	/	/	Ideal air load	/

Table 4. Input for heating and cooling setpoint for the energy simulation model.

Input	Value	Unit	Description	Reference
Air temperature ranges for heating	21.0–23.0	°C	According to the category I for indoor environment of office spaces.	EN 15251:2007 [49]
Air temperature ranges for cooling	23.5–25.5	°C	According to the category I for indoor environment of office spaces.	EN 15251:2007 [49]

Table 5. Input for heating and cooling setpoint for the thermal comfort simulation model.

Input	Value	Unit	Description	Reference
Winter air temperature setpoint	21.0	°C	From 15 November to 15 March	In accordance to EN 15251: 2007 [49]
Interim air temperature setpoint (spring and autumn)	22.5	°C	From 16 March to 15 May and 15 September to 14 November.	
Summer air temperature setpoint	24.0	°C	From 16 May to 14 September	

Table 6. EnergyPlus input variables for the Fanger thermal comfort model.

Variable	Value/Model	Reference/Description
Mean radiant temperature calculation type	Zone averaged	The mean radiant temperature is calculated for an average point in the room, based on area-emissivity weighted average of all the surfaces in the zone.
Clothing insulation calculation method	Dynamic clothing model	The clothing insulation as a function of outdoor air temperature measured at 6 a.m. Method developed by S. Schiavon and K. H. Lee [50]
Air velocity	0.15 m/s	ISO 7730: 2005 [51]

The simulation outputs, i.e., metrics used for analysing the thermal comfort and energy demand, are (Table 7): mean radiant temperature (*Tmr*), predicted mean vote (*PMV*), predicted percentage dissatisfied (*PPD*), heating energy demand, cooling energy demand, and total energy demand.

Table 7. Simulation output for thermal comfort and energy demand.

Thermal Comfort	Energy
Mean radiant temperature (*Tmr*) (°C)	Heating demand (kWh)
Predicted mean vote (*PMV*) (/)	Cooling demand (kWh)
Predicted percentage dissatisfied (*PPD*) (%)	Total demand (heating + cooling) (kWh)

As 32 different entities are analysed for the thermal comfort and energy demand, acronyms are used to present the results. In accordance with Figure 1, "Models 02" and "Models 06" are used to represent the distinct features of the simulation models in terms of the thermal transmittance values of the opaque external wall element and the corresponding thermal properties of windows (see Section 2.1.1). Thus, acronyms "02" and "06" are used to represent the values relevant for Models 02 and Models 06, respectively. To represent the difference in the thermal inertia design, "L" is used for low thermal inertia and "H" for high thermal inertia design. To separate the results for different cardinal directions, acronyms "S", "W", "E", and "N" are used. Combining the acronyms allows the specific entity to be identified (e.g., "L06, S" is the south oriented room for the low thermal inertia design of Models 06 simulation group). The presented acronyms are also used as subscripts. In this way *PMV,avg-06L,S* denotes the average *PMV* value for the south oriented room in the low thermal inertia model of the Models 06 simulation group.

2.1.3. Simulation Model Limitations and Scope

The simulation models were designed in order to show how the external wall thermal properties (in particular, the thermal transmittance and thermal inertia of the opaque part) and orientation influence the thermal comfort and the energy demand. To do this, the simulation models have specific design features and simplifications.

Some of the factors that can influence the results and are not covered in the analysis are: intensive night-time ventilation cooling, HVAC systems, location of occupants, internal loads (equipment, occupants, lighting), furniture, WWR ratio, shading devices, and shading control. An important simplification is that for the thermal comfort analysis, internal air temperature is constant and that the impact of the occupant's location in the room is not included, as the thermal comfort results are calculated for thermal zone (office room) averages. In reality, the internal air temperature fluctuates in an acceptable temperature range, depending on the external air temperatures. Moreover, we did not analyse the local thermal discomfort, which can be an important factor for the occupant's thermal discomfort. Additionally, the simulation model represents an interim office floor, and the results are calculated for office rooms facing the cardinal directions and not for a whole office building. Finally, the WWR and shading control can importantly impact the thermal comfort and energy demand results. For our study, a highly efficient external blind system is used for all windows, except the north orientation, where no shading devices are used. Moreover, corresponding window thermal properties are adopted with a 30% WWR for each model group, as the design of office rooms without windows would be too unrealistic. The above-mentioned model limitations need to be considered when interpreting the simulation results.

2.2. Comparison with ASHRAE Global Thermal Comfort Database II

The simulated thermal comfort results were compared with in situ measurements data from the ASHRAE Global Thermal Comfort Database II [40]. The database includes approximately 82,000 complete sets of indoor climatic observations with subjective evaluations by building occupants who were exposed to the thermal environments. This allows the selection of a wide range of thermal comfort data, from in situ instrumental measurements to building occupant questionnaire responses. The filtering criteria are grouped in the following key parameters: study, subjective, building, demographic, climate, comfort, and measurements.

Table 8 presents the search parameters and filter options for acquiring thermal comfort data. The goal was to collect data from air-conditioned office buildings in comparable climates and internal air temperatures. The measurements were collected separately for the heating and cooling seasons, which were controlled with the outdoor monthly temperature filter option. Only the data with recorded internal air temperatures in the 20.5–21.5 °C range for the heating and in the 23.5–24.5 °C range for the cooling season were compared. In this way, we wanted to include only data that originate from comparable boundary conditions. Because only limited number of datasets were available for the oceanic climate, we had to search for data based on external air temperatures, which provided a larger dataset for comparison.

Table 8. Search parameters in the ASHRAE Global Thermal Comfort Database II.

Parameters	Filter Option	
Study	/	
Subjective	/	
Building	Office Air Conditioned	
Demographic	/	
Climate	Outdoor Monthly Temperature (°C)	−10 to +10 +20 to +30
Comfort	*PMV*	
Measurements	Air Temperature (°C)	20.5 to 21.5 23.5 to 24.5

3. Results

3.1. Thermal Comfort

3.1.1. High Thermal Transmittance—Models 06

The room mean radiant temperature (*Tmr*) reveals the influence that the external wall design and room orientation have on the thermal comfort, as the surface temperature of the other room surfaces (floor, ceiling, internal walls) is equal to or only slightly different from the air temperature. In the appendices, the results are presented for all room orientations (Appendix A). For clarity reasons, only the results for the south and north oriented rooms are presented. Figure 3 shows the maximum, average, and minimum mean radiant temperatures for the low and high thermal inertia design for the south and north oriented rooms (S, N). Although the *Tmr,max* values indicate a notable distinction in the thermal behaviour, the *Tmr,avg* values show small differences. Comparing first the average mean radiant temperatures (*Tmr,avg*) for the different orientations reveals slightly lower values for the high thermal inertia design, from 0.1 to 0.3 °C. The main differences are notable in the heating season (winter), when the south oriented rooms receive more solar radiation and consequentially have higher mean radiant temperatures. This leads to a maximum difference of 0.3 °C for the low and 0.2 °C for the high thermal inertia design in January, compared to rooms with other orientations. In the cooling (summer) and transition (spring, autumn) periods, the *Tmr,avg* values are similar, regardless of the orientation. In reference to the average air temperature, the *Tmr,avg* values are lower by 0.5 to 0.8 °C in winter and higher by 0.4 to 0.9 °C in summer.

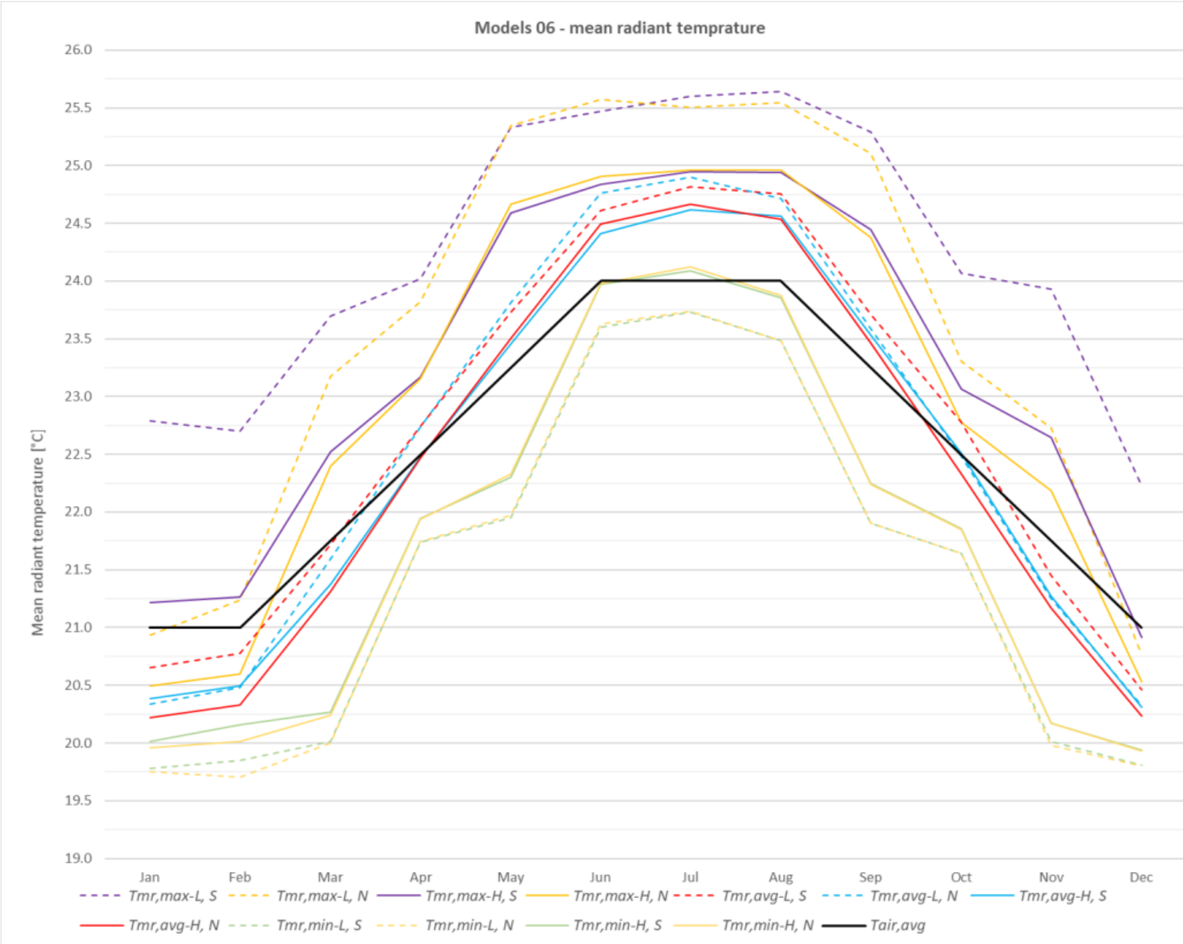

Figure 3. Monthly mean radiant temperature (*Tmr* (°C)) values for the south and north oriented rooms in Model 06 thermal comfort simulation models.

Important differences are notable for the *Tmr,max* values, both for the orientations and for the thermal inertia design. Low thermal inertia design leads to higher values of maximum mean radiant temperature. For the south oriented room with low thermal inertia design, the maximum mean radiant temperature in winter is 1.6 °C higher than the high thermal inertia design and 2.3 °C higher than the north high thermal inertia design, which has the lowest maximum mean radiant temperature. In the appendix, the data and temperature plots are shown for all the room orientations. There it can be observed that in the cooling period, the west oriented rooms show the highest mean radiant values when compared to other orientations. However, the difference is far more pronounced for the low thermal inertia design, where the mean radiant temperature is approximately 0.5 °C higher compared to other orientations. The orientation shows no influence on the *Tmr,min* values. Thermal inertia shows a small but observable influence, as the values are slightly lower—from 0.1 to 0.4—for the low thermal inertia design, with the main difference occurring in the heating season.

Based on mean radiant temperatures, it can be concluded that the orientation influences the *Tmr* values more for the low thermal inertia design and that the difference between the maximum and minimum values is also more pronounced for the low thermal inertia design than in the high thermal inertia design. This confirms the assumption that higher thermal inertia leads to a more stable thermal environment in buildings. Table 9 displays the influence of the orientation and thermal inertia design on the difference between the maximum and minimum mean radiant temperature. The east and north oriented rooms show similar thermal behaviour trends, whereas the south oriented rooms experience the largest difference in the heating season and the west oriented rooms in the cooling period (Table 9, left half). It is interesting to note that for the high thermal inertia design, the differences between *Tmr,max* and *Tmr,min* are on average 45% smaller (in the range from 30–60%, depending on the orientation and month) than for the low thermal inertia design. The right part of Table 9 shows the differences in the maximum and minimum values for the different orientations due to the influence of thermal inertia, confirming that the high thermal inertia design has smaller temperature variations. These variations are most pronounced in the south oriented room during the cooling period, with the difference between *Tmr,max* ranging from 1.3 to 1.6 °C (December, January, and February).

Table 9. Influence of orientation and thermal inertia on mean radiant temperature for Models 06. REMARK: Room temperature setpoints changes influence the results in March, May, September and November. Therefore, the differences are larger and should not be used as reference.

	Orientation Influence: Actual Difference (= *Tmr,max–Tmr, min*) (°C)								**Thermal Inertia Influence: Actual Difference (Minuend = Low Thermal Inertia Values) (°C)**							
	L06,S	***H06,S***	***L06,E***	***H06,E***	***L06,W***	***H06,W***	***L06,N***	***H06,N***	***Max, S***	***Min, S***	***Max, E***	***Min, E***	***Max, W***	***Min, W***	***Max, N***	***Min, N***
January	3.0	1.2	1.3	0.6	1.8	0.7	1.2	0.5	1.6	−0.2	0.5	−0.2	0.9	−0.2	0.4	−0.2
February	2.9	1.1	1.6	0.7	2.2	0.8	1.5	0.6	1.4	−0.3	0.6	−0.3	1.1	−0.3	0.6	−0.3
March	3.7	2.3	3.3	2.3	3.8	2.3	3.2	2.2	1.2	−0.3	0.8	−0.2	1.2	−0.2	0.8	−0.2
April	2.3	1.2	2.1	1.3	2.4	1.2	2.1	1.2	0.9	−0.2	0.7	−0.2	1.0	−0.2	0.7	−0.2
May	3.4	2.3	3.4	2.3	3.9	2.3	3.4	2.3	0.7	−0.4	0.7	−0.3	1.3	−0.4	0.7	−0.4
June	1.9	0.9	1.8	0.9	2.6	1.1	1.9	0.9	0.6	−0.4	0.6	−0.3	1.0	−0.4	0.7	−0.3
July	1.9	0.9	1.8	0.9	2.3	1.0	1.8	0.8	0.7	−0.4	0.6	−0.3	0.9	−0.4	0.5	−0.4
August	2.2	1.1	2.0	1.1	2.4	1.2	2.1	1.1	0.7	−0.4	0.6	−0.3	0.9	−0.4	0.6	−0.4
September	3.4	2.2	3.2	2.2	3.4	2.1	3.2	2.1	0.8	−0.3	0.6	−0.3	1.0	−0.3	0.7	−0.3
October	2.4	1.2	1.8	1.0	2.3	1.1	1.7	0.9	1.0	−0.2	0.6	−0.2	0.9	−0.2	0.5	−0.2
November	3.9	2.5	2.9	2.1	3.1	2.1	2.7	2.0	1.3	−0.2	0.6	−0.2	0.7	−0.2	0.5	−0.2
December	2.4	1.0	1.0	0.6	1.1	0.6	1.0	0.6	1.3	−0.1	0.3	−0.1	0.3	−0.1	0.2	−0.1

The question is how these differences, presented in Table 9 and Figure 3, reflect in the *PMV* metrics for thermal comfort. The mean radiant temperatures directly influence the thermal comfort, as they are the only parameters that change between the different orientations and thermal inertia designs (due to the simulation model design). The first thing to note is that the *PMV* values are always smaller than 0, indicating thermal sensation on the cool side of the *PMV* thermal comfort scale (Figure 4). The *PMV* values are distributed between the values -1.5 in winter and -0.15 in summer. As in the case of mean radiant temperature, the largest differences are notable when comparing the maximum *PMV* values, where the orientation and thermal inertia importantly influence the results. The low thermal inertia design (L06) shows greater influence of orientation, as the *PMV* values for the south oriented room can notable deviate (up to 27%) compared to the northern orientation in the heating season. With respect to the model with lower thermal inertia, the maximum *PMV* values for the high thermal inertia show smaller deviations. The variations in the maximum *PMV* values are not reflected in the average *PMV* values, where the orientation and thermal mass design show little influence. It can be observed that the *PMV,avg* values for the low thermal mass model are slightly higher, but the differences are small (e.g., in March *PMV,avg-L,S* = −0.70 and *PMV,avg-H,N* = −0.70). For this reason, the average thermal comfort in the observed office cells can be considered comparable for the south and north oriented office cells, regardless of the thermal inertia design. The minimal *PMV* values show negligible influence of orientation and minimal influence of thermal inertia design.

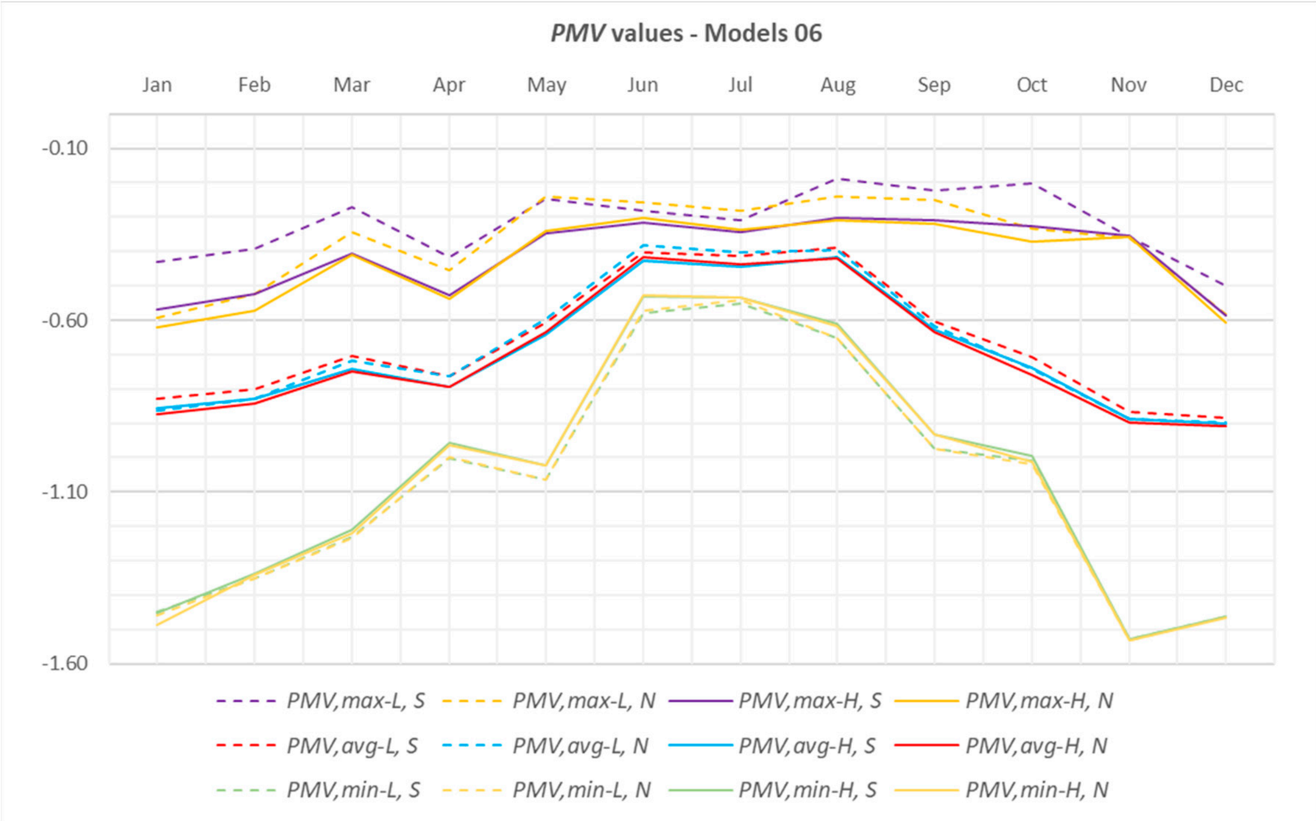

Figure 4. Monthly *PMV* simulation results for Models 06.

In Appendix A, the *PMV* values for all the room orientations are presented and commented on. The conclusions are similar. Deviations in the *PMV* values due to orientation and thermal inertia design are notable, but in general, the results indicate that the thermal comfort is comparable in all the observed office rooms, regardless of the orientation and thermal inertia design.

3.1.2. Low Thermal Transmittance—Models 02

Similar trends as in the case of Models 06 can be seen for the low thermal transmittance models, when observing the monthly mean radiant temperatures and *PMV* values. Orientation and thermal mass show considerable influence on the *Tmr,max* and *PMV*max values, both in the heating and cooling period. The impact on average and minimal values is, however, less pronounced. In reference to the average air temperature, the *Tmr,avg* values are smaller by 0.2 to 0.6 K in winter and 0.6 to 1 K larger in summer. A detailed description of the *Tmr* and *PMV* values with supplemented figures can be found in Appendix B. In the heating season, the mean radiant temperature fluctuations are the largest for the south oriented room and in the summer period for the west oriented one (Table 10, left side). An obvious distinction appears between the low and high thermal inertia models as the differences between maximum and minimum mean radiant temperatures are on average 35% lower (from 20 to 47%, depending on the orientation and month) for the high thermal inertia rooms. This becomes even more evident when comparing the influence of thermal inertia on the minimum and maximum values (Table 10, right side). As in the case of

Models 06, the high thermal inertia models show lower maximum and higher minimum mean radiant values in all months, when comparing rooms with the same orientations. In general, east and north oriented rooms show smaller fluctuations, while south oriented rooms show the largest differences in winter and west oriented rooms in summer.

Table 10. Influence of orientation and thermal inertia on mean radiant temperature for Models 02. REMARK: Room temperature setpoints changes influence the results in March, May, September and November. Therefore, the differences are larger and should not be used as reference.

	Orientation Influence: Actual Difference (= *Tmr,max–Tmr, min*) (°C)								**Thermal Inertia Influence: Actual Difference (Minuend = Low Thermal Inertia Values) (°C)**							
	L02,S	***H02,S***	***L02,E***	***H02,E***	***L02,W***	***H02,W***	***L02,N***	***H02,N***	***Max, S***	***Min, S***	***Max, E***	***Min, E***	***Max, W***	***Min, W***	***Max, N***	***Min, N***
January	2.7	1.4	1.1	0.7	1.6	0.9	1.0	0.6	1.1	−0.2	0.3	−0.2	0.6	−0.2	0.3	−0.2
February	2.5	1.4	1.3	0.8	1.8	1.0	1.4	0.7	0.9	−0.2	0.3	−0.2	0.6	−0.2	0.5	−0.2
March	3.1	2.3	3.0	2.4	3.5	2.6	3.0	2.3	0.5	−0.2	0.4	−0.2	0.7	−0.2	0.5	−0.2
April	1.7	1.1	1.7	1.2	2.2	1.3	1.9	1.2	0.4	−0.2	0.3	−0.2	0.6	−0.2	0.5	−0.2
May	3.0	2.2	3.0	2.3	3.6	2.4	3.3	2.4	0.4	−0.3	0.4	−0.3	0.8	−0.3	0.5	−0.3
June	1.5	0.8	1.4	0.9	2.2	1.3	1.8	1.0	0.3	−0.3	0.3	−0.3	0.6	−0.3	0.5	−0.3
July	1.3	0.8	1.4	0.8	1.8	1.0	1.5	0.8	0.3	−0.3	0.3	−0.3	0.5	−0.3	0.4	−0.3
August	1.6	1.0	1.6	1.0	2.0	1.2	1.8	1.1	0.3	−0.3	0.3	−0.3	0.5	−0.3	0.4	−0.3
September	3.0	2.3	3.0	2.3	3.1	2.2	3.2	2.4	0.4	−0.3	0.4	−0.3	0.5	−0.3	0.5	−0.3
October	1.9	1.2	1.5	1.0	2.0	1.3	1.5	1.0	0.5	−0.2	0.4	−0.2	0.5	−0.2	0.3	−0.2
November	3.7	2.7	2.7	2.1	2.9	2.3	2.6	2.1	0.8	−0.1	0.4	−0.1	0.5	−0.1	0.4	−0.1
December	2.2	1.2	0.9	0.6	1.0	0.6	0.9	0.6	0.9	−0.1	0.2	−0.1	0.3	−0.1	0.2	−0.1

From the presented results, we can conclude that room orientation and external wall thermal mass exert a discernible but small influence on the thermal comfort for Models 02. The thermal comfort is comparable for all the rooms, regardless of the orientation and thermal inertia design.

3.1.3. Thermal Comfort: Comparison between Models 06 and Models 02

Based on the presented results in Sections 3.1.1 and 3.1.2, we can already compare some results. With respect to the influence of thermal mass and room orientation, we can conclude that the trends for Models 06 and Models 02 are similar. The orientation and thermal mass design minimally influence the observed parameters (*Tmr*, *PMV*, *PPD*). Slight variations are noticeable, mostly for the extreme values, but on average, the thermal comfort is comparable. The main observation is that Models 02 lower the thermal transmittance value of the external wall and windows, which reflects in slightly smaller difference between the extremes in the observed metrics. When comparing the mean radiant temperatures, the difference in the extremes in the rooms with high thermal mass is on average 45% smaller for Models 06, whereas this difference is 35% for the rooms of Models 02 (Tables 9 and 10).

Comparing the mean radiant temperatures, we can observe minimal variations, even at the extremes. This is also reflected in the thermal comfort. Figures 5 and 6 show the maximal, minimal, and average *PMV* values for the south and north oriented rooms of Models 06 and 02, respectively. The differences are small, even for the maximum values which show the most notable variations when considering the influence of orientation and external wall thermal inertia. This indicates that the thermal comfort is comparable for all the observed rooms, for both thermal transmittance values of the external walls.

Appendix C presents the comparison number of hours with *PPD* above 15% of rooms with the same orientation for the low and high thermal inertia models separately. For both thermal inertia models, the rooms with lower external wall thermal transmittance values experience a slightly smaller share of hours above *PPD* 15% and the maximum deviation is approximately 20 h per month. When observing the hourly *PPD* values for a specific day (Appendix C), one can, however, see that the absolute *PPD* differences are small, as it happens that for one model, *PPD* is just below 15% and for the other slightly above.

Based on the results, we can conclude that for the analysed simulation models, the thermal comfort is comparable for all the orientations and external wall designs. Slight variations are noticeable, but on average the occupants will experience similar thermal sensation of the internal environment. Reducing the external wall thermal transmittance by an order of 3 was not reflected in improved occupant thermal comfort.

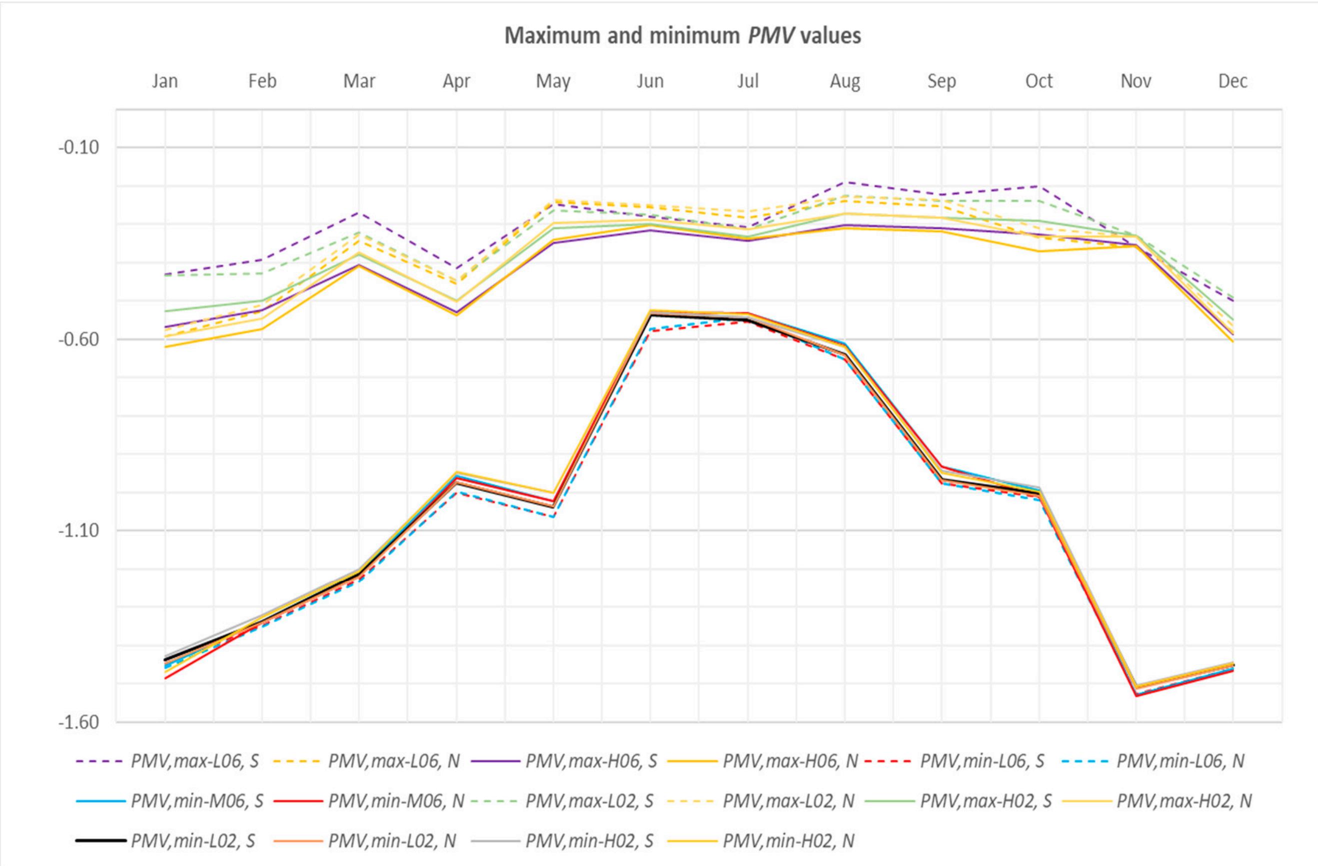

Figure 5. Maximum and minimum *PMV* values for the south and north oriented office cells of Models 06 and Models 02.

3.2. Comparison with In Situ Measurements from AHSRAE Global Thermal Comfort Database II

The results from the thermal comfort database (Table 11) reveal that occupants in air-conditioned office buildings generally have a thermal sensation corresponding to the *PMV* value ranging from neutral to slightly cool thermal sensation, when the internal air temperatures are 21 (±0.5) °C in the heating and 24 (±0.5) °C in the cooling season. Simulation results show that the *PMV* value is below −0.15 for 100% of occupied hours in both heating and cooling seasons. In the ASHRAE database, this is the case in 71.1% of the records in the heating season and in 50% in the cooling season. When we observe the share of the dataset when $PMV < -0.7$ (>15% *PPD*), we see that this is the case in approximately 20% of situations in winter and 7% in summer. The results from the ASHRAE database are in relatively good agreement with our simulation results. In the cooling season, the simulated results are in good agreement with the results from the ASHRAE database when observing the *PPD* values above 15%, whereas in the heating season a deviation is notable.

The search filters in the database do not include a more detailed parameter, e.g., *U*-value, thermal inertia, orientation, façade type, office type (closed or open), window to wall ratio, and shading controls, which could enable a more detailed comparison. Therefore, we can conclude that for the internal air temperatures used in our study, *PMV* values below −0.15 are common and that our simulation results are plausible. However, for the heating season, the results are extreme, as based on the ASHRAE thermal comfort database, a smaller share of occupants voted for the *PMV* values below −0.7 *PMV* (*PPD* above 15%).

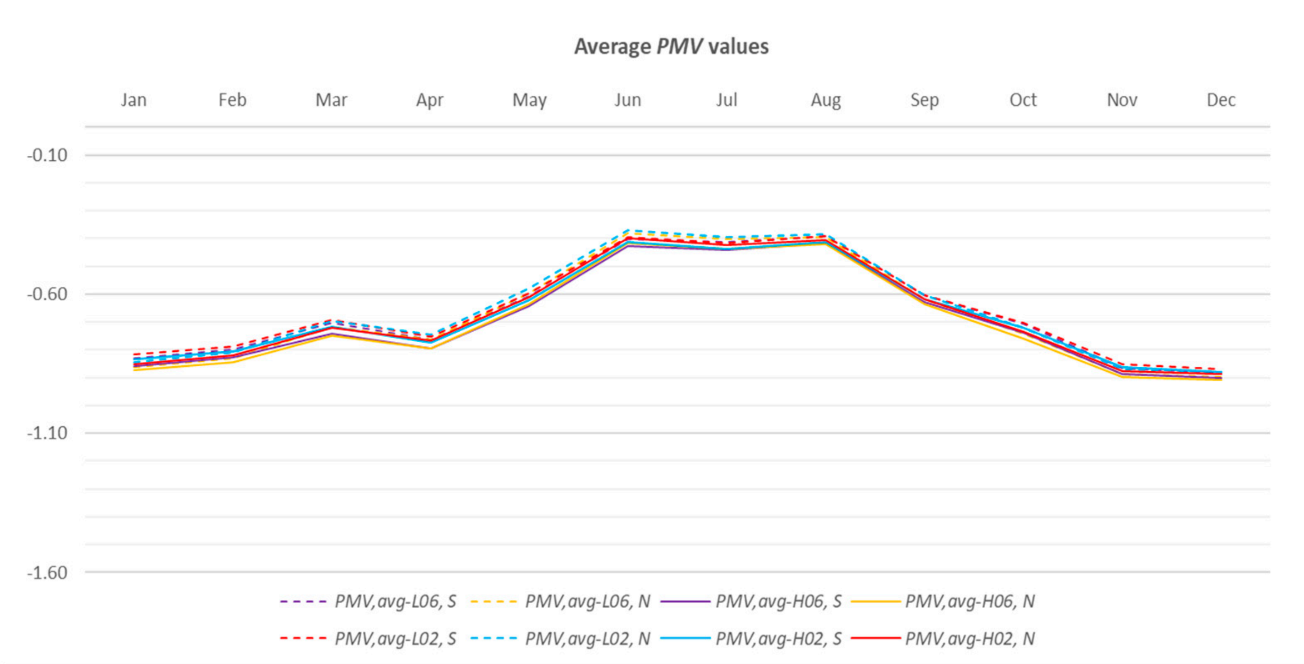

Figure 6. Average *PMV* values for the south and north oriented office cells of Models 06 and Models 02.

Table 11. Comparison of datasets from ASHRAE Global Thermal Comfort Database II.

	ASHRAE Database			Simulation Results *	
	Number of Datasets (/)	**Share of Datasets with *PMV* < −0.15 (%)**	**Share of Datasets with *PMV* < −0.7 (%)**	**Share of Hours When *PMV* < −0.15 (%)**	**Share of Hours When *PMV* < −0.7 (*PPD* > 15%) ** (%)**
Heating season	772	71.1	21.4	100	58 to 80
Cooling season	526	50.2	7.4	100	0

* Heating season; December, January, and February. Cooling season; June, July, and August, ** See Appendix C.

3.3. Energy Demand

3.3.1. Energy Demand: Models 06

Based on the data in Table 12, an influence of orientation on the room energy demand is observable for both the high and low thermal inertia models. The north oriented rooms exert 8 to 9% higher heating demand and 8% lower cooling demand, whereas the east and west oriented rooms show similar trends with a 6–7% higher heating and 1 to 4% lower cooling demand compared to the south oriented room. When comparing the total energy demand, the east, west, and north oriented rooms show similar consumption, which is approximately 2.5% more for the L06 and 4% for the H06 model when compared to the south orientation. The high thermal inertia models show slightly greater influence of orientation than the low thermal inertia models.

The influence of thermal inertia on the energy demand in rooms with identical orientations can be observed in Table 13. All the rooms in the high thermal inertia model show lower energy demand compared to the low inertia model. The heating demand difference is small (approximately 2%), whereas the cooling demand difference is substantial, from 18.7 to 20.7%. Consequently, the difference in the total energy demand is in the range of 7.7 to 9.1%.

Table 12. Heating, cooling, and total energy demand of rooms facing cardinal directions for the low and high thermal inertia designs of Models 06.

				Difference Based on South Orientation		
(a) Low Inertia	Heating (kWh)	Cooling (kWh)	Total (kWh)	Heating (%)	Cooling (%)	Total (%)
South	838.3	481.3	1319.6	0.0	0.0	0.0
East	894.0	462.7	1356.7	6.7	−3.9	2.8
West	890.7	463.3	1354.0	6.3	−3.8	2.6
North	910.7	440.4	1351.0	8.6	−8.5	2.4
				Difference Based on South Orientation		
(b) High Inertia	Heating (kWh)	Cooling (kWh)	Total (kWh)	Heating (%)	Cooling (%)	Total (%)
South	818.3	381.5	1199.8	0.0	0.0	0.0
East	875.3	373.9	1249.2	7.0	−2.0	4.1
West	873.6	376.8	1250.4	6.8	−1.2	4.2
North	893.2	352.2	1245.4	9.2	−7.7	3.8

Table 13. Comparison of energy demand between high and low thermal inertia designs for Models 06.

	Energy			**Difference**		
	Heating (kWh)	**Cooling (kWh)**	**Total (kWh)**	**Heating (%)**	**Cooling (%)**	**Total (%)**
L06, S	838.3	481.3	1319.6	0	0	0
H06, S	818.3	381.5	1199.8	−2.4	−20.7	−9.1
L06, E	894	462.7	1356.7	0	0	0
H06, E	875.3	373.9	1249.2	−2.1	−19.2	−7.9
L06, W	890.7	463.3	1354	0	0	0
H06, W	873.6	376.8	1250.4	−1.9	−18.7	−7.7
L06, N	910.7	440.4	1351	0	0	0
H06, N	893.2	352.2	1245.4	−1.9	−20	−7.8

When interpreting these results, we need to point out that the continental climate of Ljubljana enables nocturnal ventilation cooling. In the analysed models, a moderate night-time ventilation is adopted. If high intensity nocturnal ventilation cooling were applied, the difference between the high and low thermal masses could be smaller.

3.3.2. Energy Demand: Models 02

As in the case of Models 06, the influence of orientation can be seen also in Models 02 (Table 14). In the heating season, the south oriented rooms exert from 8.4 to 10.3% lower values for the L02 and from 7.2 to 8.6% lower values for the H02 model, compared to other orientations. An interesting situation occurs for the cooling season, when the north oriented rooms experience the highest energy demand. For the low thermal mass model, the difference is 5.3% and for the high thermal inertia model 3.8% compared to the south oriented rooms. This is surprising as one would expect the other orientations to have greater cooling demand, but one needs to account for the simulation model design. The shading control is important here because the south, east, and west oriented rooms have external venetian blinds that block direct solar radiation. Due to this, the north oriented room, which has no active shading devices, experiences slightly larger solar gains, due to diffuse solar radiation and direct solar radiation in summer mornings and evenings. When comparing the total energy demand, the east and west oriented rooms show similar behaviour and approximately 3.5% higher total energy demand compared to the south room. The north oriented rooms show the largest total energy demand, the difference is 7.2% for the low and 5.8% for the high thermal inertia model.

Table 14. Heating, cooling, and total energy demand of rooms facing cardinal directions for the low and high thermal inertia designs of Models 02.

(a) Low Inertia	Heating (kWh)	Cooling (kWh)	Total (kWh)	Difference Based on South Orientation Heating (%)	Cooling (%)	Total (%)
South	301.7	509.6	811.3	0.0	0.0	0.0
East	332.4	509.9	842.3	9.2	0.1	3.7
West	329.3	509.2	838.5	8.4	−0.1	3.2
North	336.4	538.0	874.3	10.3	5.3	7.2
(b) High Inertia	**Heating (kWh)**	**Cooling (kWh)**	**Total (kWh)**	**Difference Based on South Orientation Heating (%)**	**Cooling (%)**	**Total (%)**
South	302.6	445.4	747.9	0.0	0.0	0.0
East	328.4	447.6	776.0	7.9	0.5	3.6
West	325.9	447.8	773.7	7.2	0.5	3.3
North	331.1	463.0	794.1	8.6	3.8	5.8

When observing the influence of thermal inertia on the heating demand (Table 15), minimal differences can be noticed. For the south oriented room, the high thermal inertia shows a slightly higher heating demand (0.3%), whereas for the other orientations, the low thermal inertia rooms minimally exceed the energy demand of the high thermal inertia rooms (1 to 1.6%). As in the case of Models 06, the influence of thermal inertia is most notable for the cooling demand. The high thermal inertia rooms experience from 12 to 14% lower cooling demand for the same orientation. The extreme in the cooling demand is notable between the H02, S room and L02, N room, which is unexpected. The H02, S room experiences 17% lower cooling demand than the L02, N room. As explained above, this is due to the shading design and control. The difference in the total energy demand can be observed for all orientations, with the high thermal inertia rooms experiencing from 7.7 to 9.2% lower energy demand.

Table 15. Comparison of energy demand between high and low thermal inertia designs for Models 02.

	Energy Heating (kWh)	Cooling (kWh)	Total (kWh)	Difference Heating (%)	Cooling (%)	Total (%)
L02, S	301.7	509.6	811.3	0.0	0.0	0.0
H02, S	302.6	445.4	747.9	0.3	−12.6	−7.8
L02, E	332.4	509.9	842.3	0.0	0.0	0.0
H02, E	328.4	447.6	776.0	−1.2	−12.2	−7.9
L02, W	329.3	509.2	838.5	0.0	0.0	0.0
H02, W	325.9	447.8	773.7	−1.0	−12.1	−7.7
L02, N	336.4	538.0	874.3	0.0	0.0	0.0
H02, N	331.1	463.0	794.1	−1.6	−13.9	−9.2

3.3.3. Energy Demand: Comparison between Models 06 and Models 02

When comparing the energy demands between Models 06 and 02, there are obvious differences. However, some similarities do arise. In both groups, the main difference in the energy behaviour due to the influence of thermal inertia is notable in the cooling season, where the high thermal inertia models experience lower cooling demand. Between the rooms with identical orientations, these differences are approximately 20% for Models 06 (Table 13) and 13% for Models 02 (Table 15). We can conclude that thermal inertia has little influence for the heating season when observing equal orientations, as the differences are small (less than 2%). The total energy demand for the high thermal mass model is from 7 to 9% lower for both model groups. The reason is that in the case of Models 06, the average heating contribution to total energy demand is 68% (based on orientation and thermal mass from 64 to 72%) and for Model 02 the average share is 40% (from 37 to 42%). This means that the heating demand for Models 06 is approximately double the demand for cooling, whereas for Models 02 the heating demand is lower than the cooling one.

As expected, the difference in the thermal transmittance values significantly influences the energy demand for the analysed room orientations (Table 16). The reduction of *U*-value from 0.6 W/(m^{2}K) to 0.2 W/(m^{2}K) of the opaque wall assembly and the improved energy efficiency of windows (for detailed description of thermal properties of elements and materials see Section 2.1.1) reflects in average savings of 63% for heating and 37% for total energy demand. For heating and total energy demand reductions, there is small variation between the different room orientations and thermal inertia designs. In the case of cooling demand, on the other hand, the orientation and thermal inertia show important impact, as considerable variation in the results can be observed. The cooling demand is higher for the low thermal transmittance models (Models 02), which is expected (due to the impact of internal loads). The difference is between 6 and 31.5%, depending on the orientation and thermal inertia design.

Table 16. Comparison of energy demand reduction (%) for the office rooms due to change in external wall *U*-value reduction from 0.60 W/(m^{2}K) to 0.20 W/(m^{2}K).

Orientation	South		East		West		North	
Thermal Inertia	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Heating	−64.0	−63.0	−62.8	−62.5	−63.0	−62.7	−63.1	−62.9
Cooling	5.9	16.7	10.2	19.7	9.9	18.8	22.2	31.5
Total	−38.5	−37.7	−37.9	−37.9	−38.1	−38.1	−35.3	−36.2

When comparing the monthly energy demands, one can observe the yearly energy demand dynamics. Figure 7 shows heating and cooling energy demands for the south oriented room with different thermal inertia designs and external thermal transmittance values. One can notice that the heating demand in the coldest months can be slightly higher for the high thermal inertia models. This, however, does not reflect much in the total heating demand, as the high thermal mass models show lower heating demand in the transition months of May, September, and October. Moreover, the high thermal inertia models experience lower cooling demand in the transition season and summer (June, July, August).

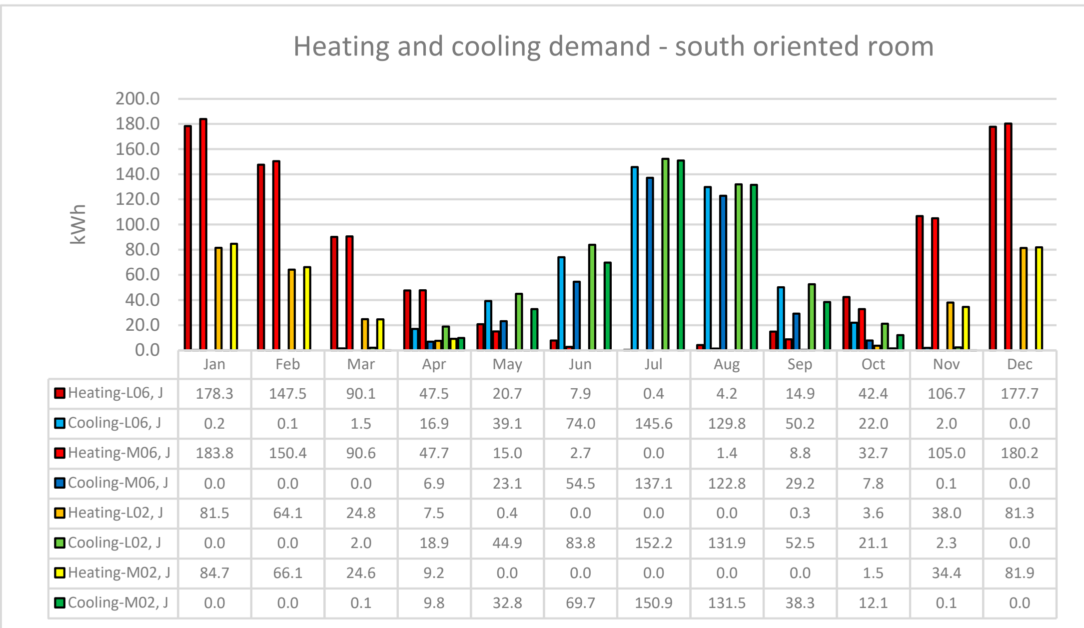

Figure 7. Monthly energy demand comparison for the south oriented room.

The thermal transmittance reduction of the external wall assembly has the most significant impact in the heating season, as a substantial heating demand reduction, from 55–65%, can be observed for both thermal inertia designs.

4. Discussion

The thermal comfort results showed an influence of the orientation and external wall thermal inertia. However, their impact on the average thermal comfort sensation is small. When comparing models, the results showed small variation in the thermal comfort metrics (*Tmr*, *PMV,* and *PPD*) and comparable thermal comfort. Based on the results, we can conclude that the thermal comfort of closed office rooms, separated from the continental outside climate environment through double pane windows (WWR 30%) and an external wall with *U*-value 0.6 W/(m^{2}K), is comparable to the thermal comfort of office spaces enclosed with modern energy efficient low *U*-value external walls. Reducing the external wall thermal transmittance by an order of 3 was not reflected in improved occupant thermal comfort. Office cell orientation and thermal inertia design showed negligible influence on thermal comfort. This is true in the case when the internal air temperature is not an influencing factor, meaning that the HVAC system is just as efficient as the maintenance of the internal air temperature at the assumed temperature setpoint. This finding correlates to the study outcomes of Dawe et al. [38], who analysed over 200,000 field and laboratory measurement in conditioned office buildings, and found that the absolute difference of air and mean radiant temperatures are small (median absolute difference is 0.4 °C). We found that due to the external wall design, the mean radiant temperature fluctuates in a similar order of magnitude around the average air temperature for all the compared alternatives. In the heating season, the average mean radiant temperature is 0.2 to 0.8 °C lower and in the cooling season 0.4 to 1.0 °C higher than the average air temperature.

In all the cases, the *PMV* value was negative, which indicates a neutral to slightly cool thermal sensation. The *PMV* values are the lowest in the heating season (*PMVavg* from −0.7 to −0.9), when the internal air temperature is 21 °C. The *PMV* value was below −0.7 (*PPD* > 15%) from 58 to 80% of occupied hours. When comparing the results with thermal comfort data from in situ measurements from the ASHRAE global thermal comfort databases, we found that when the air temperature is 21 ± 0.5 °C, the *PMV* value is below −0.15 in 70% and bellow −0.70 in over 20% of the cases. This indicates that the lowest temperature setpoint threshold of 21°C for the heating season, as prescribed for category I spaces can be too low for office spaces. This correlates to the findings of Dovjak and Kukec [1] for other building types.

As expected, the thermal transmittance values showed considerable influence on energy demand. Due to the lower thermal transmittance of the external wall, the heating and total energy demand decreased (on average by 63% and 37%, respectively) and the cooling demand increased (from 6 to 31.5%, depending on orientation and thermal inertia). Thermal inertia can notably influence the energy demand, as the high thermal inertia model showed lower total energy demand than the low thermal inertia model (up to 9.2%). This is due to the cooling demand reduction, as the heating demand was minimally influenced by thermal inertia. The cooling demand was approximately 13% lower for the higher insulation level models (U = 0.2 W/(m^{2}K)) and up to 20% lower for the models with lower insulation levels (U = 0.6 W/(m^{2}K)). An important point to note is that the models did not include intensive nocturnal ventilation cooling that could be applied in the assumed climate. If this parameter were included, the difference due to the influence of thermal mass on the cooling demand could be smaller [28,52]. Orientation had a notable effect on heating and cooling demand, but not as pronounced as thermal inertia (up to 7% total energy demand). Here, the shading devices and control need to be taken into account, as a highly efficient shading control that blocked direct solar radiation was assumed. Considering that increasing thermal insulation thickness and reducing the *U*-value have their limits, including thermal inertia in building energy design could reduce the cooling and total energy demand in office buildings.

This study is based on a model interim office floor designed to extract information about the influence of external wall thermal characteristics (*U*-value, thermal inertia) and orientation on the occupant thermal comfort and energy demand. Some simplifications and assumptions were used to control the various influencing factors (see Section 2.1.3). The results should be interpreted in consideration of these specifics of the simulation model designs. The models were developed to answer the question of the thermal comfort dilemma in office buildings, in accordance with Slovenian's legislative energy efficiency benchmarks. Although Slovenia was chosen as a benchmark for simulation design, other countries in heating driven climates have also undergone an energy efficiency transition, only the chronology and requirements are different. The study results indicate that if the HVAC system sufficiently controls the internal air temperature, then the thermal comfort in office buildings is on average comparable and is not significantly affected by the difference in external wall insulation level, thermal inertia of building elements and room orientation. However, in reality, the mentioned influencing factors can become of significance as they can impact the internal air temperature [29,53]. Regarding the energy demand, as already shown in other studies [27,28], thermal inertia showed considerable potential for cooling demand reduction. In future, the inclusion of thermal inertia in building design could become of particular relevance, as studies show an increasing cooling demand in buildings, due to the impact of climate change [54].

Our research is based on relevant issues facing today's design and construction practice in Slovenia and other countries. Thermal performance analyses of the structural assemblies are focused on partial parameters to achieve the maximum allowed *U*-factors and minimised energy demands. Other influencing factors need to be analysed to comprehensively solve the problems related to comfort and energy issues, including the *U*-factor, thermal inertia, and orientation. From this June, new legislation in Slovenia will be in force, including a thermal stability factor evaluated particularly for the roofs [55,56]. In future work, it would be interesting to study the effectiveness of this parameter. Additionally, it would also be worth investigating the influence of local thermal discomfort and heat balance of the human body.

5. Conclusions

The presented study uses a specific approach to evaluate how important influencing factors affect the building energy demand (heating, cooling) and thermal comfort. The observed influencing factor were: (i) external wall thermal transmittance, (ii) building thermal inertia, and (iii) orientation. In order to evaluate their impact, a theoretical study on interim office floor simulation models, located in the continental climate of Ljubljana (Slovenia), was conducted. The aim of the study was to study the mutual influence of external wall thermal transmittance values, thermal inertia, and orientation on occupant thermal comfort and energy demand. The observed thermal comfort parameters were: mean radiant temperature, predicted mean vote (*PMV*), and predicted percentage dissatisfied (*PPD*). The EnergyPlus simulation software was used to perform the analysis.

The study results show that when the internal air temperature in office rooms is sufficiently controlled, the change in thermal transmittance values (from 0.6 W/(m^2K) to 0.2 W/(m^2K)), different thermal inertia design (low and high thermal inertia walls), and room orientation do not impact the average occupant thermal comfort. Energy demand is notably influenced by the observed parameters, as the external wall thermal transmittance reduction from 0.6 W/(m^2K) to 0.2 W/(m^2K) reduced the heating and total energy demand on average by 63% and 37%. Thermal inertia showed important impact, particularly on the cooling demand, which was reduced by approximately 20% and 13%, depending on the external wall insulation level.

In future, the question about renovations and energy efficiency improvements of relatively new buildings but designed in accordance with outdated energy efficiency standards will become prominent. Besides energy demand, other aspects of building sustainability are also important and need to be considered simultaneously (e.g., thermal comfort, costs, environmental impact, and climate change). The multi-objective study will be required to provide valuable findings beneficial for various building stakeholders and foster additional research. Our study presents an approach to tackle the exposed question by simultaneously evaluating the impact of multiple influencing factors on thermal comfort and energy demand. The study findings could benefit policymakers, building designers, and office building owners. Additionally, possibilities for further research are identified.

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Conflicts of Interest: The authors declare no conflict of interest.

List of Symbols and Abbreviations

A_u	(m^2)	net floor area
V_e	(m^3)	conditioned volume
U	(W/(m^{2}K))	thermal transmittance
λ	(W/(mK))	thermal conductivity
ρ	(kg/m^3)	density
c	(J/(kgK))	specific thermal capacity
PMV	(/)	predicted mean vote
PPD	(%)	predicted percentage dissatisfied
WWR	(%)	window to wall ratio
Tmr	(°C)	mean radiant temperature
SHGC	(/)	solar heat gain coefficient
avg	abbreviation for average	
min	abbreviation for minimum	
max	abbreviation for maximum	
L	low thermal inertia	
H	high thermal inertia	
S	south orientation	
W	west orientation	
E	east orientation	
N	north orientation	
ETICS	external thermal insulation composite system	

Appendix A

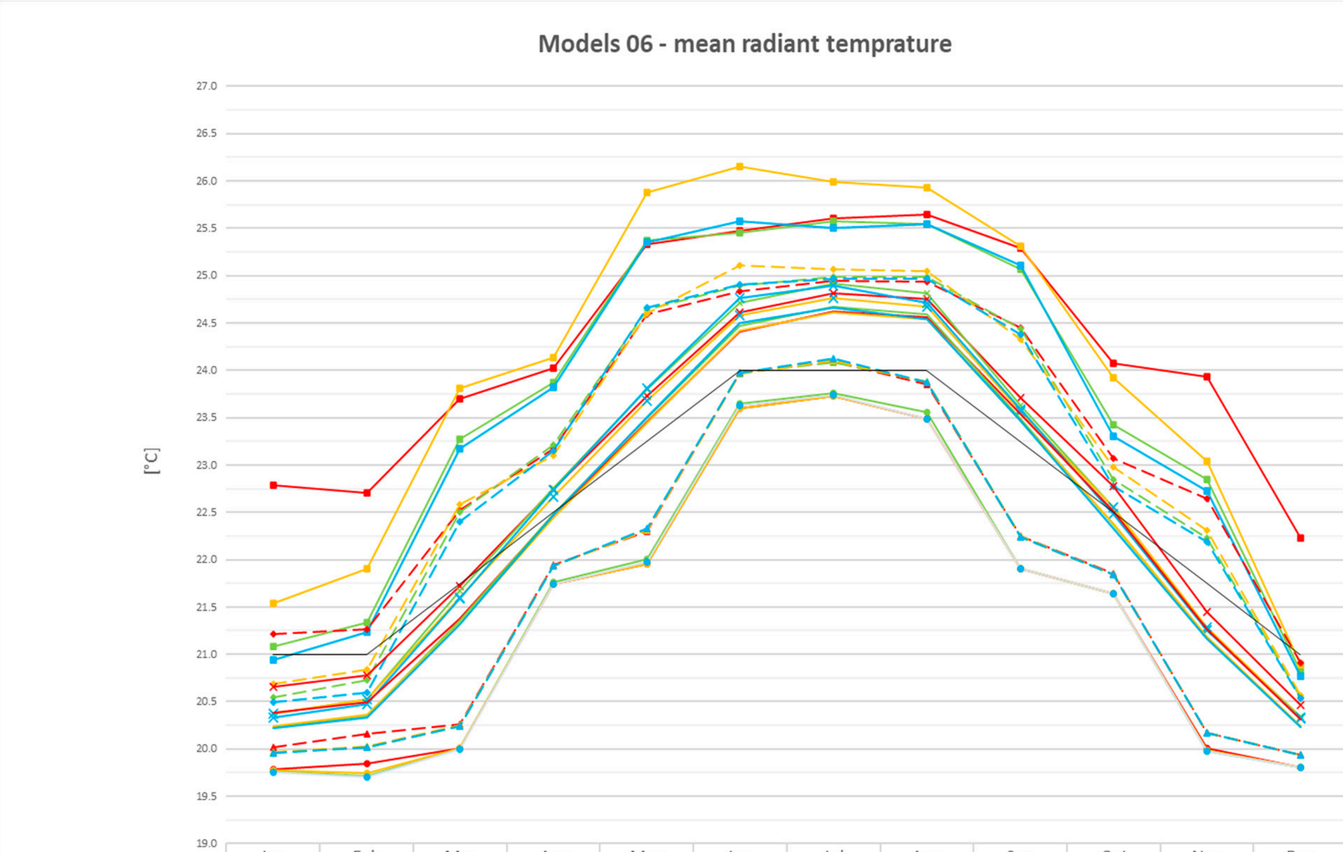
The room mean radiant temperature (*Tmr*) reveals the influence that the external wall design and room orientate have on the thermal comfort, as the surface temperature of the other room surfaces (floor, celling, internal walls) equals or variates minimally from the air temperature. Figure A1 shows the maximum, average, and minimum mean radiant temperature for the low and high thermal inertia design for each observed room orientation (S, E, W, N). Although the *Tmr,max* values reveal a notable distinction in the thermal behaviour, the *Tmr,avg* values show small differences. Comparing the average mean radiant temperatures (*Tmr,avg*) for the different orientations reveals slightly smaller values, from 0.1 to 0.3 K, for the high thermal inertia design. The main differences are notable in the heating season (winter), where the south oriented rooms receive more solar radiation and consequentially larger mean radiant temperatures. This leads to a maximum difference of 0.4 K for the low and 0.2 K for the high thermal inertia design in January, compared to rooms with other orientation. In the cooling (summer) and interim (spring, autumn) period the *Tmr,avg* values are similar, regardless of the orientation. In reference to the average air temperature, the *Tmr,avg* values are 0.5 to 0.8 K smaller in winter and 0.4 to 0.9 K larger in summer.

Important differences are notable for the *Tmr,max* values, both for the orientations and for the thermal inertia design. The low thermal inertia design leads to higher maximum mean radiant temperature values. For the L06, S room, the maximum mean radiant temperature in winter is 1.6 K higher when compared to the high thermal inertia design and 2.3 K higher when compared to the room with the lowest maximum mean radiant temperature—H06, N. In the cooling period, the west oriented rooms show the highest mean radiant values when compared to other orientations. However, the difference is far more pronounced for the low thermal inertia design, where the mean radiant temperature is approximately 0.5 K higher compared to other orientations.

The orientation shows no influence on the *Tmr,min* values. The thermal inertia shows a small but observable influence, as the values are slightly lower—from 0.1 to 0.4—for the low thermal inertia design, with the main difference occurring in the heating period.

The conclusions based on Figure A1 are that the orientation influences the *Tmr* values more for the low thermal inertia design and that the difference between the maximum and minimum values is also more pronounced when comparing to the high thermal inertia design. This confirms the notion that higher thermal mass leads to a more stable thermal environment.

The *PMV* values are distributed between the values -1.5 in winter and -0.15 in summer (Figure A2). As in the case of mean radiant temperature, the largest differences are notable when comparing the maximum *PMV* values, where the orientation and thermal inertia importantly influence the results. The low thermal inertia design (L06) shows greater influence of orientation, as the *PMV* values for the south oriented room can notably deviate (up to 27%) compared to other orientations in the heating period. Concerning the model with lower thermal inertia, the maximum *PMV* values for the high thermal inertia show smaller deviations when comparing different orientations and are smaller or comparable. The variabilities in the maximum *PMV* values do not reflect on the average *PMV* values, where the orientation and thermal mass design shows little influence. It can be observed that the *PMV,avg* values for the low thermal mass model are slightly larger and that for the south and west oriented rooms some deviations are notable, but the differences appear on the second decimal number. For this reason, the average thermal comfort in the observed office cells can be considered comparable.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tmr,max-L, S	22.8	22.7	23.7	24.0	25.3	25.5	25.6	25.6	25.3	24.1	23.9	22.2
Tmr,max-L, E	21.1	21.3	23.3	23.9	25.4	25.5	25.6	25.5	25.1	23.4	22.8	20.8
Tmr,max-L, W	21.5	21.9	23.8	24.1	25.9	26.2	26.0	25.9	25.3	23.9	23.0	20.9
Tmr,max-L, N	20.9	21.2	23.2	23.8	25.3	25.6	25.5	25.5	25.1	23.3	22.7	20.8
Tmr,max-H, S	21.2	21.3	22.5	23.2	24.6	24.8	24.9	24.9	24.4	23.1	22.6	20.9
Tmr,max-H, E	20.5	20.7	22.5	23.2	24.6	24.9	25.0	25.0	24.4	22.8	22.2	20.5
Tmr,max-H, W	20.7	20.8	22.6	23.1	24.6	25.1	25.1	25.0	24.3	23.0	22.3	20.6
Tmr,max-H, N	20.5	20.6	22.4	23.2	24.7	24.9	25.0	25.0	24.4	22.8	22.2	20.5
Tmr,avg-L, S	20.7	20.8	21.7	22.7	23.7	24.6	24.8	24.8	23.7	22.8	21.4	20.5
Tmr,avg-L, E	20.4	20.5	21.7	22.8	23.8	24.7	24.9	24.8	23.6	22.6	21.3	20.3
Tmr,avg-L, W	20.4	20.5	21.6	22.7	23.7	24.6	24.8	24.7	23.6	22.6	21.3	20.3
Tmr,avg-L, N	20.3	20.5	21.6	22.7	23.8	24.8	24.9	24.7	23.6	22.5	21.3	20.3
Tmr,avg-H, S	20.4	20.5	21.4	22.5	23.5	24.4	24.6	24.6	23.5	22.5	21.3	20.3
Tmr,avg-H, E	20.2	20.4	21.4	22.5	23.5	24.5	24.7	24.6	23.5	22.4	21.2	20.2
Tmr,avg-H, W	20.2	20.4	21.3	22.4	23.4	24.4	24.6	24.5	23.5	22.4	21.2	20.2
Tmr,avg-H, N	20.2	20.3	21.3	22.5	23.5	24.5	24.7	24.5	23.5	22.3	21.2	20.2
Tmr,min-L, S	19.8	19.8	20.0	21.7	22.0	23.6	23.7	23.5	21.9	21.6	20.0	19.8
Tmr,min-L, E	19.8	19.7	20.0	21.8	22.0	23.6	23.8	23.6	21.9	21.6	20.0	19.8
Tmr,min-L, W	19.8	19.7	20.0	21.7	22.0	23.6	23.7	23.5	21.9	21.6	20.0	19.8
Tmr,min-L, N	19.8	19.7	20.0	21.7	22.0	23.6	23.7	23.5	21.9	21.6	20.0	19.8
Tmr,min-H, S	20.0	20.2	20.3	21.9	22.3	24.0	24.1	23.9	22.2	21.9	20.2	19.9
Tmr,min-H, E	20.0	20.0	20.2	21.9	22.3	24.0	24.1	23.9	22.2	21.8	20.2	19.9
Tmr,min-H, W	20.0	20.0	20.3	21.9	22.3	24.0	24.1	23.9	22.2	21.8	20.2	19.9
Tmr,min-H, N	20.0	20.0	20.2	21.9	22.3	24.0	24.1	23.9	22.2	21.8	20.2	19.9
Tair,avg	21.0	21.0	21.75	22.5	23.25	24.0	24.00	24.0	23.25	22.5	21.75	21.0

Figure A1. Monthly mean radiant temperature (*Tmr* (°C)) fluctuations for the observed orientations in Model 06 thermal comfort simulation models.

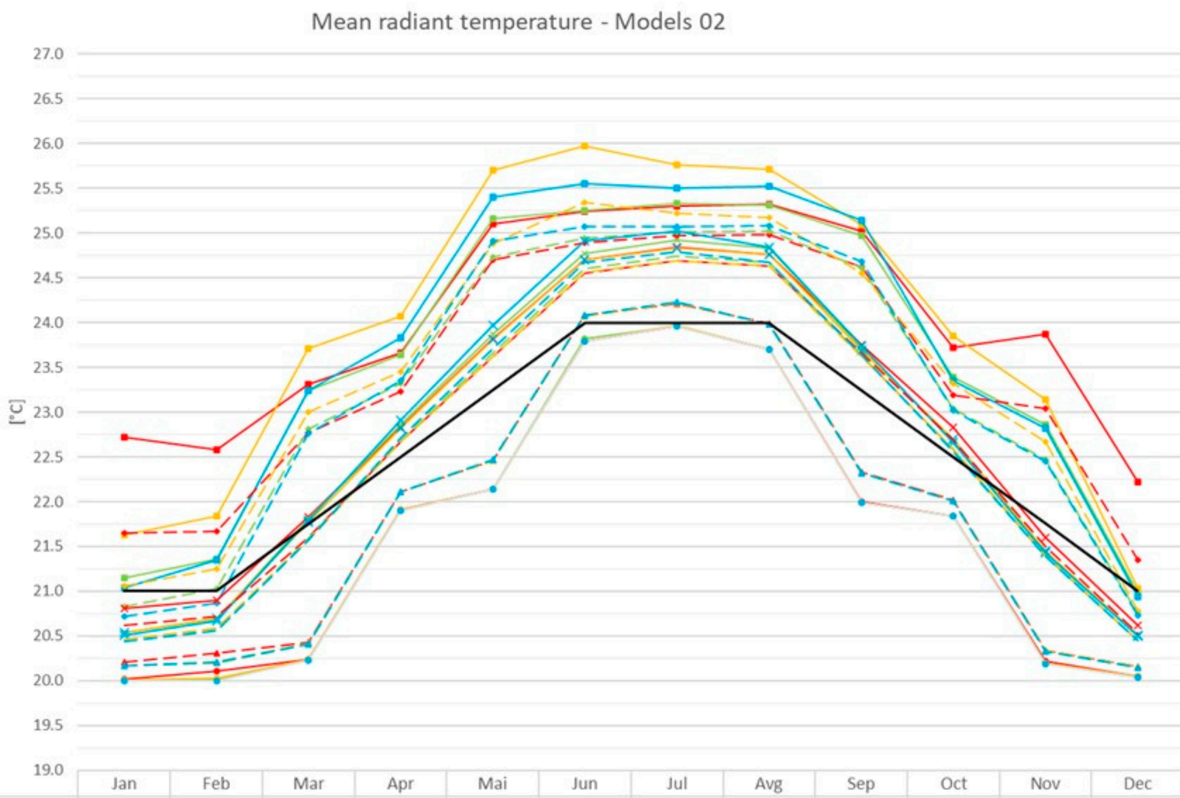
Appendix B

The low thermal mass model experiences higher *Tmr,max* when comparing equal orientations (Figure A2)). In January, the maximum mean radiant temperature difference between the south and the north oriented room is 1.7 K for the low and 0.9 K for the high thermal mass model. In summer, the situation changes and the west oriented rooms experience the largest maximum mean radiant temperatures. Interesting to note is that the north oriented rooms show higher *Tmr,max* values in summer than the south and east oriented rooms. This can only be explained with the shading controls of the simulation models, as the north oriented rooms do not have a shading device, whereas the other rooms have an external venetian blind, which blocks the direct solar component.

These considerable variations in the maximum values are not reflected in the average mean radiant temperatures (*Tmr,avg*). The influence of thermal mass is only merely notable, as the low thermal mass model experiences slightly larger *Tmr,avg* values. The maximum *Tmr,avg* difference, which can be observed in January, is 0.4 K between the L02, S and H02, N. In other months, the differences are even smaller or non-existent. The orientation shows minimal influence, as in the case of thermal mass, the observed variations are small (0.1 to 0.3 K) or none (March). An interesting observation is that in the summer, the *Tmr,avg* values for the north oriented rooms are slightly larger (0.1 to 0.2 K) when compared to other orientations for each of the thermal mass model separately. In reference to the average air temperature, the *Tmr,avg* values are 0.2 to 0.6 K smaller in winter and 0.6 to 1 K larger in summer.

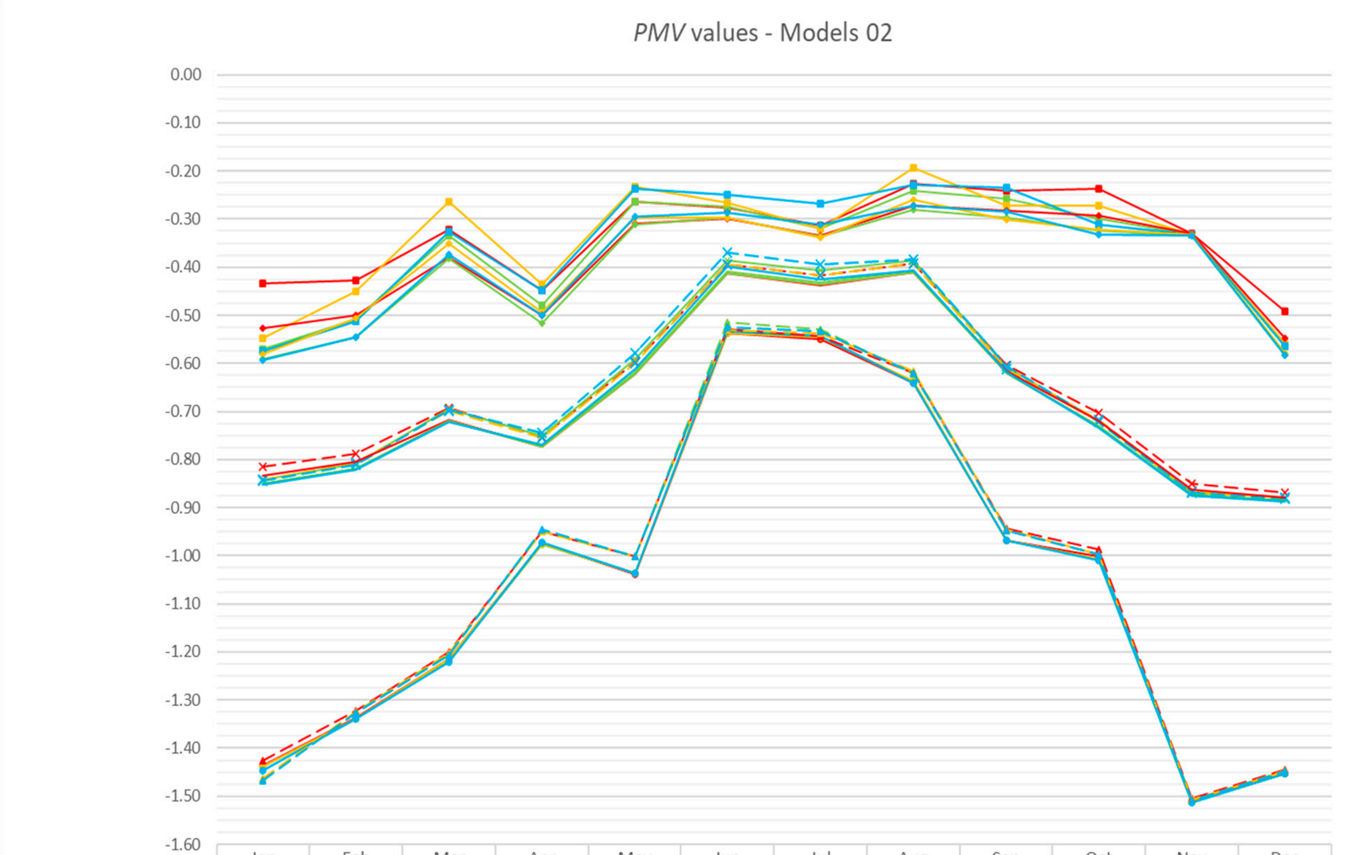
As in the case of Models 06, orientation shows no influence on *Tmr,min* values and the low thermal mass models experience slightly smaller values, from 0.1 to 0.4 K.

Due to the fact that the simulation models are designed in a way, that the mean radiant temperature is the only variable that influences the thermal comfort, the observations presented for the mean radiant temperature reflect in the *PMV* values (Figure 4). As in the case of Models 06, the *PMV* values are always negative, indicating a slightly cold sensation of the thermal environment. The *PMV,max* values show the most obvious orientation and thermal mass influence, but not so pronounced as for the mean radiant temperatures. In the case of *PMV,avg*, the difference between the orientations and thermal mass models is minimal, as in the case of minimal *PMV* values. This indicates that the thermal comfort is similar regardless of the room orientation and external wall thermal mass.



	Jan	Feb	Mar	Apr	Mai	Jun	Jul	Avg	Sep	Oct	Nov	Dec
Tmr,max-L, S	22.7	22.6	23.3	23.7	25.1	25.2	25.3	25.3	25.0	23.7	23.9	22.2
Tmr,max-L, E	21.1	21.4	23.2	23.6	25.2	25.2	25.3	25.3	25.0	23.4	22.9	21.0
Tmr,max-L, W	21.6	21.8	23.7	24.1	25.7	26.0	25.8	25.7	25.1	23.8	23.1	21.0
Tmr,max-L, N	21.0	21.4	23.2	23.8	25.4	25.6	25.5	25.5	25.1	23.3	22.8	20.9
Tmr,max-H, S	21.6	21.7	22.8	23.2	24.7	24.9	25.0	25.0	24.6	23.2	23.0	21.3
Tmr,max-H, E	20.8	21.0	22.8	23.3	24.7	24.9	25.0	25.0	24.6	23.0	22.5	20.7
Tmr,max-H, W	21.1	21.2	23.0	23.4	24.9	25.3	25.2	25.2	24.5	23.3	22.7	20.8
Tmr,max-H, N	20.7	20.9	22.8	23.3	24.9	25.1	25.1	25.1	24.7	23.0	22.5	20.7
Tmr,avg-L, S	20.8	20.9	21.8	22.8	23.8	24.7	24.8	24.8	23.7	22.8	21.6	20.6
Tmr,avg-L, E	20.5	20.7	21.8	22.9	23.9	24.8	24.9	24.8	23.7	22.7	21.4	20.5
Tmr,avg-L, W	20.5	20.7	21.8	22.8	23.8	24.7	24.8	24.8	23.7	22.7	21.4	20.5
Tmr,avg-L, N	20.5	20.7	21.8	22.9	24.0	24.9	25.0	24.8	23.7	22.7	21.4	20.5
Tmr,avg-H, S	20.6	20.7	21.6	22.7	23.6	24.6	24.7	24.6	23.7	22.7	21.5	20.5
Tmr,avg-H, E	20.5	20.6	21.6	22.7	23.7	24.6	24.7	24.7	23.6	22.6	21.4	20.5
Tmr,avg-H, W	20.5	20.6	21.6	22.7	23.6	24.6	24.7	24.6	23.6	22.6	21.4	20.5
Tmr,avg-H, N	20.4	20.6	21.6	22.7	23.7	24.7	24.8	24.7	23.6	22.6	21.4	20.4
Tmr,min-L, S	20.0	20.1	20.2	21.9	22.1	23.8	24.0	23.7	22.0	21.8	20.2	20.0
Tmr,min-L, E	20.0	20.0	20.2	21.9	22.1	23.8	24.0	23.7	22.0	21.8	20.2	20.0
Tmr,min-L, W	20.0	20.0	20.2	21.9	22.1	23.8	24.0	23.7	22.0	21.8	20.2	20.0
Tmr,min-L, N	20.0	20.0	20.2	21.9	22.1	23.8	24.0	23.7	22.0	21.8	20.2	20.0
Tmr,min-H, S	20.2	20.3	20.4	22.1	22.5	24.1	24.2	24.0	22.3	22.0	20.3	20.2
Tmr,min-H, E	20.2	20.2	20.4	22.1	22.5	24.1	24.2	24.0	22.3	22.0	20.3	20.2
Tmr,min-H, W	20.2	20.2	20.4	22.1	22.5	24.1	24.2	24.0	22.3	22.0	20.3	20.2
Tmr,min-H, N	20.2	20.2	20.4	22.1	22.5	24.1	24.2	24.0	22.3	22.0	20.3	20.2
Tair, avg	21.0	21.0	21.75	22.5	23.25	24.0	24.00	24.0	23.25	22.5	21.75	21.0

Figure A2. Monthly mean radiant temperature fluctuations for the observed orientations in Models 02.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
PMV,max-L, S	-0.43	-0.43	-0.32	-0.45	-0.26	-0.28	-0.31	-0.23	-0.24	-0.24	-0.33	-0.49
PMV,max-L, E	-0.57	-0.51	-0.33	-0.48	-0.26	-0.27	-0.32	-0.24	-0.26	-0.30	-0.33	-0.56
PMV,max-L, W	-0.55	-0.45	-0.26	-0.44	-0.23	-0.27	-0.32	-0.19	-0.27	-0.27	-0.33	-0.56
PMV,max-L, N	-0.57	-0.51	-0.33	-0.45	-0.24	-0.25	-0.27	-0.23	-0.24	-0.31	-0.33	-0.57
PMV,max-H, S	-0.53	-0.50	-0.38	-0.50	-0.31	-0.30	-0.33	-0.27	-0.28	-0.29	-0.33	-0.55
PMV,max-H, E	-0.59	-0.55	-0.38	-0.52	-0.31	-0.30	-0.34	-0.28	-0.30	-0.32	-0.33	-0.58
PMV,max-H, W	-0.58	-0.51	-0.35	-0.49	-0.30	-0.30	-0.34	-0.26	-0.30	-0.32	-0.33	-0.58
PMV,max-H, N	-0.59	-0.55	-0.37	-0.50	-0.30	-0.29	-0.31	-0.27	-0.28	-0.33	-0.33	-0.58
PMV,avg-L, S	-0.82	-0.79	-0.69	-0.75	-0.60	-0.39	-0.42	-0.39	-0.60	-0.70	-0.85	-0.87
PMV,avg-L, E	-0.84	-0.81	-0.69	-0.75	-0.59	-0.39	-0.41	-0.39	-0.61	-0.72	-0.87	-0.88
PMV,avg-L, W	-0.84	-0.81	-0.70	-0.76	-0.60	-0.39	-0.42	-0.39	-0.61	-0.72	-0.87	-0.88
PMV,avg-L, N	-0.84	-0.81	-0.70	-0.74	-0.58	-0.37	-0.39	-0.38	-0.61	-0.72	-0.87	-0.88
PMV,avg-H, S	-0.83	-0.81	-0.72	-0.77	-0.62	-0.41	-0.44	-0.41	-0.62	-0.72	-0.86	-0.88
PMV,avg-H, E	-0.85	-0.82	-0.72	-0.77	-0.62	-0.41	-0.43	-0.41	-0.62	-0.73	-0.87	-0.89
PMV,avg-H, W	-0.85	-0.82	-0.72	-0.77	-0.62	-0.41	-0.44	-0.41	-0.62	-0.73	-0.87	-0.89
PMV,avg-H, N	-0.85	-0.82	-0.72	-0.77	-0.61	-0.40	-0.42	-0.41	-0.62	-0.73	-0.88	-0.89
PMV,min-L, S	-1.44	-1.34	-1.21	-0.97	-1.04	-0.54	-0.55	-0.64	-0.97	-1.00	-1.51	-1.45
PMV,min-L, E	-1.44	-1.34	-1.22	-0.98	-1.04	-0.53	-0.54	-0.64	-0.97	-1.01	-1.51	-1.45
PMV,min-L, W	-1.44	-1.34	-1.21	-0.97	-1.04	-0.54	-0.55	-0.64	-0.97	-1.01	-1.51	-1.45
PMV,min-L, N	-1.45	-1.34	-1.22	-0.97	-1.04	-0.53	-0.54	-0.64	-0.97	-1.01	-1.51	-1.45
PMV,min-M, S	-1.43	-1.32	-1.20	-0.95	-1.00	-0.53	-0.54	-0.62	-0.94	-0.99	-1.51	-1.44
PMV,min-M, E	-1.46	-1.33	-1.20	-0.95	-1.00	-0.51	-0.53	-0.62	-0.95	-1.00	-1.51	-1.45
PMV,min-M, W	-1.46	-1.32	-1.20	-0.95	-1.00	-0.53	-0.54	-0.62	-0.94	-1.00	-1.51	-1.45
PMV,min-M, N	-1.47	-1.33	-1.21	-0.95	-1.00	-0.52	-0.53	-0.62	-0.95	-1.00	-1.51	-1.45

Figure A3. Monthly *PMV* simulation results for Models 02.

Appendix C

Table A1. Comparison of share of hours when *PPD* is higher than 15% for the low thermal inertia models.

	L06, S (%)	L02, S (%)	Δ (h)	L06, E (%)	L02, E (%)	Δ (h)	L06, W (%)	L02, W (%)	Δ (h)	L06, N (%)	L02, N (%)	Δ (h)
January	66.7	60.5	23	69.1	64.2	18	70.4	64.2	23	70.4	65.1	20
February	62.8	59.5	11	64.9	61.3	12	66.4	61.6	16	66.7	62.5	14
March	49.2	43.8	20	47.6	43.3	16	51.6	45.7	22	50.8	45.4	20
April	71.7	73.3	−6	74.2	73.3	3	75.6	74.2	5	73.3	71.7	6
May	45.2	45.2	0	45.4	46.8	−5	46.2	46.5	−1	44.9	44.4	2
June	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
July	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
August	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
September	51.7	53.3	−6	53.3	53.3	0	52.2	53.1	−3	53.3	53.3	0
October	57.0	57.5	−2	64.2	63.7	2	63.2	61.3	7	66.7	12	63.4
November	75.0	73.3	6	79.4	76.1	12	78.9	75.8	11	80.3	76.7	13
December	76.1	70.4	21	79.8	74.7	19	79.8	75.0	18	79.8	75.0	18

Table A2. Comparison of share of hours when *PPD* is higher than 15% for the high thermal inertia models.

	H06, S (%)	H02, S (%)	Δ (h)	H06, E (%)	H02, E (%)	Δ (h)	H06, W (%)	H02, W (%)	Δ (h)	H06, N (%)	H02, N (%)	Δ (h)
January	65.1	60.8	16	69.6	64.0	21	69.6	64.5	22	70.2	65.1	20
February	61.0	58.0	10	69.0	60.7	28	69.3	61.0	18	70.2	61.9	16
March	51.3	48.4	11	51.6	47.8	14	54.0	48.9	10	54.6	48.7	8
April	81.4	78.9	9	81.4	78.6	10	81.4	78.6	−11	81.9	78.1	−17
May	48.4	48.1	1	48.4	48.4	0	48.4	48.4	−8	48.4	47.6	−10
June	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
July	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
August	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0	0
September	53.3	52.8	2	53.3	53.3	0	53.3	53.3	−4	53.3	52.8	2
October	66.4	64.2	8	69.4	66.1	12	69.4	65.6	−9	70.2	67.2	−2
November	76.9	76.4	2	81.4	78.3	11	81.7	78.6	1	81.7	78.6	6
December	78.8	75.0	14	79.0	75.5	13	79.0	75.5	16	79.3	75.5	16

Table A3. Comparison of *PPD* values at chosen days. One can observe small variation in the absolute *PPD* values for the observed office cells.

M/d hh:mm:ss	L06, S	M06, S	M/d hh:mm:ss	L02, S	M02, S	M/d hh:mm:ss	L06,W	L02,W	M/d hh:mm:ss	H06,W	H02,W
10/04 07:00:00	22.2	19.7	10/10 07:00:00	20.5	19.1	01/06 07:00:00	18.1	17.5	02/09 07:00:00	17.6	17.3
10/04 08:00:00	21.5	19.6	10/10 08:00:00	20.3	19.1	01/06 08:00:00	18.0	17.5	02/09 08:00:00	17.6	17.2
10/04 09:00:00	20.1	18.9	10/10 09:00:00	19.0	18.4	01/06 09:00:00	17.5	16.9	02/09 09:00:00	17.2	16.7
10/04 10:00:00	17.9	17.8	10/10 10:00:00	17.2	17.1	01/06 10:00:00	16.8	16.1	02/09 10:00:00	16.5	15.6
10/04 11:00:00	15.9	16.9	10/10 11:00:00	15.5	15.8	01/06 11:00:00	16.2	15.5	02/09 11:00:00	15.8	14.8
10/04 12:00:00	14.5	16.5	10/10 12:00:00	14.9	15.2	01/06 12:00:00	15.8	15.1	02/09 12:00:00	15.3	14.1
10/04 13:00:00	13.8	16.4	10/10 13:00:00	14.8	14.9	01/06 13:00:00	15.4	14.8	02/09 13:00:00	14.9	13.6
10/04 14:00:00	13.5	16.4	10/10 14:00:00	15.0	15.3	01/06 14:00:00	15.2	14.7	02/09 14:00:00	14.4	13.2
10/04 15:00:00	13.4	16.4	10/10 15:00:00	15.0	15.4	01/06 15:00:00	15.2	14.7	02/09 15:00:00	14.0	12.9
10/04 16:00:00	13.5	16.3	10/10 16:00:00	15.2	15.7	01/06 16:00:00	15.3	15.0	02/09 16:00:00	13.6	12.7
10/04 17:00:00	13.7	16.0	10/10 17:00:00	15.7	15.9	01/06 17:00:00	15.6	15.2	02/09 17:00:00	13.6	13.0
10/04 18:00:00	14.7	16.2	10/10 18:00:00	16.2	16.1	01/06 18:00:00	15.8	15.3	02/09 18:00:00	13.8	13.4

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