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Optimisation of Nearly Zero Energy Building Envelope for Passive Thermal Comfort in Southern Europe

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Abstract: The pursuit of sustainable and energy-efficient construction is vital to mitigate climate change and reduce carbon emissions. The application of the concept of nearly Zero Energy Building (nZEB) is now a reality for new buildings in the European Union, helping to achieve those goals. However, there is significant complexity in achieving acceptable thermal comfort levels in warmer climates such as the one in Southern Europe. This study carried out a multi-objective optimisation of the nZEB envelope using current construction solutions and nZEB regulations currently in force in different climate zones in this region, aiming to reduce thermal discomfort according to EN 16798-1. The results indicate that passive measures induced by regulatory requirements can significantly reduce discomfort at an affordable cost. However, great caution must be taken in relation to regulatory requirements, mainly for the cooling season, aiming to avoid summer overheating of dwellings and guaranteeing that nZEB's buildings are sustainable and comfortable in the Mediterranean climate regions. In addition, designers should be aware that increasing the insulation layer beyond regulatory requirements does not necessarily imply an increase in passive thermal comfort. Often, this implies, in addition to an increase in construction costs, an increase in discomfort, particularly during the cooling season.

Keywords: nZEB/NZEB; envelope optimisation; thermal comfort; regulatory requirements; Southern Europe

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1. Introduction

1.1. Introduction and Background

The quest for sustainable and energy-efficient construction practices has become increasingly indispensable in the context of global climate change and the pressing need to reduce carbon emissions. Buildings represent 40% of final energy consumption and 36% of energy-related greenhouse gas emissions in the European Union, while around 75% of its buildings are still energy inefficient [1].

In this context, Europe adopted the nZEB concept as an obligation for all new buildings constructed in its Member States (MS) [2,3]. Each MS has the autonomy to transpose the Directives according to its local particularities in order to achieve, in its own way, the common goals defined by the Directives. In addition to the European-wide definition of the concept, there are other applicable definitions worldwide. The same occurs with the concept of Net Zero Energy Buildings (NZEBs), and due to different contexts and realities around the world, there is no common understanding regarding this kind of concept [4]; thus, a common definition may never be reached [5]. However, two main strategies are always involved in nZEB/NZEB construction: reducing energy needs through the implementation of passive strategies and using energy from renewable sources, preferably local, to meet those already-reduced needs [6].

Besides the first nZEB, most basic approaches are already included in MS national regulations; further approaches are more comprehensive and consider the whole life cycle of the building, considering the embodied energy in each of its materials and components [7] and the embodied carbon [8]. In this scope, the new European Directive that was published very recently goes further in this direction than the last transposed version.

However, although the nZEB/NZEB simplest "recipe" seems simplistic, it is not quite so. Its design requires a holistic approach, and its objective can be achieved with the best combination of envelope, systems, and energy sources under technical and financial constraints that change with context and time. Social engagement and the attitudes of key stakeholders in the industry are also important to achieve the goal in practice [9]. The use of multi-objective optimisation tools can certainly help in this complex relationship between the inputs and outputs of nZEB/NZEB construction [10,11].

Regardless of the concept or metric considered, minimising energy use must be a fundamental design requirement and the highest priority of nZEB/NZEB. Energy efficiency measures are typically the most cost-effective approach with the highest return on investment. Prior to developing local renewable energy strategies, optimising efficiency opportunities would reduce the number and cost of renewable energy sources [6].

Building envelopes, including walls, windows, floors and roofs, have a substantial impact on energy needs, so these construction elements must be selected with awareness [12,13]. It is known that the construction of nZEB/NZEBs is becoming more feasible owing to the advancements in building technology, renewable energy systems and academic research [6]. Given that improving energy performance has become a priority for current buildings, it is possible to ensure that nZEB/NZEB construction objectives can be achieved through current practices. However, a fundamental factor, namely thermal comfort, has been neglected in the most recent studies [14].

1.2. Literature Review

The theoretical basis of adaptive thermal comfort models has matured, and, therefore, several models have already been integrated into regulations worldwide, which is fundamental for their acceptance and implementation [15]. In Europe, the EN 16798-1 [16] standard establishes limits for indoor conditions to ensure occupant comfort. A critical interplay exists between thermal comfort parameters and energy demand, particularly in regions with warmer climates, as in Southern European countries [17]. That interplay is critical and difficult to predict due to various factors, from the designer's choices to the users' preferences and behaviour. This underscores the need for tailored solutions that consider regional climate, socioeconomic conditions and occupant behaviour. A study [18] proposed that for existing homes, the most effective initial reduction in energy use should come from changing occupant behaviour, followed by improving existing building envelopes. The adoption of a realistic adaptive thermal comfort model can help in reducing energy demand while ensuring occupant comfort, especially in Mediterranean regions [19].

There is complexity in achieving nearly or net-zero energy objectives while maintaining indoor thermal comfort, which requires a careful balance between energy efficiency measures and occupant comfort requirements [14]. In [20], the authors shed light on the importance of considering occupants' cultural practices and traditional adaptive behaviours in achieving thermal comfort in vernacular dwellings.

As we strive to move towards a future of sustainable building practices, it is essential to recognise the challenges and opportunities. The most advanced technologies are available, from the production of building components to the automation of a building's operational phase, making it a so-called smart building. However, a comprehensive assessment is needed to ensure that their application corresponds to a truly sustainable improvement because, sometimes, current simple solutions may be the most sustainable. For a nearly zero-energy building design, De Masi et al. [21] analysed the environmental impact of increasing envelope insulation and the integration of photovoltaic panels in different climates, and they concluded that the most energy-efficient solutions do not always correspond to the optimal environmental result, showing the need for a case-by-case assessment. Furthermore, the articulation of energy-saving potentials, as discussed in [22], underscores the significance of simple adaptive strategies, such as natural ventilation and adaptive setpoint temperatures, in mitigating energy expenditure.

Adaptive comfort is also crucial in relation to overheating in dwellings, a global concern that is increasing due to global warming and more frequent and extreme heat waves. Forecasts indicate that cooling will be increasingly needed in buildings [23]. A study presented in [24] revealed that apartments built under current Spanish energy regulations do not show a significant reduction in hours of indoor overheating compared to those built before any energy regulations came into force. This demonstrates there is an increasing need to adapt current building energy regulations to face warmer conditions, which the world is already facing and can be expected to get worse.

An extensive literature review presented in [25] on strategies for achieving net-zero energy and net-zero carbon buildings identified studies that made a critical analysis of the existing governance guidelines. In a recent article [26], Capeluto calls attention to the "unsustainable direction of Green Building Codes", proposing an Occupation Correction Factor that could alter the energy ratings of buildings, taking into account the occupancy and actual usage patterns since these factors are crucial for achieving broader environmental and social sustainability goals. All the raised questions show how complex the challenge can be of transforming sustainable building concepts into real-life practices.

The trend of European regulations towards a constant increase in the required level of thermal insulation of the building envelope raises justified concerns in Southern European countries due to an increased risk of overheating.

Considering all the mentioned aspects, from the scarcity of studies that consider adaptive thermal comfort to the importance of multi-objective optimisation and focusing on the particularities of the Southern European climate, the present envelope optimisation study aims at minimising passive thermal discomfort and initial construction cost, allowing at the same time the discussion of some aspects of regulatory requirements.

By doing so, this study tries to respond to the following questions:

- To what extent do current regulatory requirements prevent passive discomfort?
- Given that winter and summer passive comfort point mostly to opposite strategies, what would be the most balanced envelope options for achieving nZEB/NZEB status?
- Is the trend of an increasing regulatory requirement for the level of envelope thermal insulation recommendable for Southern Europe?
- What would be the consequences for the choice of heating and cooling systems and renewable energy sources of the optimised envelope options?

2. Materials and Methods

2.1. Climate Zoning

Climate zoning in Portugal is defined by dividing the territory into three winter climate zones (I1, I2 and I3) and three summer climate zones (V1, V2 and V3). Zones numbered with one have milder climates, which get more severe from one to three. Winter climate zones are defined according to the number of heating degree-days (HDD) for a base temperature of 18 °C, corresponding to the heating season. Summer climate zones are defined based on the average outdoor temperature for the conventional cooling season ($\theta_{ext,v}$) [27].

To calculate HDD and $\theta_{ext,v}$, reference values are indicated for each region of the country, and an adjustment for each specific location must be made depending on its altitude [28,29]. Figure 1 shows the geographic representation of winter and summer climate zoning. After overlaying these maps and checking the criteria for Portuguese municipalities through their altitude, eight possible combinations were identified in mainland Portugal (there is no location in mainland Portugal that corresponds to the combination I1V1) [27,30]. Table 1 shows the municipalities chosen to represent each of these climate zone combinations, their altitude, and the criteria for defining the zones. In Figure 1, the geographic locations of the representative municipalities are also identified.

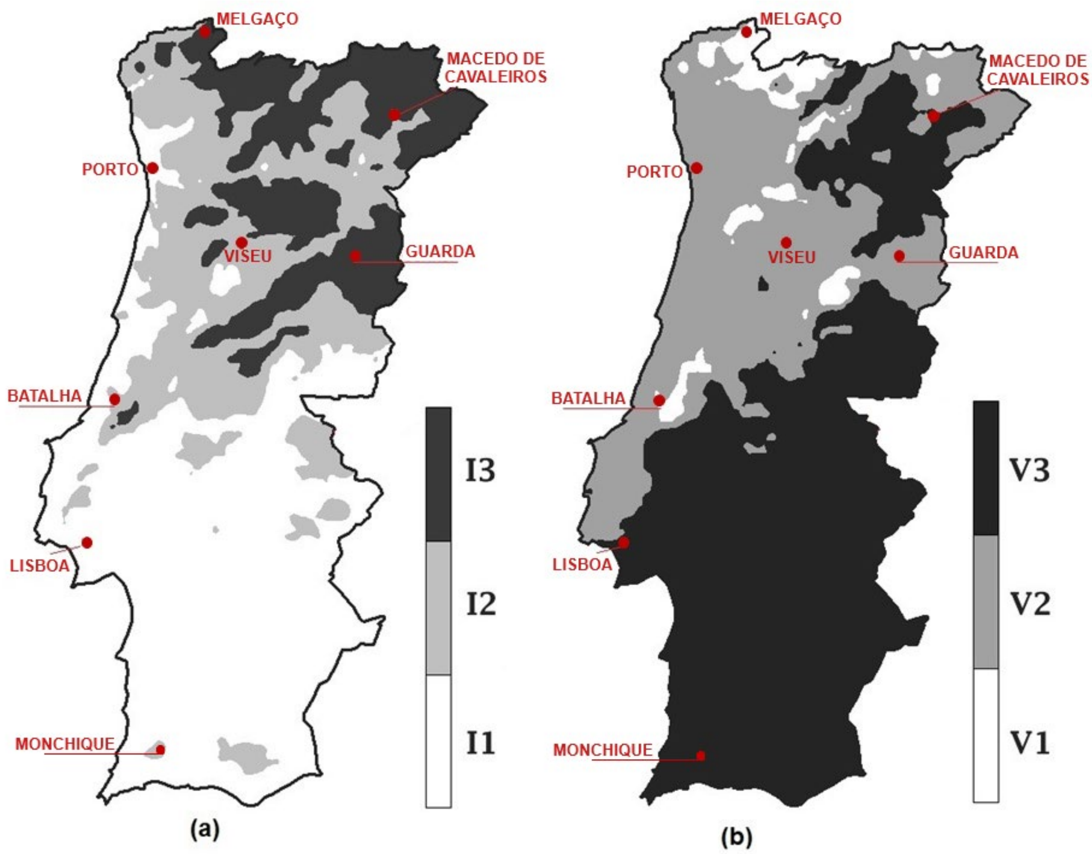

Figure 1. Graphical representation of the (**a**) winter climate zones and (**b**) summer climate zones and locations of the studied municipalities.

Table 1. Combinations of climate zones, representative municipality, location altitude and criteria for defining the Portuguese climate zones.

Climate Zones	Municipality		Altitude
I1V2	Porto		83 m
I1V3	Lisboa		4 m
I2V1	Batalha		247 m
I2V2	Viseu		475 m
I2V3	Monchique		446 m
I3V1	Melgaço		678 m
I3V2	Guarda		1017 m
I3V3	Macedo de Cavaleiros		572 m
Winter climate zone	I1	I2	I3
Winter criteria	HDD $\leq$ 1300	1300 < HDD $\leq$ 1800	HDD > 1800
Summer climate zone	V1	V2	V3
Summer criteria	$\theta_{ext,v} \leq 20\ ^\circ C$	$20\ ^\circ C < \theta_{ext,v} \leq 22\ ^\circ C$	$\theta_{ext,v} > 22\ ^\circ C$

2.2. Standard Dwelling

For the purposes of the study, a standard dwelling (Figure 2), a single house, is considered based on the data available for the floor area of new single houses at the Building Energy Certification System statistics since nZEB regulatory requirements came into force in July 2021 [31].

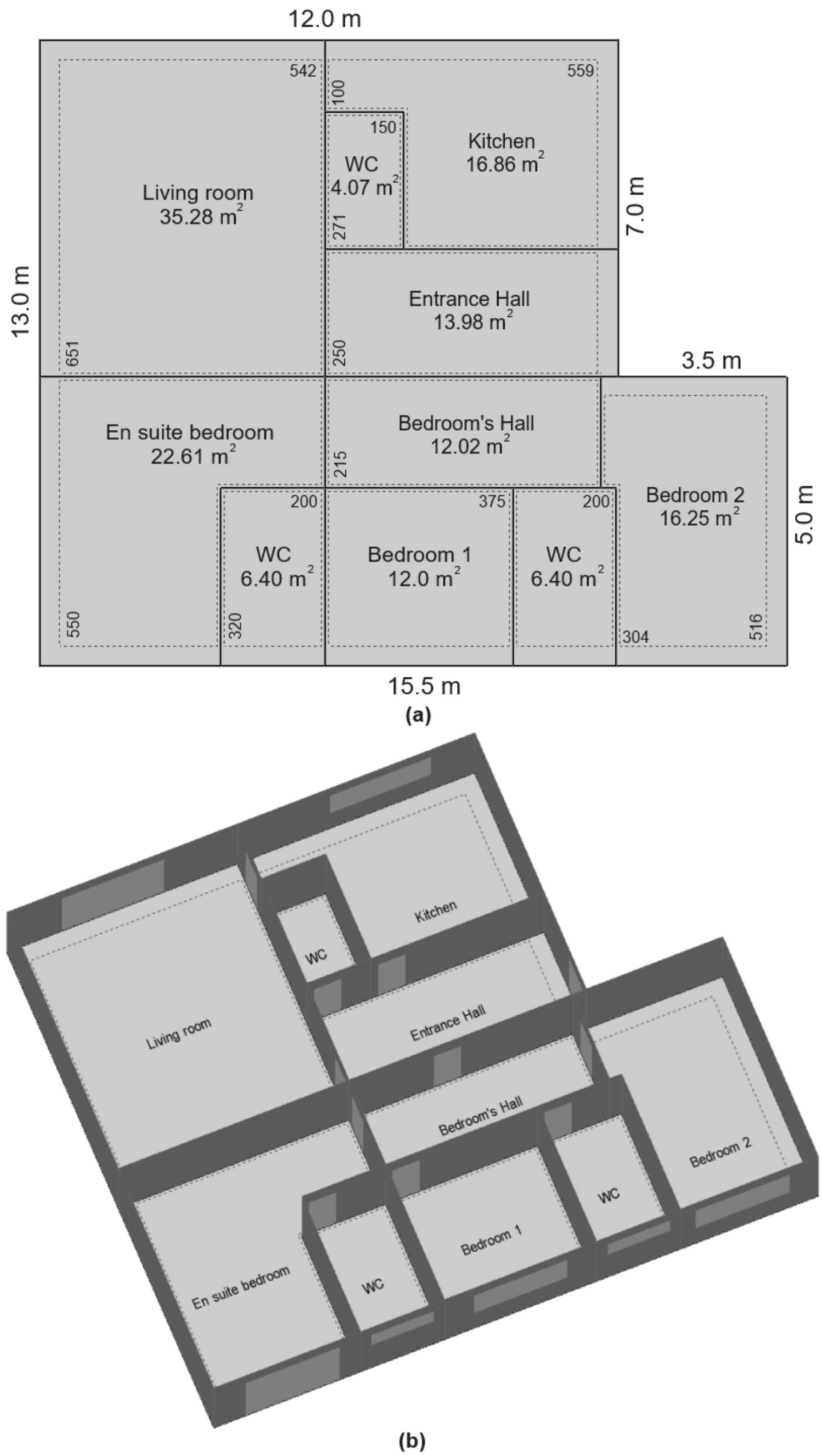

Figure 2. (**a**) Floor plan and (**b**) axonometric projection of the considered standard dwelling.

Table 2 presents the reference U-values defined by the Portuguese regulations for each element of the building envelope [27,32].

Table 2. Regulatory reference U-values for the envelope components.

Envelope Component	Winter Climate Zone	Regulatory Reference U-Value [W/m^2.°C]
External Wall	I1 I2 I3	0.50 0.40 0.35
Roof	I1 I2 I3	0.40 0.35 0.30
Ground Floor	I1, I2 and I3	0.50
Glazing	I1 I2 I3	2.80 2.40 2.20

For the standard single house, various combinations of envelope solutions were considered, for which U-values and costs were estimated.

Table 3 presents the considered envelope solutions and their characteristics. For each of the studied locations, current construction options with a U-value equal to the regulatory reference U-value were defined, as well as solutions with slightly less demanding U-values and with slightly more demanding U-values. According to the regulations in force, U-values above the regulatory reference value are permitted as long as the building meets the requirement of maximum allowable nominal useful energy needs for heating and cooling [32–34], with a maximum of 0.90 W/m^2.°C for opaque components and 3.00 W/m^2.°C for glazing.

Table 3. Studied envelope solutions.

Envelope Component	Winter Climate Zone	U-Value [W/m^2.°C]	Solution	Cost [€/m^2] [35]
External Wall	I1	0.40	Double wall [1]	145.50
		0.40	Single wall [2]	135.81
		0.50	Double wall [1]	142.88
		0.50	Single wall [2]	133.18
		0.60	Double wall [1]	141.07
		0.60	Single wall [2]	131.38
	I2	0.30	Double wall [1]	149.77
		0.30	Single wall [2]	140.24
		0.40	Double wall [1]	145.50
		0.40	Single wall [2]	135.81
		0.50	Double wall [1]	142.88
		0.50	Single wall [2]	133.18
	I3	0.25	Double wall [1]	153.37
		0.25	Single wall [2]	143.68
		0.35	Double wall [1]	147.31
		0.35	Single wall [2]	137.61
		0.45	Double wall [1]	144.03
		0.45	Single wall [2]	134.33

Table 3. *Cont.*

Envelope Component	Winter Climate Zone	U-Value [W/m^2.°C]	Solution	Cost [€/m^2] [35]
Roof	I1	0.30	Flat roof (α = 0.5) [3]	104.49
		0.30	Flat roof (α = 0.4) [3]	107.04
		0.40	Flat roof (α = 0.5) [3]	100.06
		0.40	Flat roof (α = 0.4) [3]	102.61
		0.50	Flat roof (α = 0.5) [3]	97.44
		0.50	Flat roof (α = 0.4) [3]	99.99
	I2	0.25	Flat roof (α = 0.5) [3]	107.94
		0.25	Flat roof (α = 0.4) [3]	110.49
		0.35	Flat roof (α = 0.5) [3]	102.03
		0.35	Flat roof (α = 0.4) [3]	104.58
		0.45	Flat roof (α = 0.5) [3]	98.75
		0.45	Flat roof (α = 0.4) [3]	101.30
	I3	0.20	Flat roof (α = 0.5) [3]	113.18
		0.20	Flat roof (α = 0.4) [3]	115.73
		0.30	Flat roof (α = 0.5) [3]	104.49
		0.30	Flat roof (α = 0.4) [3]	107.04
		0.40	Flat roof (α = 0.5) [3]	100.06
		0.40	Flat roof (α = 0.4) [3]	102.61
Ground Floor	I1, I2 and I3	0.40	Ground floor with insulation [4]	81.77
		0.50	Ground floor with insulation [4]	75.68
		0.60	Ground floor [4]	72.03
Glazing	I1	2.40	Double glass	467.91
		2.80	Double glass	406.19
		3.20	Double glass	308.54
	I2	2.00	Low-e double glass	497.68
		2.40	Low-e double glass	463.54
		2.80	Low-e double glass	438.50
	I3	1.80	Low-e double glass	537.36
		2.20	Low-e double glass	475.82
		2.60	Low-e double glass	451.10

[1] Thermal insulation between walls; [2] external thermal insulation; [3] flat roof with external thermal insulation, where α is the solar absorptance; [4] reinforced ground floor with light concrete.

The maximum allowable values of the annual nominal needs of useful heating energy (N_i) and the annual nominal needs of useful cooling energy (N_v) are defined by the regulations based on reference values of the relevant parameters applied to the geometry of the actual building. The values of the annual nominal needs of useful heating energy (N_{ic}) and cooling energy (N_{vc}) of the actual building are determined using the real thermal characteristics of the building under analysis and considering the heat transfer by transmission through the building envelope, the heat transfer by ventilation and the useful thermal gains resulting from solar and internal gains [27]. The latter are not considered for the calculation of the maximum allowable values, Ni and Nv.

For winter climate zones, the regulations establish the following requirements: for I1, N_{ic}/N_i must be less than or equal to 75%; for I2, N_{ic}/N_i must be less than or equal to 85%; for I3, N_{ic}/N_i must be less than or equal to 90% [33].

Table 4 shows the dimensions and the glazed area of windows and glazed doors, as can be seen in Figure 2b. All glazed areas have external roller shutters closed at night

(7 p.m. to 7 a.m.) throughout the year. In the conventional cooling season (June, July, August and September), they are also partially closed in the daytime (7 a.m. to 9 p.m.) for solar protection, as follows: on the north façade, it is not necessary to close in the daytime; on the façades that face east, west and south, the shutters are configured as closed 60% of daytime. For the analysis, the orientation of the building was rotated, with the main façade successively facing the four cardinal points, which is the one with the most significant number and area of glazing (the façade of the bedrooms). The air change rate is equal to 0.6 air changes per hour.

Table 4. Dimensions and area of windows and glazed doors.

Indoor Space	Dimensions	Glazing Area
Living room	2.60 m × 2.20 m	5.72 m^2
Kitchen	2.60 m × 1.20 m	3.12 m^2
En suite bedroom	2.40 m × 2.20 m	5.28 m^2
WCs (with windows)	1.60 m × 0.70 m	1.12 m^2
Bedroom 1	2.40 m × 1.20 m	2.88 m^2
Bedroom 2	2.40 m × 1.20 m	2.88 m^2

Later, when analysing overheating in summer, additional tests were carried out by positioning the shutters on the indoor side of the windows to explore this type of option that is sometimes chosen by designers for new buildings. The risk of overheating in summer was also analysed for the case in which the users do not use the shutters in the daytime.

Natural ventilation is used under the following conditions: whenever the indoor temperature is higher than the outdoor temperature, the outside temperature is at least 18 °C and less than 25 °C and the indoor temperature is above 24 °C, with a limit of four air changes per hour (a constant air change rate of 0.6 is considered, but when the conditions defined for natural ventilation to work are met, this rate can reach a maximum of 4.0). The occupancy was configured to represent a family of four people in the house daily, from 6 p.m. to 8 a.m. No HVAC system was used, nor were lighting and equipment considered.

2.3. Discomfort Assessment

The discomfort analysis is carried out using the concept of Degree Hours of Discomfort combined with the EN 16798-1 Standard [16]. The optimal operative temperature (Θc) is given by (1), which considers the weighted average outdoor temperature (Equation (2)). For this study, firstly, Category II was considered, which defines the upper limit at 3 °C more and the lower limit at 4 °C less than the optimal operative temperature. When the operative temperature of each thermal zone of the building is outside the upper or lower limit, the difference is accounted for. A calculation is carried out weighted by the area of each thermal zone, and a sum of all hours analysed is made:

$$\Theta_c = 0.33\ \Theta_{rm} + 18.8 \quad (1)$$

$$\Theta_{rm} = (\Theta_{ed\text{-}1} + 0.8\ \Theta_{ed\text{-}2} + 0.6\ \Theta_{ed\text{-}3} + 0.5\ \Theta_{ed\text{-}4} + 0.4\ \Theta_{ed\text{-}5} + 0.3\ \Theta_{ed\text{-}6} + 0.2\ \Theta_{ed\text{-}7})/3.8 \quad (2)$$

where Θ_{rm} = Outdoor Running mean temperature for the considered day; $\Theta_{ed\text{-}1}$, $\Theta_{ed\text{-}2}\ldots\ \Theta_{ed\text{-}i}$ = daily mean outdoor air temperature for the i-th previous day.

After this first step, to analyse summer overheating, an optimisation was performed for the four months of the cooling season with the upper limit following Category II criteria, with an adaptation to the recommended design values of operative temperature for residential buildings design, as presented in the Standard, with an upper limit not exceeding 26 °C [16]. This adaptation is explained further on.

2.4. Optimisation Settings

DesignBuilder version 7.2 software was used in this study to create models and run dynamic simulations and optimisations. DesignBuilder is an EnergyPlus-based software tool for assessing and controlling energy, carbon emissions, lighting and comfort. It is widely used to create and assess building design projects. However, due to the large volume of simulations and the lengthy duration of each optimisation process, the jEPlus software version 2.1.0 was also used to carry out all possible combinations more quickly, using the EnergyPlus IDF files generated by DesignBuilder.

The objectives of the optimisations are to find the optimal cases by minimising the initial construction cost (considering only the sum of the envelope components costs presented in Table 3) and minimising the amount of Degree Hours of Discomfort. The variables are shown in Table 3, in which, for each climate zone, six external wall options, six roof options, three ground floor options and three glazing options are considered. Initially, optimisations are performed for the 8760 h of the year. The main façade faces each of the four cardinal points successively, leading to four optimisation processes.

The Degree Hours of Discomfort analysis is not among the objectives available by default in the DesignBuilder optimisation options. However, starting with version 7 of the software, creating Scripts to perform calculations according to specific objectives is possible. Therefore, a Python Script was developed to calculate this optimisation objective.

To analyse summer overheating, the Script was adapted to encompass just the 2928 h of the cooling season and to consider that the upper limit follows the Category II criteria of Standard EN 16798-1 until reaching the value of 26 °C fixed from then on. The temperature of 26 °C was chosen following the maximum operative temperature for cooling in residential buildings with mechanical cooling systems, established by Standard EN 16798-1.

2.5. Checking nZEB Regulatory Requirements

In the optimisation process, there was a possibility that some solutions containing U-values greater than the maximum regulatory reference values would prove to be optimal. Therefore, additional verification of their compliance with the requirements of nominal useful energy needs for heating and cooling was necessary. Therefore, the spreadsheet developed and made available by the Platform for Energy Efficiency in Buildings (P3E) of the Institute for Research and Technological Development in Construction, Energy, Environment and Sustainability (Itecons) [36] was used to verify compliance with nZEB regulatory standards.

3. Results

3.1. Annual Optimisation

Figure 3 shows the result of optimising the standard dwelling envelope in Porto, with the main façade facing south. This graph was chosen as an example in order to explain how other results will be shown throughout this study. The Y axis presents the construction cost, considering only the envelope components (presented in Table 3), and the X axis gives the number of Degree Hours of Discomfort, calculated using EN 16798-1 Category II criteria.

Solutions with lower cost and discomfort combinations form a Pareto front of optimal solutions along the lower left edge of the "cloud" of data points. The optimal solutions are highlighted in orange and joined by a line. All points in the cloud that are not considered optimal solutions are greyed out. Among the solutions of the Pareto front, a point is marked in green, representing the solution immediately before the first significant increase in discomfort for just a slight or zero reduction of cost, when the Pareto front is analysed from the highest to the lowest cost. This solution was considered as the ideal solution.

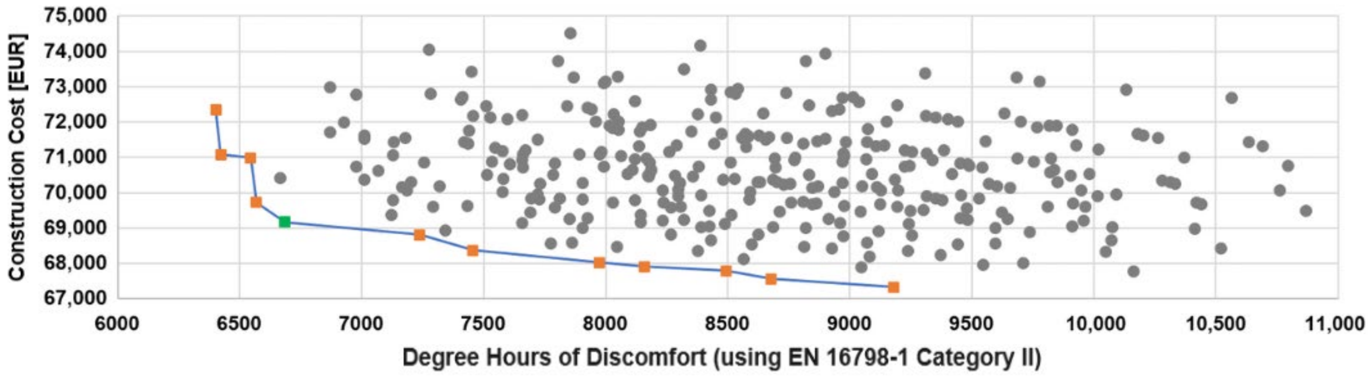

Figure 3. Annual optimisation result for the standard dwelling with the main façade facing south, located in Porto.

The results in several of the following figures will show more than one optimisation process in the same graph, which is why the corresponding data clouds are not represented, showing only the Pareto front with the optimal solutions of each optimisation. The point that best represents the balance between both objectives is also highlighted on the curve in green.

Table 5 shows the composition of the solutions that form the Pareto front of the optimisation of the standard dwelling facing south and located in Porto, detailing each of the four variables. The solution highlighted in green in Figure 3 is highlighted in bold in the table as the best balance between the two variables. It is interesting to note that the ground floor solution, in all optimal solutions, is the less demanding tested floor option in terms of U-value. The ideal solution, in bold, presents the following composition and the following kind of demand: a single external wall with the most demanding option (lowest U-value), a flat roof with the most demanding option (lowest U-value with a solar absorptance of 0.50), glazing with the less demanding option (highest U-value) and ground floor with the less demanding option (highest U-value).

Table 5. Characterisation of the variables that make up the Pareto front solutions for the annual optimisation of standard dwelling facing south, located in Porto.

Objective	Objective	Variables			
Degree Hours of Discomfort (EN 16798-1 Standard—Cat. II)	Total Construction Cost [EUR]	External Wall [W/m^2.°C]	Flat Roof [W/m^2.°C]	Glazing [W/m^2.°C]	Ground Floor Construction [W/m^2.°C]
6401.93	72,348.70	DW U = 0.40	U = 0.30	U = 2.40	U = 0.60
6422.74	71,089.20	SW U = 0.40	U = 0.30	U = 2.40	U = 0.60
6544.56	70,986.84	DW U = 0.40	U = 0.30	U = 2.80	U = 0.60
6567.63	69,727.34	SW U = 0.40	U = 0.30	U = 2.80	U = 0.60
6687.49	**69,161.38**	**SW U = 0.40**	**U = 0.30**	**U = 3.20**	**U = 0.60**
7237.85	68,819.56	SW U = 0.50	U = 0.30	U = 3.20	U = 0.60
7455.38	68,377.34	SW U = 0.40	U = 0.40	U = 3.20	U = 0.60
7974.40	68,035.52	SW U = 0.50	U = 0.40	U = 3.20	U = 0.60
8158.52	67,913.50	SW U = 0.40	U = 0.50	U = 3.20	U = 0.60
8491.26	67,801.62	SW U = 0.60	U = 0.40	U = 3.20	U = 0.60
8678.19	67,571.68	SW U = 0.50	U = 0.50	U = 3.20	U = 0.60
9180.67	67,337.78	SW U = 0.60	U = 0.50	U = 3.20	U = 0.60

DW = Double wall; SW = Single wall.

Figure 4 presents the optimisation results for each orientation and the two analysed locations in winter climate zone I1, Porto and Lisboa.

For both graphs presented in Figure 4, the point that would be the ideal solution in each of these optimisation processes is highlighted in green. This ideal solution has the same composition for all eight Pareto fronts generated for winter climate zone I1, which corresponds to the same kind of demand already described in Figure 3.

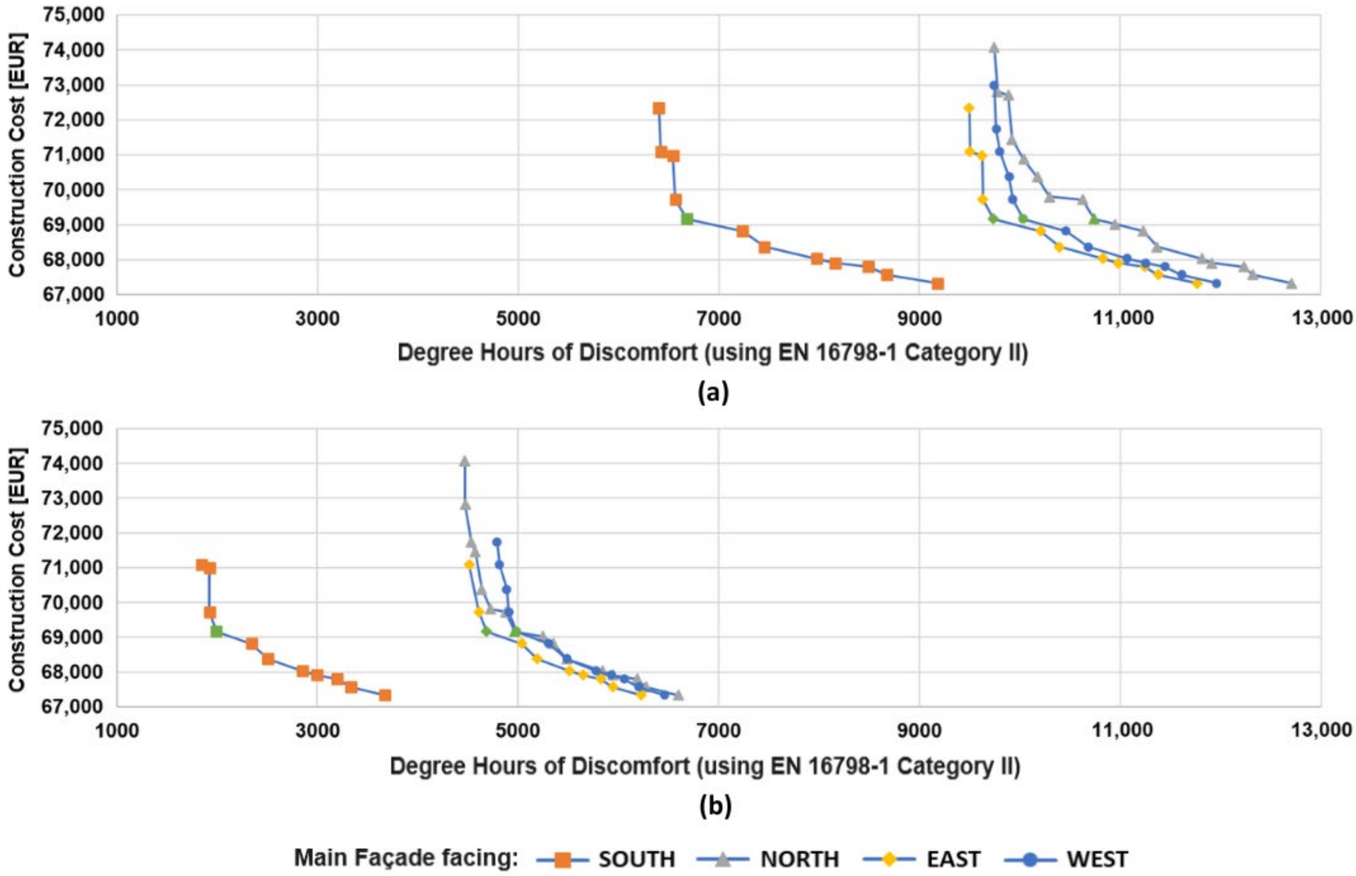

Figure 4. Annual optimisation results (Pareto fronts) for each orientation and two I1 locations: (**a**) Porto and (**b**) Lisboa.

Figure 5 presents the optimisation results for each orientation and the three analysed locations in winter climate zone I2: Batalha, Viseu and Monchique. In all the curves presented in Figure 5, the point that would be the ideal solution is highlighted in green. As shown in the results in Figure 4, this ideal solution has the same composition in all Pareto fronts for south, east and west orientations generated for the winter climate zone I2, which corresponds to the same kind of demand previously described but now concerning zone I2 defined U-values. However, the Pareto fronts for the north orientation in the three I2 locations present an ideal solution with a more demanding ground floor U-value that is equal to the regulatory reference U-value.

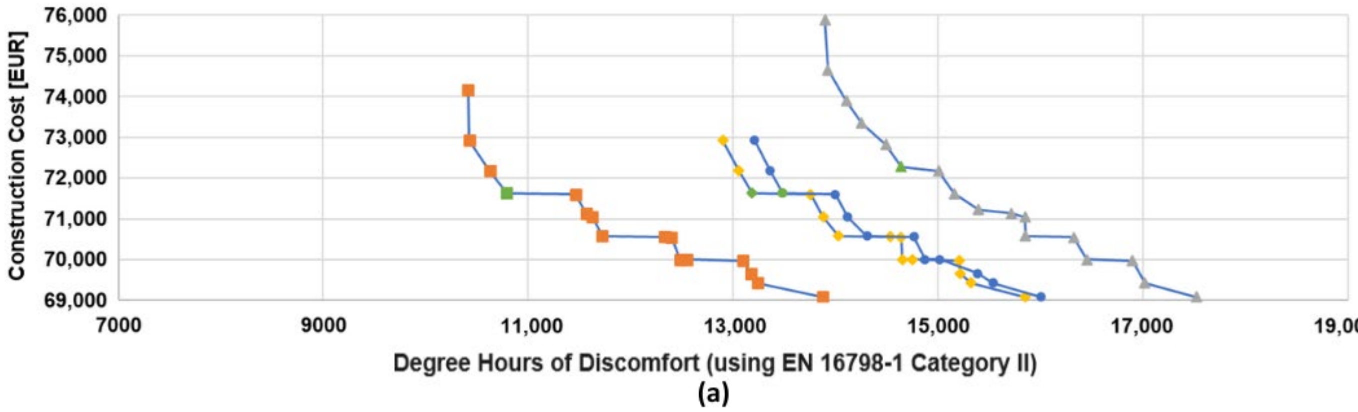

Figure 5. *Cont*.

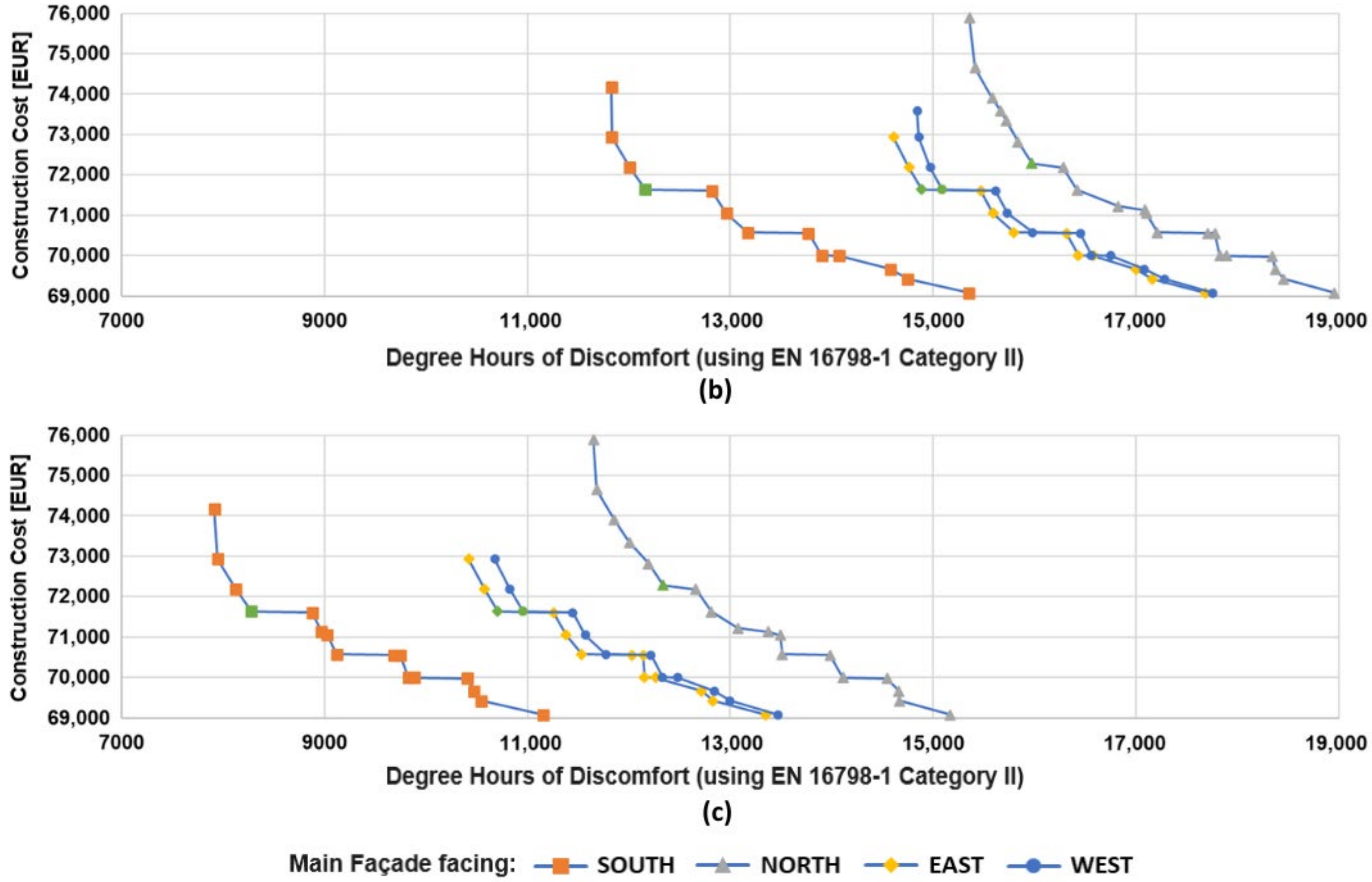

Figure 5. Annual optimisation results (Pareto fronts) for each orientation and three I2 locations: (**a**) Batalha, (**b**) Viseu and (**c**) Monchique.

Figure 6 presents the optimisation results for each orientation and the three analysed locations in winter climate zone I3: Melgaço, Guarda and Macedo de Cavaleiros. Again, in all the curves presented in Figure 6, the point that would be the ideal solution is highlighted in green. As shown in the results in Figure 5, this ideal solution has the same composition in all Pareto fronts for south, east and west orientations generated for the winter climate zone I3, which corresponds to the same kind of demand previously described but now concerning zone I3 defined U-values. However, the Pareto fronts for the north orientation in the three I3 locations present an ideal solution with a more demanding ground floor U-value equal to the regulatory reference U-value.

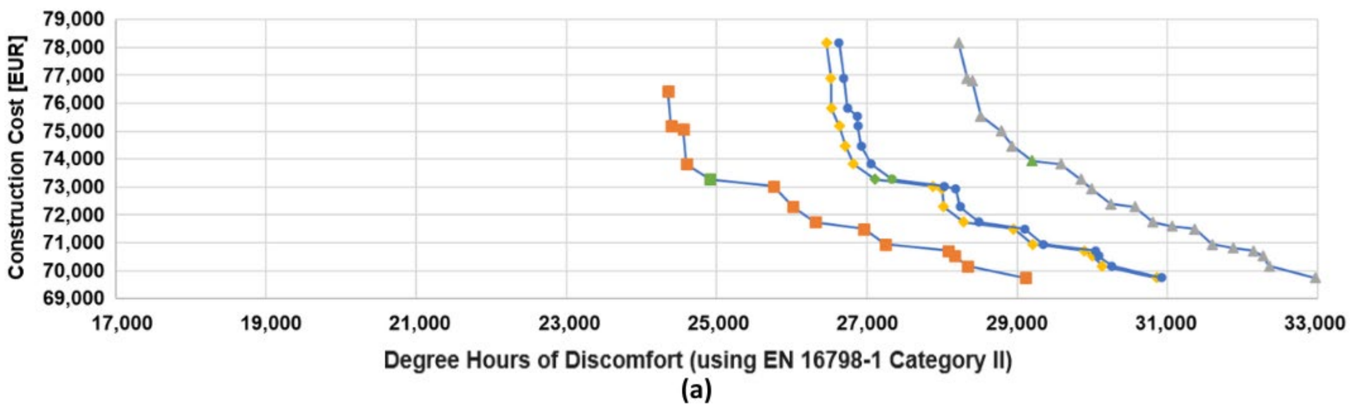

Figure 6. *Cont*.

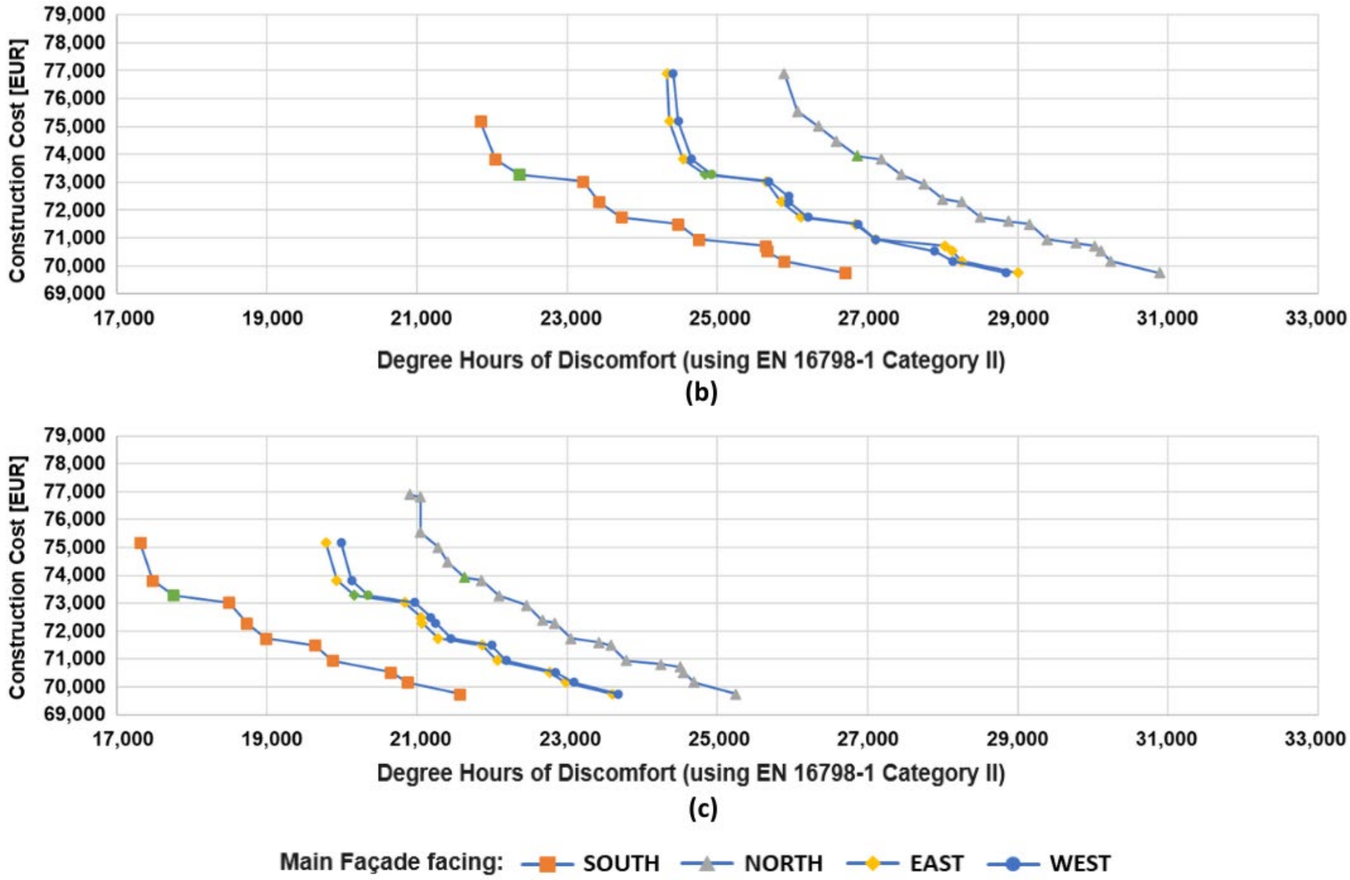

Figure 6. Annual optimisation results (Pareto fronts) for each orientation and three I3 locations: (**a**) Melgaço, (**b**) Guarda and (**c**) Macedo de Cavaleiros.

3.2. Checking nZEB Regulatory Requirements of Ideal Solutions

The glazing of all the ideal solutions presents U-values above the regulatory reference values, and the ground floor of the great majority of the ideal solutions also presents U-values above the regulatory reference values. Therefore, it was necessary to verify whether this variable combination of the ideal solution meets the regulatory requirement for nominal useful energy needs for heating and cooling [32–34]. Table 6 presents the results of applying Portuguese regulations to verify this issue [36]. It can be noted that regulatory requirements (N_{vc}/N_v < 100% for all summer climate zones; N_{ic}/N_i < 75% for I1 locations, N_{ic}/N_i < 85% for I2 locations, and N_{ic}/N_i < 90% for I3 locations) are met for each orientation and for all eight locations.

Table 6. Results of nominal useful energy needs for heating and cooling, in kWh/m^2.year, of the identified ideal solutions according to Portuguese regulations.

	Orientation South						**Orientation North**					
	N_i	N_{ic}	N_{ic}/N_i	N_v	N_{vc}	N_{vc}/N_v	N_i	N_{ic}	N_{ic}/N_i	N_v	N_{vc}	N_{vc}/N_v
Porto	58.45	34.15	**58.43%**	9.13	3.86	**42.28%**	58.45	39.76	**68.02%**	9.13	4.10	**44.91%**
Lisboa	39.01	18.41	**47.19%**	16.50	11.69	**70.85%**	39.01	22.75	**58.32%**	16.50	12.25	**74.24%**
Batalha	70.42	42.68	**60.61%**	6.55	2.22	**33.89%**	70.42	45.91	**65.19%**	6.55	2.67	**40.76%**
Viseu	75.10	45.34	**60.37%**	10.32	4.87	**47.19%**	75.10	48.75	**64.91%**	10.32	5.62	**54.46%**
Monchique	74.40	52.41	**70.44%**	18.97	13.92	**73.38%**	74.40	54.84	**73.71%**	18.97	15.02	**79.18%**
Melgaço	104.25	74.21	**71.18%**	4.24	1.25	**29.48%**	104.25	77.04	**73.90%**	4.24	1.52	**35.85%**
Guarda	103.24	72.62	**70.34%**	7.32	2.64	**36.07%**	103.24	75.65	**73.28%**	7.32	3.13	**42.76%**
Macedo de Cavaleiros	83.67	55.55	**66.39%**	13.67	8.51	**62.25%**	83.67	58.39	**69.79%**	13.67	9.44	**69.06%**

Table 6. *Cont.*

	Orientation East						Orientation West					
	N_i	N_{ic}	N_{ic}/N_i	N_v	N_{vc}	N_{vc}/N_v	N_i	N_{ic}	N_{ic}/N_i	N_v	N_{vc}	N_{vc}/N_v
Porto	58.45	40.59	**69.44%**	9.13	4.67	**51.15%**	58.45	40.59	**69.44%**	9.13	4.70	**51.48%**
Lisboa	39.01	23.42	**60.04%**	16.50	13.49	**81.76%**	39.01	23.42	**60.04%**	16.50	13.55	**82.12%**
Batalha	70.42	50.39	**71.56%**	6.55	2.87	**43.82%**	70.42	50.39	**71.56%**	6.55	2.89	**44.12%**
Viseu	75.10	53.52	**71.26%**	10.32	6.02	**58.33%**	75.10	53.52	**71.26%**	10.32	6.07	**58.82%**
Monchique	74.40	59.27	**79.66%**	18.97	16.29	**85.87%**	74.40	59.27	**79.66%**	18.97	16.35	**86.19%**
Melgaço	104.25	83.39	**79.99%**	4.24	1.52	**35.85%**	104.25	83.39	**79.99%**	4.24	1.54	**36.32%**
Guarda	103.24	81.97	**79.40%**	7.32	3.35	**45.77%**	103.24	81.97	**79.40%**	7.32	3.38	**46.17%**
Macedo de Cavaleiros	83.67	63.66	**76.08%**	13.67	9.69	**70.89%**	83.67	63.66	**76.08%**	13.67	9.76	**71.40%**

3.3. Cooling Season Optimisation

The following results refer to the conventional four months of the cooling season (from 1st June to 30th September). Initially, the optimisation was carried out strictly following the criteria established by Standard EN 16798-1—Category II, and the results of the optimal solutions for all simulations showed no discomfort. Therefore, the combination with the lowest absolute cost was, logically, considered the optimal case. In fact, the methodology of the Standard allows very high indoor temperatures if the average outdoor temperature is also very high. Despite warm summers, the use of cooling systems is not common in Portuguese dwellings. However, because of global warming, higher temperatures are expected. Thus, if these kinds of analyses are carried out during the design phase of a new building, admitting an excessive tolerance towards high indoor temperatures instead of imposing a demanding upper limit will certainly lead to an increase in the use of those systems.

Therefore, for a more demanding assessment of summer overheating risk, in the scope of the present study, the Standard EN 16798-1—Category II criteria were subjected to an adaptation concerning the recommended design values of indoor temperature for residential buildings, introducing a limitation for its upper limit definition. The application of EN 16798-1 formulae for the calculation of that upper limit must not lead to a temperature exceeding 26 °C.

Figure 7 shows the limits considered for the evaluation of summer overheating, where it is possible to notice the adaptation of the upper limit: when the Operative Temperature (Θ_O) reaches 26 °C, the upper limit is fixed and no longer follows Equation (1), represented by the dotted line.

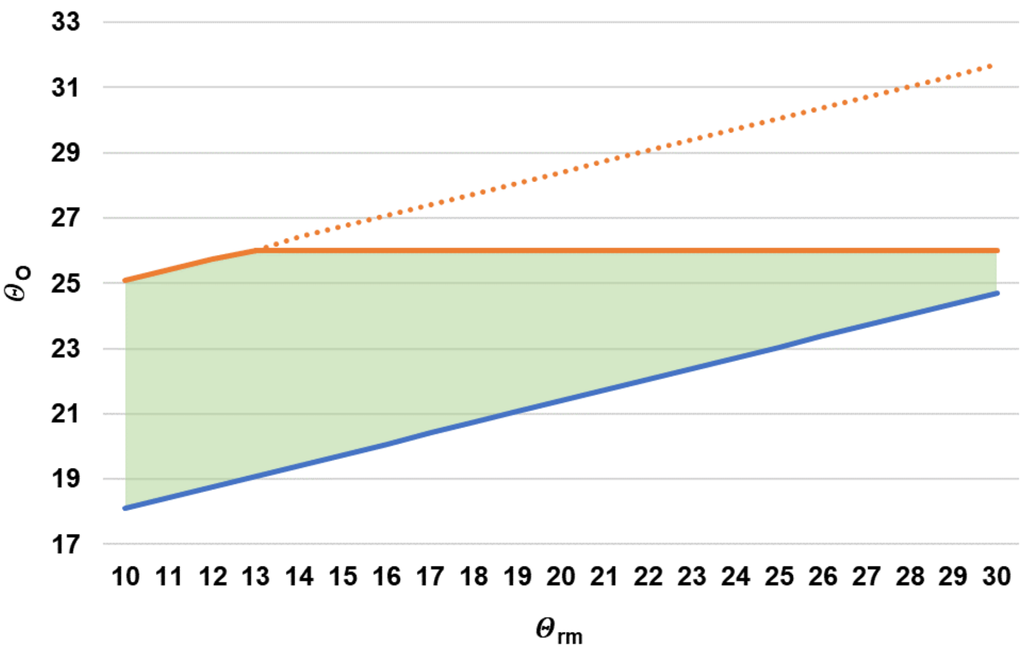

Figure 7. Adaptation of EN 16798-1—Category II criterium for the Degree Hours of Discomfort analysis in the cooling season.

To simplify the visualisation of the results, only two orientations will be presented for each analysed location: south and west. This is because, due to the balanced distribution of the glazed area on opposite façades, the results for the other two orientations are very similar.

All the presented results for annual optimisations correspond to the use, as solar protection, of a roller shutter placed on the outdoor side of the windows according to a schedule previously described. For the specific cooling season analysis, the use of a shutter placed on the indoor side of the windows was also tested with the same schedule, as well as the non-use of any shutter by the occupants in the daytime.

The two locations in the V1 summer climate zone, Batalha and Melgaço, did not present significant discomfort in any of the three shading configurations, even with the upper limit adaptation explained above, for the summer overheating analysis. Therefore, graphical results for locations in this climate zone are not displayed for this specific analysis.

Figure 8 presents the optimisation results for the cooling season of the three summer climate zone V2 locations: Porto, Viseu and Guarda. As shown in the previous figures, the points considered the ideal solution in each graph are highlighted in green. In this figure, the comparison is made between three locations that present different combination possibilities since they are located in different winter climate zones for which the regulatory reference values were established, and it is possible to see that the composition of the ideal solution and its cost is different for each location. However, in relative terms, the ideal solution, coloured in green, has the same kind of demand for the 18 Pareto fronts, which is as follows: a single external wall with the less demanding option, a roof with the less demanding option (but with a solar absorptance of 0.40), glazing with the less demanding option and ground floor with the less demanding option.

Figure 9 presents the optimisation results for the cooling season of the three summer climate zone V3 locations: Lisboa, Monchique and Macedo de Cavaleiros. Each ideal solution is highlighted in green, which, in relative terms, presents the same kind of demand described for the V2 zone.

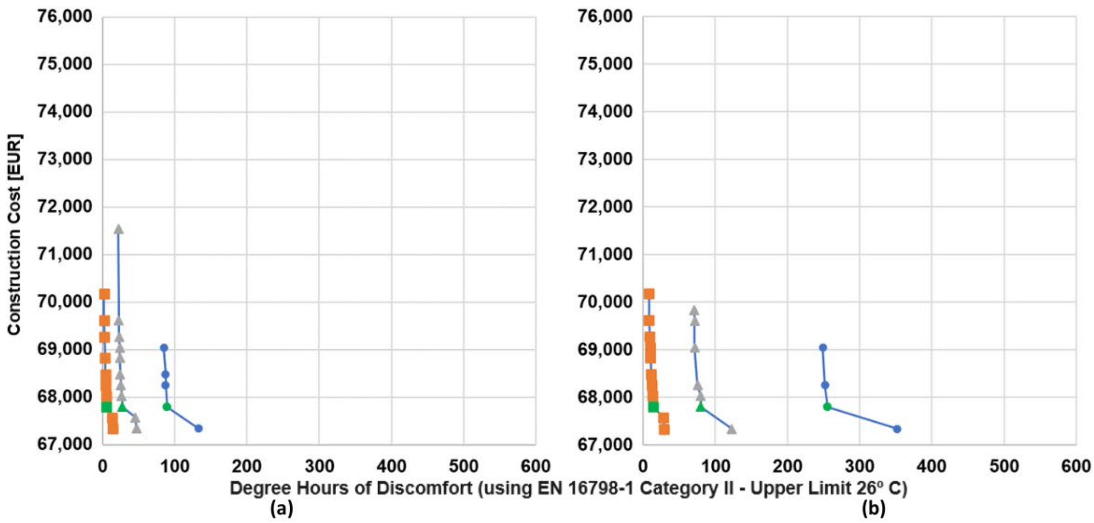

Figure 8. *Cont.*

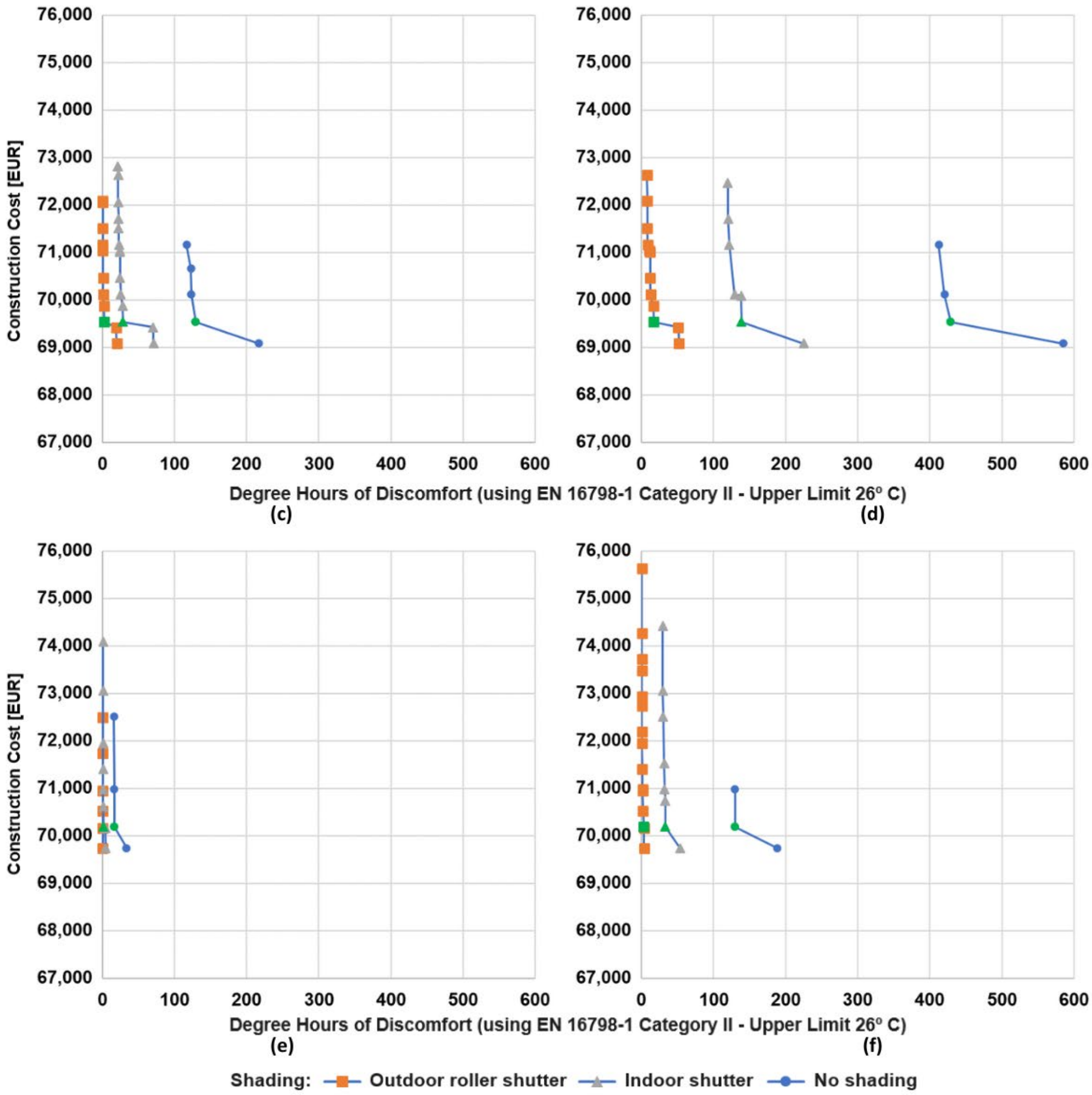

Figure 8. Optimisation results for the cooling season for V2 locations: Porto (**a**) south and (**b**) west orientations; Viseu (**c**) south and (**d**) west orientations; and Guarda (**e**) south and (**f**) west orientations.

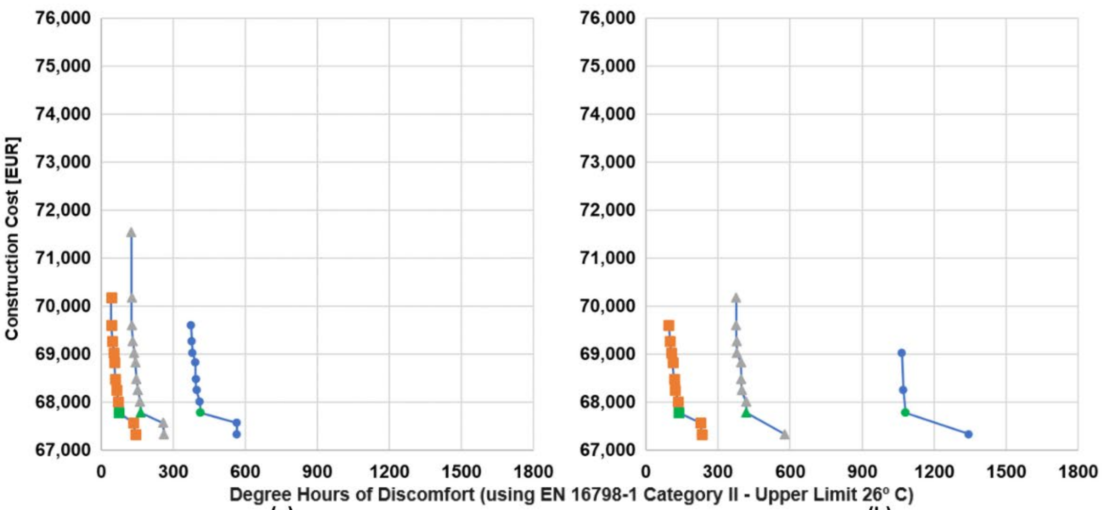

Figure 9. *Cont.*

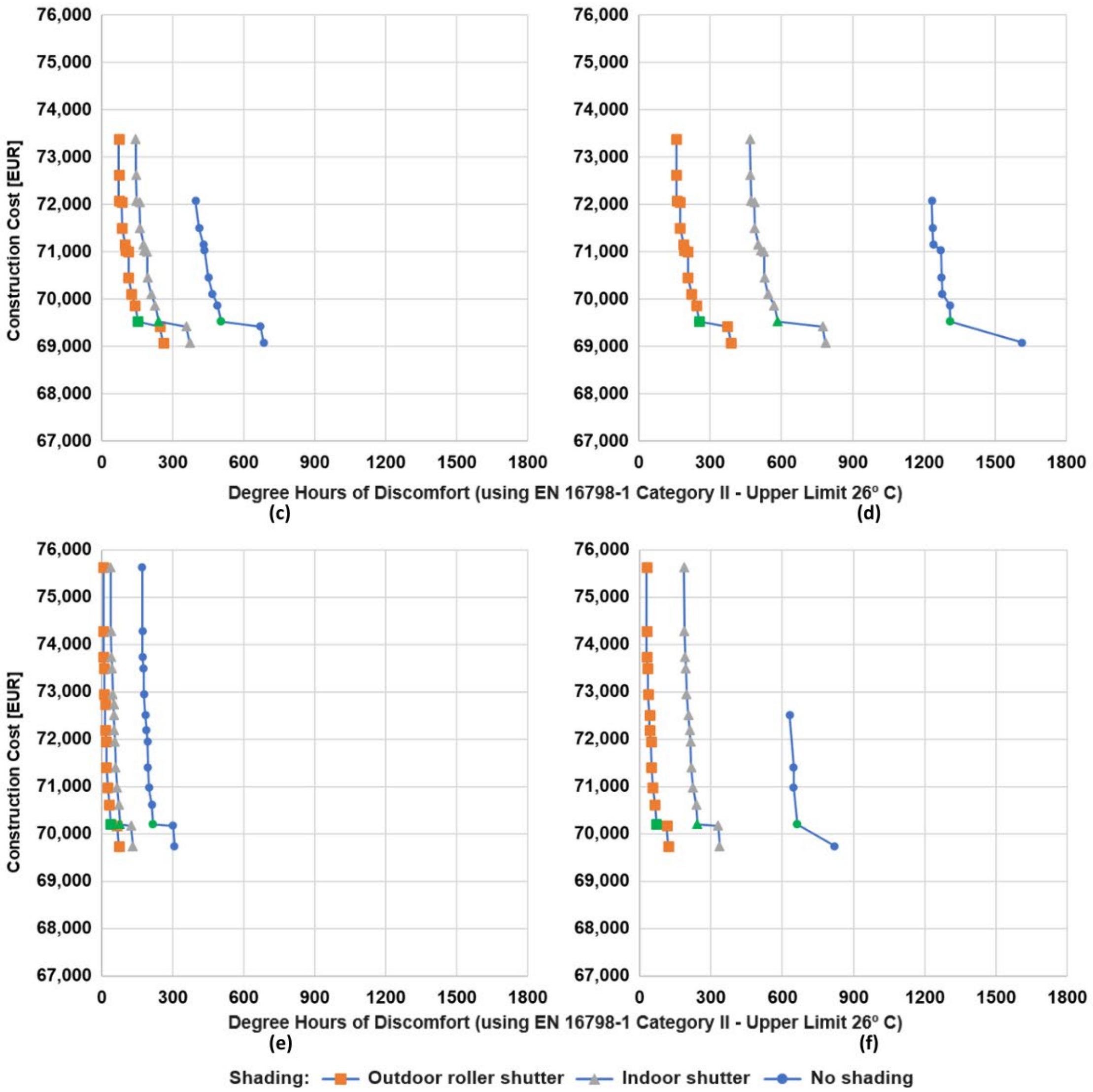

Figure 9. Optimisation results for the cooling season for V3 locations: Lisboa (**a**) south and (**b**) west orientations; Monchique (**c**) south and (**d**) west orientations; and Macedo de Cavaleiros (**e**) south and (**f**) west orientations.

3.4. Additional Analysis on Summer Overheating

The analyses presented in the results of Figures 8 and 9 were carried out according to the base case configurations defined for this study. However, this base case follows what we can consider as good practices, namely having high thermal inertia, an excellent window-to-floor ratio and adequate operation of natural ventilation and the shutters. Unfortunately, these practices may not be followed by designers regarding the inertia and glazing ratio and by occupants in relation to the operation of natural ventilation and shutters. With this in mind, it is necessary to make a quick analysis of each of these situations when they do not follow the practices determined for the base case.

To carry out this analysis, the house with the main façade facing West, located in Lisboa, was chosen, which, in the base case (Figure 8b), already has some discomfort during the cooling season. To analyse the situation of low thermal inertia, the insulation layer was positioned on the indoor side of the external walls, roof and floor (when applicable). In the analysis of a larger glazing area, the percentage of the window-to-floor ratio was doubled (in the base case, it was around 15%; in this new analysis, it is around 30%). In relation to natural ventilation, for it to be running, it no longer depends on the difference between the outdoor and indoor temperatures but rather only on the user's routine; the user will open the windows every morning and close them only in the late afternoon, regardless of outdoor and indoor temperatures, maintaining the limit of four air changes per hour.

Aiming to bring more elements for further discussion, instead of presenting only the Pareto fronts with the optimal solutions of each optimisation, the complete cloud with all possible combinations of each case will be presented, highlighting the optimal solutions that form the Pareto curves. However, to bring information with this presentation, it was necessary to leave aside the adoption of the same scale for the Degree Hours of Discomfort. Therefore, when analysing the graphs in Figures 10–12 it is necessary to pay particular attention to the different scales of the X axes.

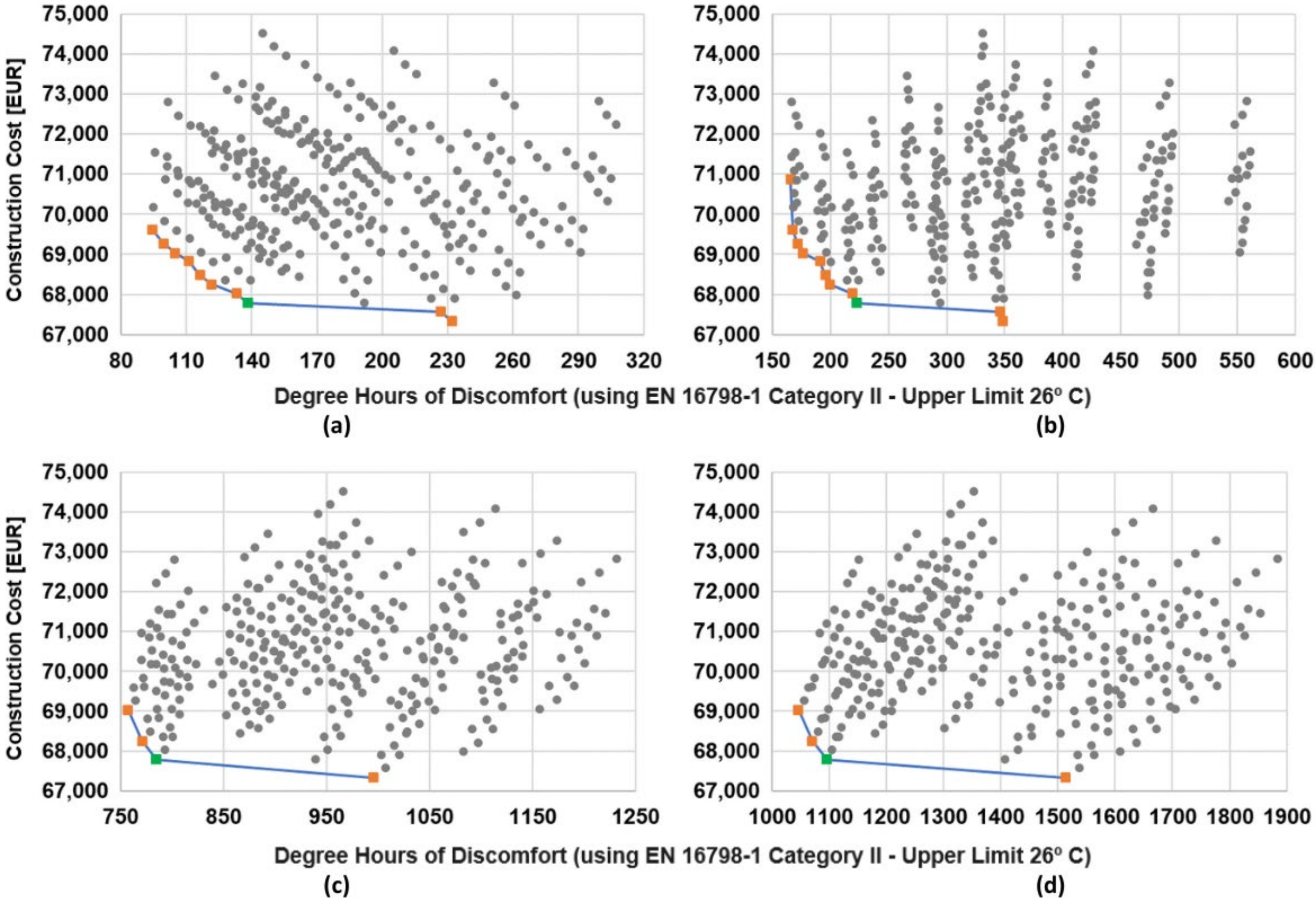

Figure 10. Optimisation results for the cooling season for Lisboa west orientation with outdoor roller shutter: (**a**) base case; (**b**) low thermal inertia; (**c**) higher window-to-floor ratio; and (**d**) whole daytime natural ventilation.

Figure 10 shows the cases with a roller shutter placed on the outdoor side of the windows as glazing shading. The graph presented in (a) corresponds to the case whose Pareto front is the curve of orange points in Figure 9b, and its optimal solutions lead to a discomfort of 94 to 232 Degree Hours. The case with low thermal inertia presents optimal solutions that lead to a discomfort of 171 to 348 Degree Hours. The case with a higher window-to-floor ratio presents optimal solutions corresponding to 757 to 996 Degree Hours of Discomfort. Finally, the case with whole daytime natural ventilation presents optimal solutions that show from 1045 to 1513 Degree Hours of Discomfort. The ideal solution, highlighted in green, for all the scenarios follows the same configuration previously presented in the base case: a single external wall with the least demanding option, a roof with the least demanding option (with a solar absorptance of 0.40), glazing with the least demanding option and ground floor with the least demanding option.

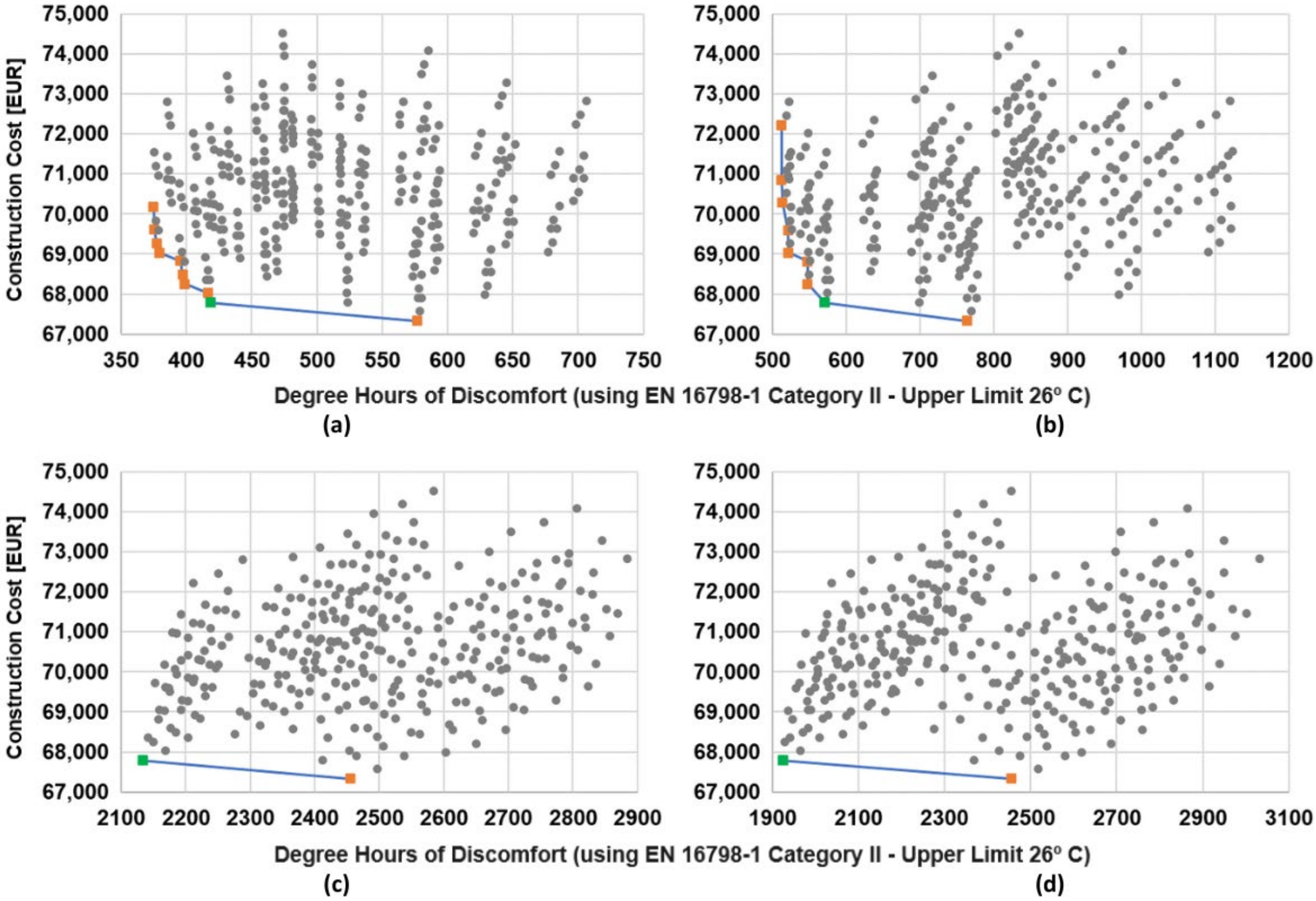

Figure 11. Optimisation results for the cooling season for Lisboa west orientation with indoor shutter: (**a**) base case; (**b**) low thermal inertia; (**c**) higher window-to-floor ratio; and (**d**) whole daytime natural ventilation.

Figure 11 shows the cases with an indoor shutter as unique solar protection of the window. The graph presented in (a) corresponds to the case whose Pareto front is the curve of grey points in Figure 9b, and its optimal solutions lead to a discomfort from 374 to 577 Degree Hours. The case with low thermal inertia presents optimal solutions that lead to a discomfort from 512 to 764 Degree Hours. The case with a higher window-to-floor ratio presents optimal solutions with 2134 to 2455 Degree Hours of Discomfort. Finally, the case with whole daytime natural ventilation presents optimal solutions corresponding to a discomfort of 1926 to 2456 Degree Hours. The ideal solution, highlighted in green, follows the same configuration previously presented in the base case.

Figure 12 shows the cases with no glazing shading. The graph presented in (a) corresponds to the case whose Pareto front is the curve of blue points in Figure 9b, and its optimal solutions lead to a discomfort between 1064 and 1345 Degree Hours. The case with low thermal inertia presents optimal solutions that lead to a discomfort from 1302 to 1637 Degree Hours. The case with the higher window-to-floor ratio presents optimal solutions with 4718 to 5175 Degree Hours of Discomfort. Finally, the case with whole daytime natural ventilation presents optimal solutions corresponding to a discomfort of 3826 to 4499 Degree Hours. The ideal solution, highlighted in green, follows the same configuration previously presented in the base case.

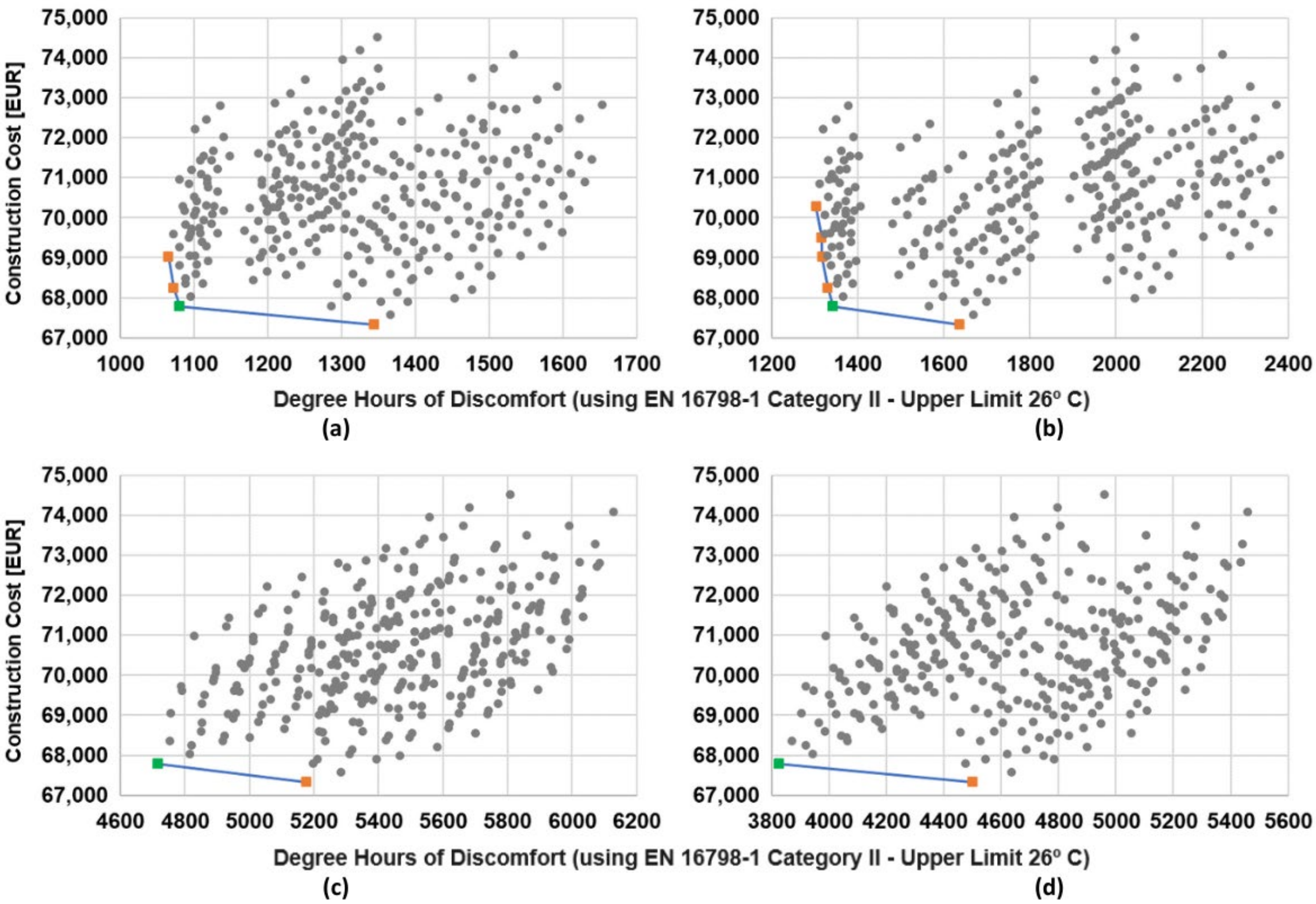

Figure 12. Optimisation results for the cooling season for Lisboa west orientation with no glazing shading: (**a**) base case; (**b**) low thermal inertia; (**c**) higher window-to-floor ratio; and (**d**) whole daytime natural ventilation.

4. Discussion

To begin the discussion of the results, it is essential to highlight some choices made in preparing this study. Firstly, the main focus is on obtaining passive comfort through the optimisation of the building envelope. Therefore, the HVAC system was not used in this investigation, aiming to get the best comfort levels without energy consumption through best construction practices. This choice meets the most common behaviour of the Southern European population in a Mediterranean climate, where people do not have the habit of maintaining their indoor environment at a highly demanding level of comfort through active acclimatisation. In contrast to Central and Northern Europe, this cultural behaviour was, in a certain way, shaped both by the milder climate and by the average financial conditions of the populations of these regions. Considering these factors, Category II of Standard EN 16798-1 was used in the annual comfort analysis in the investigated locations.

Although the exact definitions of nZEB/NZEB concepts vary greatly between organisations and countries, there is a "rule" that is universal to all definitions and has been very well established in the literature for a long time: "tackle demand first, then supply" [37,38]. Portuguese regulations, as mentioned before, allow the criteria related to passive comfort to be separated from those related to renewable energy supply. In this sense, it was possible and necessary to verify compliance with the nZEB requirements of the passive part of the construction. This also explains the choice of the values for the variation of the U coefficient, which were taken around the regulatory reference U-values within a narrow range. Logically, the nZEB/NZEB concepts require, at their very core, a supply of renewable energy. However, this step is outside the scope of the present paper.

It was also an option of the authors to perform the annual optimisation on a base case that complies with good practices related to other characteristics of the building and their use, namely, a recommendable window-to-floor ratio (15%), a high thermal inertia, the sensible use of external roller shutters and an energy-conscious natural ventilation schedule.

According to the Pareto fronts, the optimal annual results are presented in Figures 4–6. It is noticed that the results clearly agree with a principle that is already very well established as a good practice for energy efficiency in buildings, which is that the façade with the largest glazing area should be facing south for locations in the northern hemisphere. In the eight studied locations, it is possible to notice that the south orientation curve notably presents the lowest annual thermal discomfort.

It is interesting to note that in all 24 Pareto fronts related to the south, east and west orientations, the so-called ideal solution, highlighted in green in all of them, has the same kind of demand in relative terms (obviously respecting the different requirements in different climate zones). This ideal solution presents the best theoretical balance between the two optimisation objectives: minimisation of the cost of the analysed envelope components and minimisation of thermal discomfort based on the concept of Degree Hours of Discomfort, calculated using EN 16798-1—Category II. For each climate zone, the ideal solution consists of a single external wall with external thermal insulation, with a U-value lower than its regulatory reference value, a roof with external thermal insulation also with a U-value lower than its regulatory reference, glazing with a U-value higher than its reference value and a ground floor also with a U-value higher than its reference value.

Concerning the Pareto fronts for the north orientation, which is the ideal solution for zones I2 and I3, they present practically the same previous kind of demand, with the exception of the ground floor, which must now be a little more demanding, with a U-value equal to the regulatory reference.

These results can be explained by some factors, considering, of course, the best balance between the optimisation objectives. The external wall and roof variables, which have a larger exposed area and consequently have a more significant influence on heat exchange, are the ones that presented the most demanding options in the composition of the ideal solution. Meanwhile, the ground floor and glazing, in their less demanding options, provide sufficient conditions within the analysed objectives. It is essential to highlight that even though the ground floor presents, in most cases, the least demanding option, with a U-value above the maximum regulatory reference values, it continues to be a variable option with an acceptable and effective U-value.

Glazing, as the envelope component with the highest cost per m^2 but without a too-large area that could allow high heat losses in winter, seems to be the component where the cost is the most determinant. However, the least demanding option of the glazing for climate zone I1 (3.2 $W/m^2.°C$), which makes up the optimal solutions, cannot be used in current construction practice because the regulations limit the maximum U-value for glazing up to 3.0 $W/m^2.°C$ [32]. However, this option was considered, mainly to follow the same kind of variation as the other climate zone options. If this restriction did not exist, the combination would pass all other regulatory requirements, as shown in the results in Table 6. Therefore, this issue deserves greater attention in the subsequent revisions of the regulations.

It is also essential to mention the importance of an informed and reasoned choice within the possible existing variables. As an additional example of the importance of choosing an optimised solution for the users' comfort, let us assume that the designer had opted for the further-to-the-right point case in the cloud of the graph in Figure 3 (a single external wall with the least demanding option, a roof with the least demanding option (with a solar absorptance of 0.40), glazing with the least demanding option and ground floor with the most demanding option). The nZEB regulatory requirements related to passive options would also be met (Nic/ Ni < 75% and Nvc/Nv < 100%), but the total cost of this choice would be slightly higher than that of the ideal solution (€69,513 versus €69,161) and, more significantly, it would lead to around a 62% higher number of Degree

Hours of Discomfort (10,867 against 6687). Figure 13 compares the optimised solution (the one identified as ideal) and this possible uninformed choice (non-optimised solution but still complying with the regulations). In the coldest week of the year, it is possible to notice that the indoor hourly operative temperature is more than one degree higher in the ideal solution than in this other possible solution. This comparison translates into a smaller difference from the lower limit of the EN 16798-1 Standard; therefore, lower Degree Hours of Discomfort in a situation without an HVAC system, which would consequently translate into lower energy consumption for heating due to a passive choice made thoughtfully.

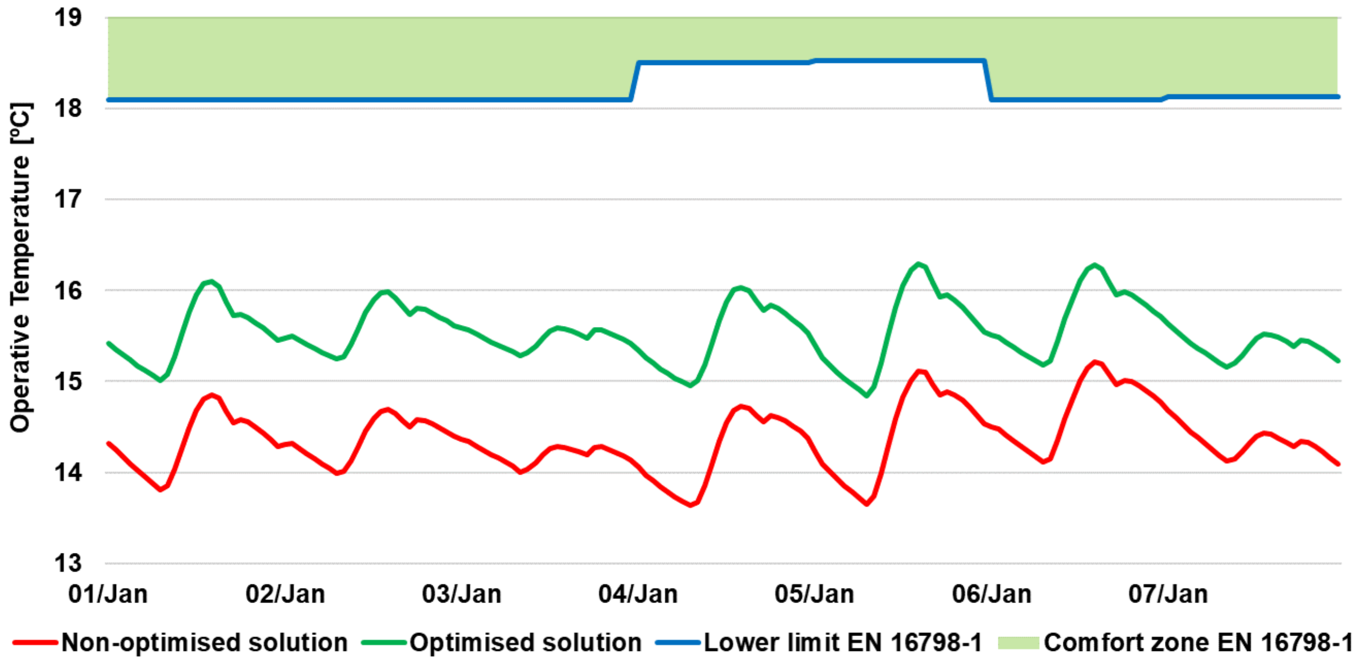

Figure 13. Comparison between the optimised solution and a non-optimised solution in the coldest week of the year for the standard dwelling with the main façade facing south, located in Porto.

As explained before, with the aim of analysing summer overheating risk, an adaptation was made to Standard EN 16798-1, with the upper limit fixed at 26 °C. The results presented in Figures 8 and 9 show that the ideal solution would combine all less-demanding variables.

In the base case, the values of Degree Hours of Discomfort of the optimal solutions for the cooling season are quite low when compared to the annual results, showing that without HVAC, discomfort in winter is much higher. However, in this case, the assessment was made for ideal conditions.

Thus, some additional analyses were carried out, and the results are presented in Figures 10–12 to expand the analysis of summer overheating risk. For this analysis, it was essential to present the entire cloud of results in each graph because they show us, in many graphs, the shape of the cloud with a tilt to the right, which means that a higher cost would translate into a greater number of hours of discomfort. This fact reaffirms that excessive insulation is harmful for summer comfort in this region. In the most recent years, excessive insulation has often been the choice of designers who go beyond regulatory requirements, believing they are making a better choice.

In addition to these issues, several others can be noted in the analyses of the cooling season. It is worth highlighting the importance of paying attention to solar gains in this season. It is clear that when shading is placed on the outdoor side of the glazing, there is less discomfort in all situations, a factor that designers must consider. Furthermore, the behaviour of users is also fundamental in this matter. When they do not follow good practices, the consequence is a very significant increase in discomfort. When no shading is used and, for example, there is a large glazing area (Figure 12c), the Degree Hours of

Discomfort can reach 6000 or more. If this value is compared to the values of the annual Pareto front for Lisboa west orientation (Figure 4b), it can be seen that in certain conditions, discomfort in summer may turn out to be the most critical. This is most likely to occur in regions of a particularly mild winter (I1) and a severe summer (V3), like Lisboa.

From the additional analyses, it is also observed that the option for low thermal inertia or a higher window-to-floor ratio translates into greater discomfort in summer for all analysed cases, two factors for which designers have a responsibility and must be carefully chosen. Again, on the part of users' behaviour, the use of natural ventilation in a prudent manner can be translated into a reduction in discomfort.

Another point that is important to highlight is an absorptance value of 0.40 for the ideal roof solutions in the cooling season analyses, while in the annual analyses, the optimal cases (not just the ideal solutions) present a solar absorptance of 0.50. The choice must be made through a sensible balance between annual analysis and seasonal analysis, taking into account all the factors involved in a case-by-case assessment. However, in Southern Europe, where solar irradiation can be very intense, light colours are preferable for thermal comfort in summer but also, in large measure, for the higher durability of the outer material layers. In winter, the possible increase in solar gains through an opaque element by increasing its solar absorptance is normally negligible when the envelope component in question has a low U-value.

Furthermore, reference year climate data were used in this study, which is the most common procedure in scientific studies. However, in recent years, more constant and longer-lasting heat waves have occurred, and they may tend to get worse in the future. This fact is still not reflected in the reference year climate data. Researchers are aware of the limitations of using these data. However, increased attention must be paid to this issue, especially when the comfort analysis is carried out for regions of the world that have a greater tendency to overheat in summer, as is the case.

Finally, the key characteristic of the optimisation results is to highlight the optimal cases that form the Pareto front, but it is necessary to always keep in mind when carrying out the analyses that these cases are the optimal ones for the combination of the two selected objectives. The practical choice depends, obviously, on the relative importance of each objective.

5. Conclusions

As stated before, focusing on Southern European climate and considering a standard single house complying with nZEB requirements, the present study aimed to perform an optimisation of the envelope by minimising passive thermal discomfort and initial construction cost, allowing at the same time the discussion of some aspects of regulatory requirements.

The main conclusions of this paper can be summarised by answering the questions raised at the beginning of it:

- To what extent do current regulatory requirements prevent passive discomfort?

With current construction solutions that comply with the regulatory requirements for nZEB, it is possible to find a set of optimised solutions that do not totally prevent discomfort but lead to a considerably reduced value of annual Degree Hours of Discomfort at an affordable cost. However, other design options and the pattern of usage have a great influence on comfort conditions, and even with envelope solutions complying with the reference values for the nZEB envelope, the discomfort may result in being much higher than one of the optimised solutions.

- Given that winter and summer passive comfort point mostly to opposite strategies, what would be the most balanced envelope options for achieving nZEB/NZEB status?

Winter passive comfort relies mainly on the thermal insulation level of the envelope and its U-value, as well as solar heat gains and the capacity of the building to store them.

Summer passive comfort relies mainly on protection from solar heat gains and the potential for night heat losses through the envelope and by ventilation.

Winter passive strategies are not very dependent on the user, and the designer can easily optimise them.

On the contrary, several very influential factors on summer comfort were identified, and some of them, namely the ones that depend on user behaviour, are obviously not controllable. Some design options that have an influence on summer passive comfort are also free from any requirements or just have indirect requirements, and designers are less aware of their influence. This scenario, associated with climate change predictions of higher temperatures and longer and more intense heat waves, stresses the need for increased attention to summer requirements.

For the moment, as the present study shows, the annual optimisation process is highly influenced by the heating season since it is the longer one, and the differences between outdoor and indoor comfort temperatures are undeniably greater than those differences in the cooling season. However, this scenario tends to change with time.

It can be concluded that envelope U-values around the current reference U-values allow for optimised solutions. But there is a need for a compromise between the contradictory optimal solutions for winter and summer, especially for the external walls and roof, the larger and more exposed components of the envelope: in winter, the ideal solutions recommend a U-value slightly lower than the reference; and in summer, the ideal solutions propose a U-value slightly higher than the reference. Since, in both seasons, other passive strategies can (much easier in winter than in summer, though) compensate for the fewer good options for U-values, as a general rule, for a balanced envelope solution, U-values should be as close as possible to the reference, and designers should optimise solar heat gains in winter and provide the means for allowing night ventilation of the building in summer. Regulations should reinforce the requirements for summer by prescribing the external shading of the windows and/or defining a maximum window-to-floor ratio.

Concerning solar absorptance, summer optimisation should be prevalent.

- Is the trend of an increasing regulatory requirement for the level of envelope thermal insulation recommendable for Southern Europe?

As can be implied by the answer to the former question and confirmed by the presented results, a regulatory requirement imposing a higher level of thermal insulation for the building envelope in Southern Europe is not recommendable. For the moment, the current requirements seem adequate.

- What would be the consequences for the choice of heating and cooling systems and renewable energy sources of the optimised envelope options?

As a known general principle, heating and cooling systems must be as efficient as possible, and for an nZEB, renewable energy sources must cover at least a regulated percentage of the energy needs of the building. An optimised envelope, by reducing the discomfort, also reduces heating and cooling energy needs, obviously. Thus, the demand put on the systems and on renewable energy sources will be lower. Even if changes to the optimised solutions must be made to reach a compromise between winter and summer comfort, other passive strategies, as said before, will compensate for those changes.

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