Title:

Towards the implementation of periodic thermal transmittance in Spanish building energy regulation

Highlights:

- 2,413 wall typologies are compared as per ISO 13786 and ISO 6946 calculation procedure.
- Thermal mass and thermal capacity should be larger than 150 kg/m^2 and 150 kJ/m^{2}K to minimize energy demand in the two zones studied.
- If the time shift is larger than 15 h, periodic thermal transmittance should not be limited in warm climates.

Abstract:

The recent development of the calculation methodology for dynamic thermal properties of buildings has opened new possibilities for reducing their energy demand; however, building codes still rely on the traditional static approach. This research aims at filling in this gap by exploring how periodic thermal properties can be implemented in the Spanish regulatory framework. For this purpose, 2,413 wall typologies were analysed in the two extreme climate zones as per the Spanish regulation pertaining to energy efficiency. Results show that the static U-value itself is not sufficient to optimize the energy demand of buildings, as for a single value of U variations of 4,000 kWh in the energy demand are expected. Regarding periodic variables, decrement factor and time shift were the most effective to minimize the energy demand, along with flexible limitations for the periodic thermal transmittance and the time shift. In warm climates, the former can be disregarded if the latter is greater than 15 hours. The findings from this study disscuss the applicability of the static thermal transmittance and propose a methodology to select and limit periodic variables for the two most extreme climates in Spain.

Keywords:

Energy demand; Spanish building energy regulation; envelope; periodic thermal transmittance; time shift.

Nomenclature

Symbols

c: Specific thermal capacity

d_i: Thickness of each layer of the wall

f: Decrement factor

$R_{s,ext}$: External surface resistances

$R_{s,int}$: Internal surface resistances

U: Thermal transmittance

Y_{11}: Internal thermal admittance

Y_{12}: Periodic thermal transmittance

Y_{22}: External thermal admittance

Z: Heat transfer matrixes are built for each layer of the wall

Z_{s1}: Thermal resistance of internal air layers

Z_{s2}: Thermal resistance of external air layers

Greek letters

λ_i: Thermal conductivity of each layer of the wall

ξ: Ratio of thickness and density

ρ: Density

φ: Time shift periodic thermal admittance

φ_{11}: Time shift internal side

φ_{22}: Time shift external side

Abbreviations

CED: Cooling energy demand

CTE-DB-HE: Basic Document - Energy Conservation of the Spanish Building Code

EPS: Expanded polystyrene

EPW: Energy Plus weather

EU: European Union

GHG: Greenhouse gas

HED: Heating energy demand

IPCC: Intergovernmental Panel on Climate Change

MW: Mineral wool

nZEB: Nearly zero energy buildings

PUR: Polyurethane rigid foam

SCS: Summer climate severity

TED: Total energy demand

WCS: Winter climate severity

XPS: Extruded polystyrene

1. Introduction

1.1. Climate change and energy efficiency in the building industry

The Intergovernmental Panel on Climate Change (IPCC) has been working for the last decades in foreseeing the possible combinations of future scenarios of climate change throughout the 21st century and their consequences for the life in the planet [1,2]. Most of them would lead to serious environmental problems, mainly due to greenhouse gas (GHG) emissions, whose main cause is the depletion of non-renewable sources. Energy consumption is steadily growing due to the rapid economic growth in developing countries and the progressive improvement of life quality in developed countries [3]. This increase has been reflected in many sectors of the economy, amongst which the building sector stands out because of the poor energy performance of the extant building stock [4–7]. As for the European Union, buildings were responsible for 36% of GHG emissions [8,9] and for 40% of the total energy consumption [10,11].

Consequently, the European Union has devised a strategy to reach what it is called a low carbon economy by 2050 [12]; for this objective, the reduction of GHG emissions remains essential in various sectors, including the building industry, for which the European Union (EU) expects to cut GHG emissions by 90%. Moreover, the Directive 2018/844 [13] has compelled European countries to devise strategies for improving the energy efficiency of existing buildings before 2050. It has been proved that inefficient building envelopes are the main responsible for excessive heat gains or losses [14–17], and for that reason the building industry has progressively adopted thicker insulation, solar control devices, and improved air tightness to improve its efficiency. However, dynamic thermal properties are usually underestimated in the design of envelopes [18].

At present time, the EU does not have a common legal framework regarding energy efficiency for buildings. As for Spain, the basic document on Energy Efficiency, which abides by the Basic Document - Energy Conservation of the Spanish Building Code (CTE-DB-HE in its Spanish acronym) [19], limits the U value and other parameters to guarantee minimum energy efficiency standards for both new and existing structures. This Code is expected to be updated in 2020 to implement the concept of nearly zero energy buildings (nZEB), following in such way the mandate from the Directive 2010/31/UE, which make the nZEB standard mandatory for public buildings before 2019 and for all buildings before 2021. Nevertheless, several authors have expresses their concern about the applicability of such standards to buildings in warm climates in Southern Europe [20], amongst which Spain stands out as a compelling case-study because of the great variety of climates, which make difficult to stablish common design criteria for the whole country [21]. As an example of this, previous research has proved that building located in the same climate zone in Sothern regions of Spain may need corrections of around 6% in their limit U-value due to local variations of climate [22]

1.2. Background and motivation

It is expected that the modification of the CTE-DB-HE will consider that all buildings meeting with this regulation are nZEB. As for the thermal properties of the envelope, there are limitations for the stationary thermal transmittance depending on the climate zone of the building. However, previous research has proved that stationary properties of walls do not consider the effect of thermal inertia on the building performance [23]. Thermal mass, along with the stationary thermal transmittance exert an influence on building energy performance [24] and also depends on the location: this influence is more evident in warm climates [25].

Consequently, the ISO 13786 standard [26] offers an opportunity to overcome these limitations by including a novel calculation procedure that assess building envelopes under a dynamic regime, considering, among other variables, thermal inertia, decrement factor and time shift. Input data for these calculations are similar to those required for stationary thermal transmittance per the ISO 6946 [27] (implemented in the calculation procedure of the CTE-DB-HE); these are, basically, the thermophysical properties and the thickness of each layer. The control of periodic properties may allow the building energy performance to be optimized. In this sense, low values of the periodic thermal transmittance reduce the impact of the external thermal load [28].

For this reason, some countries are gradually updating their legislation and introducing dynamic thermal properties as mandatory, being Italy a paradigmatic case within the European context. The Italian Decree Interministeriale 26 giugno 2015 [29] establishes limit values for both thermal mass (greater than 230 kg/m^2) and periodic thermal transmittance (lower than 0.12 W/(m^{2}K)). On top of that, the Decree Ministeriale 26/6/2009 [30] establishes a qualitative classification of the envelope depending on the time shift and the decrement factor. As a result of that, Italian researchers are leading the way in clarifying how these properties may affect the energy performance of buildings.

Previous research has been focused both on the importance of periodic parameters and the existing limitations in the Italian regulation: (i) Aste et al. [31] analysed 6 façade typologies in a case study located in Milan, showing that the periodic thermal transmittance and the thermal admittance would guarantee a reduction of the building energy demand. Besides, for the same thermal transmittance, these authors proved that thermal inertia might be irrelevant depending on other aspects, such as the design of the wall. Other studies also support these claims, highlighting the potential of energy saving of façades with external insulation and high internal mass [32,33]; (ii) Di Perna et al. [34] analysed a school building in the city of Loreto ;using a simulation model, 3 wall typologies with different thermal mass were analysed and results showed that a high internal inertia would foster thermal comfort in summer; (iii) a similar study was conducted by Rossi and Rocco [28], who analysed 8 different wall typologies in Catania and Milan (4 with heavy and 4 with light construction) to assess the suitability of limit values for the periodic variables established in the Italian regulation. The results revealed the existing limitations in the Italian regulation by establishing only limit values in the periodic thermal transmittance; and (iv) Stazi et al. [35] analysed the performance of periodic properties in a case study in Agugliano using 4 envelope typologies. The results showed that the control of the decrement factor and of the internal thermal inertia would ensure a lower energy consumption in the building.

As these as theoretical calculations, other important aspect to consider is the on-site testing of the thermal properties of the building envelope to assess whether they match the specifications of the project. A variety of methods are available to measure the stationary thermal transmittance, such as the heat flow meter method [36], the thermometric method [37] or quantitative methods through infrared thermography [38]. However, many studies have faced severe limitations when analysing in-situ periodic thermal properties. (i) Gagliano et al. [39] experimentally assessed the periodic thermal properties of a historical building in Catania by using temperature sensors, a heat flux, and pyranometers; (ii) Baldinelli et al. [40] attempted to reproduce the theoretical sinusoidal conditions per ISO 13786 by using a hot box, being results satisfactory with an acceptable margin of error. (iii) Aversa et al. [41] used infrared thermography to assess the dynamic thermal performance of walls; measurements were compared with simulations conducted in COMSOL per ISO 13786. (iv) Pernigotto et al [42] compared theoretical calculation and laboratory measurements of periodic thermal properties for a single-layered timber wall and remarkable differences were obtained: -12% to 20% for the periodic thermal transmittance and 2-4% for the time shift; other study found that theoretical and simulated data also differs for walls composed by hollow bricks [41]. Results showed that differences between the theoretical and on-site or tested values were too large, thus new studies are deemed necessary.

Paradoxically, Spain lags behind Italy in the development of such studies, although both countries have very similar climates. This remains particularly important in a context where a better understanding of periodic thermal properties would bring resilient buildings under climate change scenarios [43]; what is more, it would allow for an easy implementation of the nZEB standard in warm climates [44] and economically viable refurbishment of existing buildings [45]. Other issues within the Spanish context also support this claim: the country is heavily dependent on non-renewable energy resources [46] and cases of energy poverty are progressively increasing [47]. More efficient buildings would bring better quality of life, and thus economic savings for the Spanish healthcare system [48]. For that reason, the Spanish Government is allocating a great amount of funds to foster the improvement of the existing building stock [49].

Given this context, this study aims at filling this research gap and proposing a strategy to implement periodic thermal properties in the Spanish regulatory framework. For this purpose, a case study is designed and located in two different climate zones per CTE-DB-HE. The analysis was focused on the façades, as they constitute the majority of the external envelope. By using different combination of elements, 2,413 different wall typologies were analysed, a considerably larger number when compared with similar research. The results of the present study will help in understanding the potential and the limitations of periodic thermal properties in a new regulatory framework, as well as generate a methodology that allows for the implementation of periodic thermal properties in other climatic and geographical contexts.

Thus, this study aims at building knowledge in the regulation of periodic thermal properties of building envelopes by analysing a considerable large number of walls, covering the most used constructive systems. Likewise, another novel aspect of the investigation is the analysis of the influence of the periodic thermal properties of the buildings in two extreme climates of Spain. The results of this research could allow the design of energy-efficient buildings close to the to zero energy standard in southern European regions.

The article is structured into three main sections. Firstly, the methodology is described by analysing the following aspects: (i) the theory and the calculation method of the ISO 13786; (ii) definition of the case study and the wall typologies; and (iii) analysis of the climate zones. Secondly, the results obtained are analysed and discussed. Finally, the main conclusions and the implications for future policies are presented.

2. Methodology

2.1. Calculation procedure for periodic thermal properties.

The calculation procedure for the static thermal transmittance is well known and widely adopted in different countries [50,51]; U values are calculated per ISO 6946 standard under a constant difference of temperature [27] (Eq. 1).

$$U = \frac{1}{R_{s,ext} + \sum_{i=1}^{n} \frac{d_i}{\lambda_i} + R_{s,int}} \tag{1}$$

Where λ_i [W/(m·K)] and d_i [m] are the thermal conductivity and thickness of each layer of the wall, and $R_{s,ext}$ and $R_{s,int}$ [(m^2·K)/W] are the external and internal surface resistances, respectively.

In contrast, the ISO 13786 calculates the thermal properties under a dynamic regime [26]; the procedure is based on the key study by Carslaw and Jaeger [52], who analysed how the variation of temperature could be adjusted to a sinusoidal function. This variation is dependent on time (T), so different periods of variation might be considered. As for building energy demand, the usual period is 24 h, which corresponds to the oscillation of external temperatures for one day [26].

For each material, three basic properties are needed as input data: thermal conductivity (λ), density (ρ), and specific thermal capacity (c). Thermal bridges are not considered due to their low effect on dynamic thermal properties [26]. Then, heat transfer matrixes are built for each layer of the wall (Z); for a single layer the matrix is as follows (Eq. 2)

$$\begin{gathered} Z = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \\ Z_{11} = Z_{22} = \cosh(\xi)\cos(\xi) + j \cdot \operatorname{senh}(\xi)\operatorname{sen}(\xi) \\ Z_{12} = -\frac{\delta}{2\lambda}\{\operatorname{senh}(\xi)\cos(\xi) + \cosh(\xi)\operatorname{sen}(\xi) + j \cdot [\cosh(\xi)\operatorname{sen}(\xi) - \operatorname{senh}(\xi)\cos(\xi)]\} \\ Z_{21} = -\frac{\lambda}{\delta}\{\operatorname{senh}(\xi)\cos(\xi) - \cosh(\xi)\operatorname{sen}(\xi) + j \cdot [\cosh(\xi)\operatorname{sen}(\xi) + \operatorname{senh}(\xi)\cos(\xi)]\} \end{gathered} \tag{2}$$

For each element of this matrix δ [m] is the depth of periodic penetration of a thermal wave into the layer (Eq. 3) and ξ [dimensionless] is the ratio of d and δ (Eq. 4)

$$\delta = \sqrt{\frac{\lambda T}{\pi \rho c}} \tag{3}$$

$$\xi = \frac{d}{\delta} \tag{4}$$

For each layer with uniform thermal properties a Z matrix is built. In case of multilayer walls, one Z matrix should be built for each layer; then, the transfer equation for the wall is created by multiplying the matrices of the different layers (Z_i) from the exterior ($i = N$) to the interior ($i = 1$); the thermal resistance of external (Z_{s2}) and internal air layers (Z_{s1}) is added in the required order to build the transfer matrix of the wall (Z_{ee}) (eq. 5)

$$Z = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} = \prod_{i=N}^{1} Z_i \rightarrow Z_{ee} = Z_{s2} \cdot Z \cdot Z_{s1} \tag{5}$$

Once the matrix equation is solved, the seven main variables that characterize the periodic thermal properties can be calculated (Table 1)

Table 1. Variables that define the periodic thermal properties.

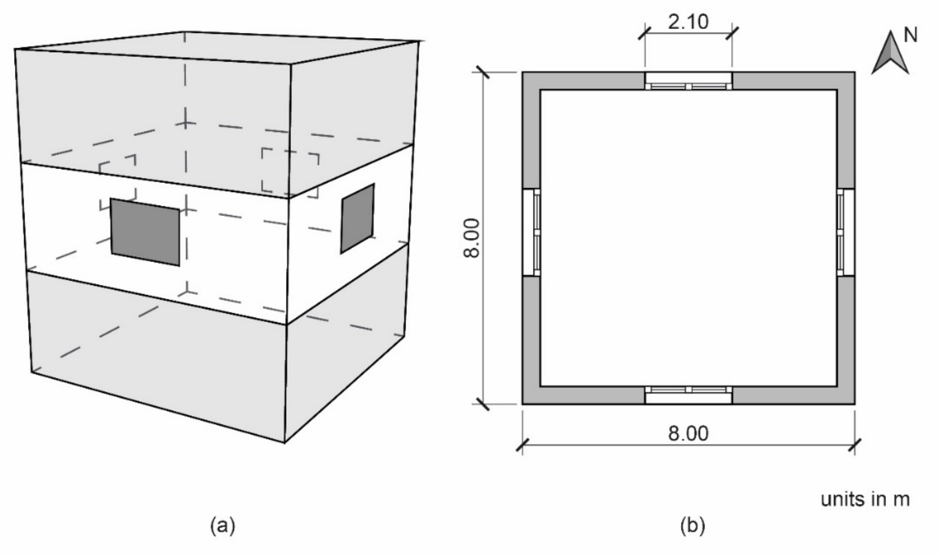
Variable	Equation	
Periodic thermal transmittance	$Y_{12} = -\frac{1}{Z_{12}}$	(6)
Time shift periodic thermal admittance	$\varphi = \frac{T}{2\pi} \arg(Z_{12})$	(7)
Decrement factor	$\mathrm{f} = \frac{\lvert Y_{12} \rvert}{U}$	(8)
Internal thermal admittance	$Y_{11} = -\frac{Z_{11}}{Z_{12}}$	(9)
Time shift internal side	$\varphi_{11} = \frac{T}{2\pi} \arg(Y_{11})$	(10)
External thermal admittance	$Y_{22} = -\frac{Z_{22}}{Z_{12}}$	(11)
Time shift external side	$\varphi_{22} = \frac{T}{2\pi} \arg(Y_{22})$	(12)

2.2. Simulation model

This study aimed at analysing the possibility of establishing limit values in the periodic thermal parameters of façades and for this purpose, a wide sample of wall typologies was analysed. A simplified prototype, which reproduces common characteristics of residential building in Spain [24,28], was modelled. (Figure. 1). The case study corresponded to an intermediate floor, so that elements that transfer heat are reduced to a minimum. Only external walls and windows are considered to transfer heat, as upper and lower slabs are adiabatic.

The independent variables of the study were the different types of facades, which are defined by the 4 variables that characterize single material of them (Table. 2). A total of 2,413 different wall typologies were generated taking as a base different documents, such as the Constructive Elements Catalogue of the CTE-DB-HE [53] and other research studies and standards [54,55]. These walls are representative of the constructive standards adopted for both new and existing buildings and can be grouped into two categories: First, light and heavy construction, depending on the types of bricks: solid or perforated ceramic bricks, ceramic blocks and standard or light concrete blocks; second, insulation thickness, ranging from 1 to 15 cm and comprising commonly used materials in the construction industry in Spain, such as expanded polystyrene (EPS), mineral wool (MW), polyurethane rigid foam (PUR), extruded polystyrene (XPS), and cork [56]. The thermophysical properties of the materials were obtained from the CTE-DB-HE and from ISO 10456 [57]. Prior to the energy analysis, these 2,413 walls were characterized by their static and periodic thermal variables (Table. 3): static properties were calculated per ISO 6946, and dynamic per ISO 13786.

The rest of variables were considered as control variables and, therefore, constant. Four double glazed windows, with a 6 mm air layer between two panes of glass with a thickness of 4 mm and a dimension of 2.10x2.50 m were considered for all simulations. Set point temperatures for heating and cooling were 20ºC and 25ºC respectively. Internal loads were considered as follows: 0.08 people/m^2 engaged in sedentary metabolic activities, 3 W/m^2 for lighting and 1.5 W/m^2 for equipment. No artificial ventilation system was considered, and the infiltration rate was fixed at 0.5 ACH.



(a) (b)

Figure 1. Case study analysed: (a) 3D sketch; and (b) floor.

Table 2. An example of some of the wall typologies analysed according to the Constructive Elements Catalogue of the CTE-DB-HE.

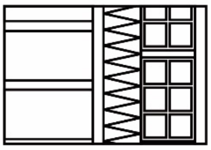
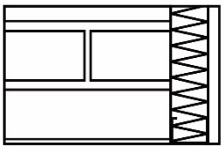
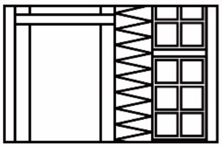
Code	Component	Thickness [m]	Thermal conductivity [W/(mK)]	Specific heat capacity [J/(kgK)]	Density [kg/m^3]	Sketch
F01.01	Solid brick	0.115	0.850	1,000.00	2,300.00	
	Cement mortar	0.015	1.000	1,000.00	1,700.00	
	EPS insulation	0.090	0.029	1,450.00	40.00	
	Hollow brick	0.070	0.320	1,000.00	770.00	
	Gypsum plaster	0.015	0.570	1,000.00	1,000.00	
F01.07	Perforated brick	0.240	0.350	1,000.00	780.00	
	Cement mortar	0.015	1.000	1,000.00	1,700.00	
	MW insulation	0.040	0.031	1,030.00	190.00	
	Laminated plasterboard	0.015	0.250	1,000.00	800.00	
F03.09	Cement mortar	0.020	0.800	1,000.00	1,500.00	
	Concrete block	0.140	0.450	1,000.00	790.00	
	Cement mortar	0.015	1.000	1,000.00	1,700.00	
	Cork insulation	0.040	0.049	1.560.00	150.00	
	Hollow brick	0.070	0.320	1,000.00	770.00	
	Gypsum plaster	0.015	0.570	1,000.00	1,000.00	
F11.01	Aluminium	0.001	230.00	880.00	2,700.00	
	MW insulation	0.03	0.034	1,030.00	90.00	
	Aluminium	0.001	230.00	880.00	2,700.00	

Table 3. Description of the value ranges associated with the different thermal variables of walls.

Variable	Unit	Minimum value	Average value	Maximum value
Thermal transmittance	$W/(m^2K)$	0.16	0.48	2.84
Thermal mass	kg/m^2	4.40	307.92	717.90
Thermal capacity	$kJ/(m^2K)$	6.98	310.42	718.62
Periodic thermal transmittance	$W/(m^2K)$	0.01	0.20	2.78
Time shift periodic thermal transmittance	h	0.18	9.87	20.93
Decrement factor	-	0.03	0.37	1.00
Internal thermal admittance	$W/(m^2K)$	0.42	3.45	5.37
Time shift internal side	h	0.32	2.26	4.66
External thermal admittance	$W/(m^2K)$	0.43	4.17	8.40
Time shift external side	h	0.57	3.28	5.28

2.3. Climate zones

The Spanish regulatory framework CTE-DB-HE uses two indexes to deal with the great variety of climates within its territory: summer (SCS) and winter (WCS) climate severity:

$$SCS = 2.990 \cdot 10^{-3} \cdot DD_S - 1.1597 \cdot 10^{-7} \cdot DD_S^2 - 1.713 \cdot 10^{-1} \tag{13}$$

$$WCS = 3.546 \cdot 10^{-4} \cdot DD_W - 4.043 \cdot 10^{-1} \cdot \frac{n}{N} + 8.394 \cdot 10^{-8} \cdot DD_W^2 - 7.325 \cdot 10^{-2} \cdot \left(\frac{n}{N}\right)^2 - 1.137 \cdot 10^{-1} \tag{14}$$

Where DD_S [ºC] is the sum of summer degree-days for a base temperature of 20 ºC during the cooling season; $\frac{n}{N}$ [dimensionless] is the quotient between the number of sun hours and the theoretical maximum number of sun hours during the heating season; and DD_W [ºC] is the sum of winter degree-days for base temperature of 20 during the heating season.

Regions in Spain are classified according to SCS and WCS, for SCS a number between 1 and 4 is assigned, the larger the number the larger the expected cooling energy demand; for WCS, a letter between A and E is assigned, being E the one that corresponds to the larger expected heating demand (Table 4). In this study two cities that represents the two extremes of this classification were chosen, Sevilla, which is classified as B4, and Avila, which is classified as E1 (Table 5); mild winters and hot summers are expected in the former, while the opposite is expected in the latter. It should be noted that not all combinations of SCS and WCS are possible: E4, E3, E2, D4, B1, A1 are not found in the Spanish territory. This classification also determines the limit of the static U value for external walls (Table 5). Despite being very operational for professional practice, this classification has several drawbacks, as pointed out by Attia et. Al [21] when trying to establish a common framework to implement the nZEB standard in the construction industry. That is why a deeper analysis, which considers other variables, is deemed necessary.

Table 4. Climate classification of SCS and WCS.

Classification of SCS		Classification of WCS	
Class	Value	Class	Value
1	$SCS \leq 0.50$	A	$0 \leq WCS \leq 0.23$
2	$0.50 < SCS \leq 0.8$	B	$0.23 < WCS \leq 0.5$
3	$0.83 < SCS \leq 1.3$	C	$0.50 < WCS \leq 0.9$
4	$SCS > 1.38$	D	$0.93 < WCS \leq 1.5$
		E	$WCS > 1.51$

Table 5. Cities selected for the study.

City	Longitude	Latitude	Altitude	Climate zone	U-value limit [W/(m^{2}K)]
Avila	-4.696222	40.654347	1,131	E1	0.55
Seville	-5.98333	37.383333	11	B4	1.00

The prototypes were modelled in the software Design Builder, which includes a visual modelling tool coupled to a simulation module based on the Energy Plus engine. Despite several plugins involving modelling, data automation and parametric analysis have been recently developed, in this case Design Builder was used as a stand-alone Graphical User Interface based on a simulation engine [58]; individual templates for all construction materials where combined using the construction model data tab to generate the 2,413 walls considered. Then, simulations were carried out using the tools available in this software, which allow to automatize a large number of processes at once. The Energy Plus weather (EPW) files of the two cities were generated with the software METEONORM [59], which creates a EPW file for any location through interpolation by using the nearest weather stations. The period 2000-2009 was considered for the external temperatures and 1991-2010 for solar radiation. In total, 4,826 simulations were carried out one by one, that is, 2,413 for each of the two locations.

3. Results and discussion

Results are presented, firstly, in relation with the static variables and, secondly, in relation with the dynamic parameters. As expected, the cooling, heating and total energy demand bear some relation with the three parameters that define the static approach: Thermal transmittance, thermal mass and thermal capacity. This holds true, with some remarks, for both zones: B4 (Figure 2) and E1 (Figure 3).

In warmer climates (zone B4) heating demand seems to be independent from these three parameters, but that is not the case for cooling demand, where higher thermal transmittance means higher cooling demand; heavyweight construction have a positive impact during the cooling season, albeit to a moderate degree. Combining the two of them, the total energy demand is heavily influenced by the cooling demand, which is, roughly, 4 to 6 times larger than the expected heating demand. Quite the opposite, in zone E1, the cooling demand seems not to be influenced by the variation of these 3 variables, except for the case of lightweight construction, where it may double or triple. This might explain the unusual distribution of the cloud points for the thermal transmittance, with two different branches; indeed, for a single value of thermal transmittance, different values of cooling demand might be obtained. A similar phenomenon is observed for the heating demand: According to the traditional approach, in cold climates, higher U values would automatically mean higher heating demand, but that does not always hold true in this case, probably because thermal mass and thermal capacity are exerting some sort of influence in the final demand. The values for the total energy demand are similar to the zone B4, but keeping in mind that, in this case, heating demand is dominant.

In general, U value seems to be the parameter that can predict with more accuracy the cooling, heating and total energy demand, with correlation coefficients higher that 0.75, except for the cooling demand in the zone E1 (Table 6). These demands might not be explained by thermal mass and thermal capacity alone, as their correlation coefficients are remarkably lower; however, as pointed out previously, they might be helpful to explain in detail unusual relations between U and the energy demand. As U value seems to be an accurate predictor of the energy demand, additional analyses were conducted (Figure 4). For both zones, it seems evident that limiting the thermal transmittance has a positive effect on reducing the energy demand, but the effect on the minimum energy demand is not so evident, especially for the lower tier of U values.

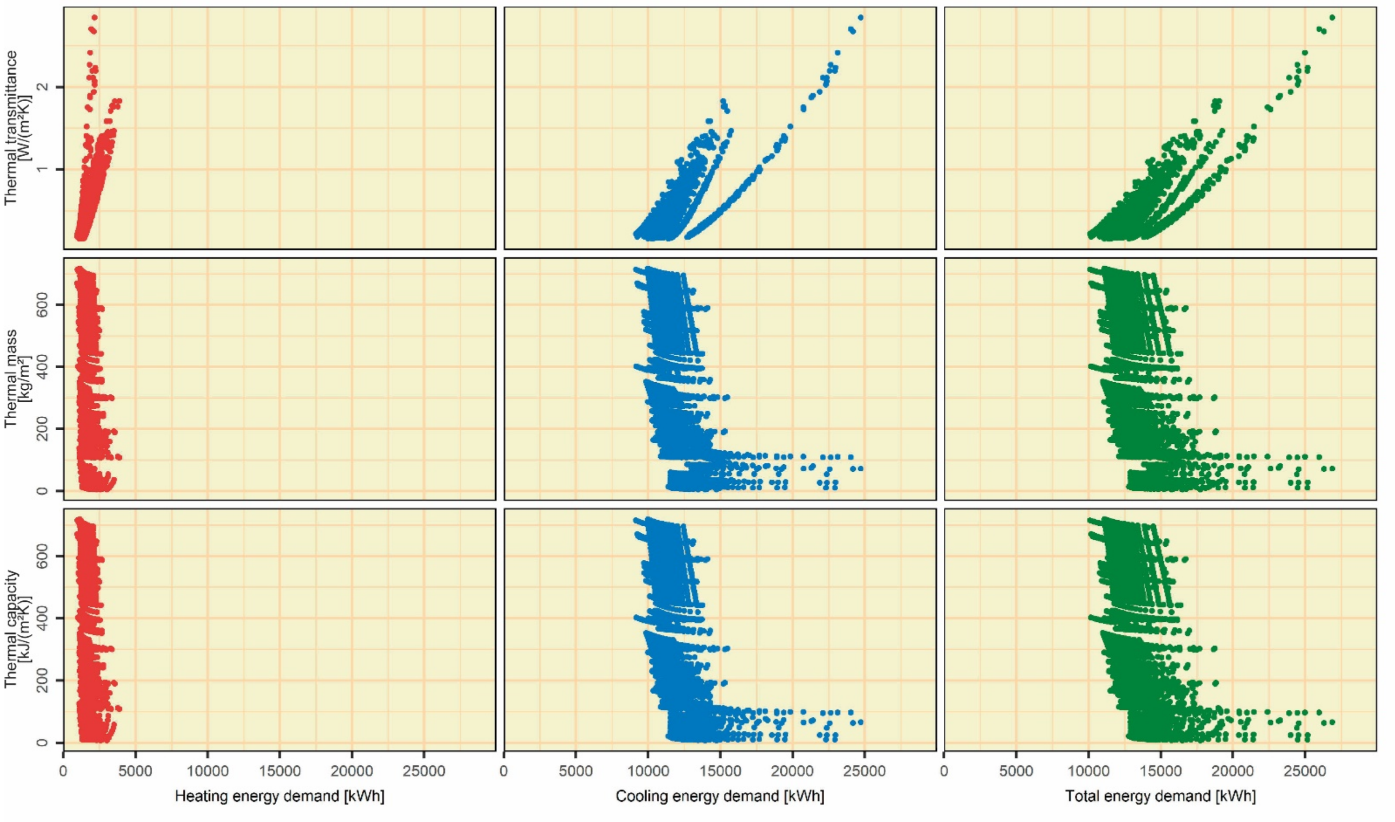


Figure 2. Scatterplot: Energy demand and the static thermal variables in the zone B4.

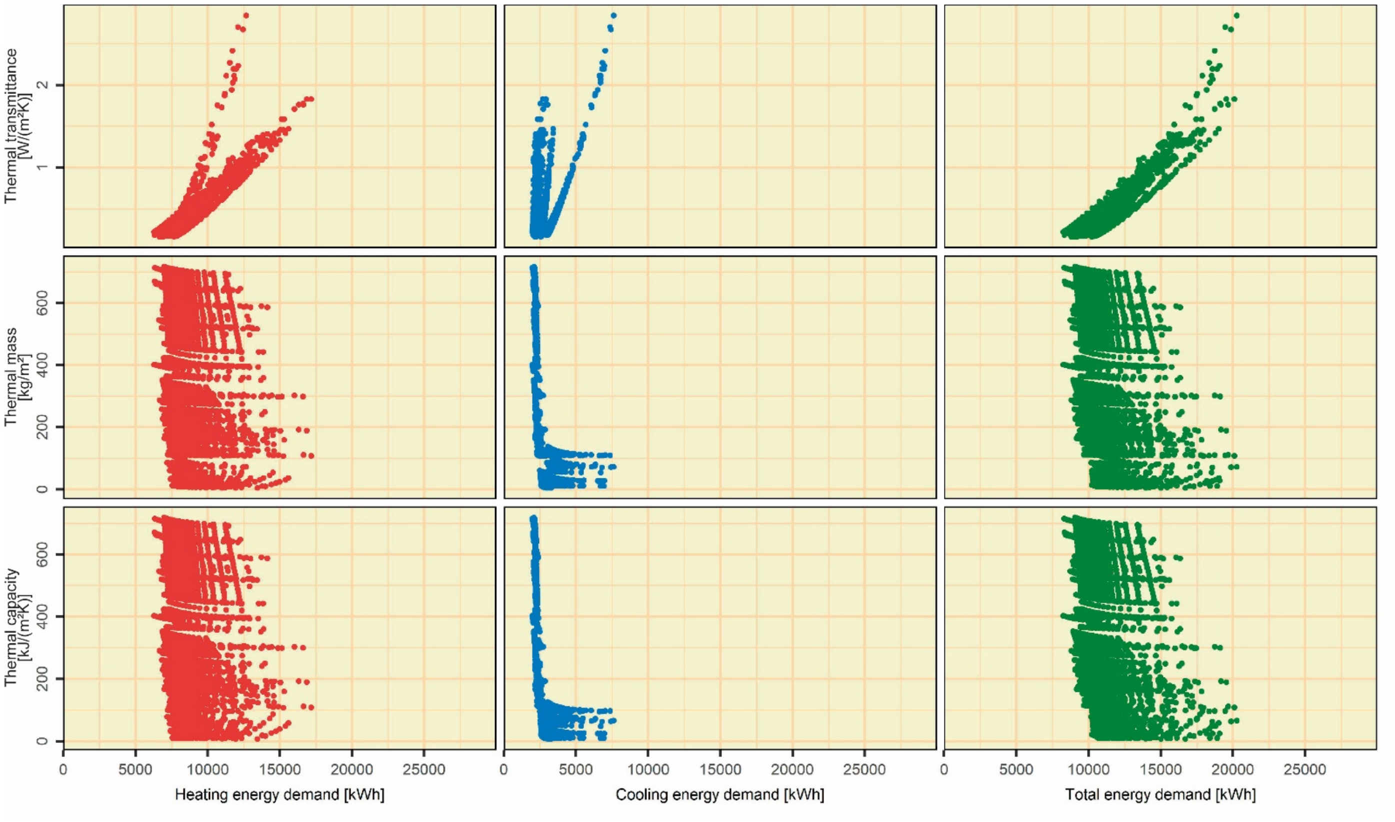


Figure 3. Scatterplot: Energy demand and the static thermal variables in the zone E1.

Table 6. Correlation coefficient between the static thermal variables and the energy demand.

Variable	B4			E1		
	HED	CED	TED	HED	CED	TED
Thermal transmittance	0.81	0.75	0.82	0.88	0.47	0.92
Thermal mass	0.23	0.49	0.47	0.17	0.52	0.31
Thermal capacity	0.23	0.49	0.47	0.17	0.53	0.32

HED: Heating energy demand; CED: Cooling energy demand; TED: Total energy demand.

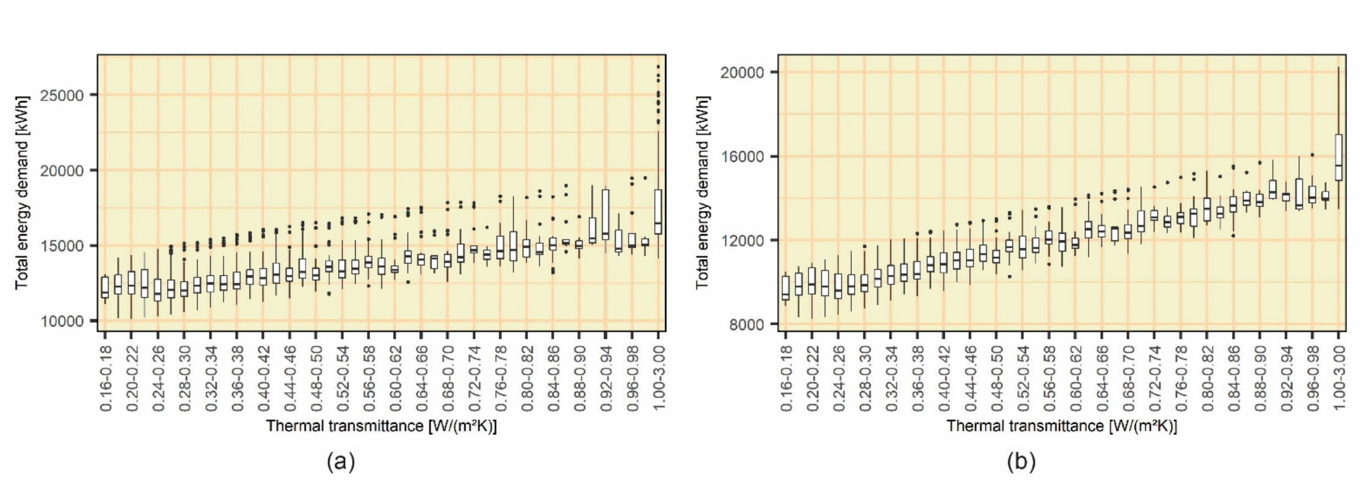


Figure 4. Box-plots of the total energy demand according to the value ranges of thermal transmittance of the walls analysed: (a) zone B4, and (b) zone E1.

In view of these data, it seems evident that standards based solely on U values do not automatically guarantee lower energy demands. It is commonly assumed that, under a constant temperature difference between the interior and the exterior, lower U values would limit the heat transfer. However, thermal oscillations during a 24-hour cycle mean that these assumptions are not always true; indeed, thermal mass and thermal capacity may explain why lower U values give higher energy demands. This calls for a deeper analysis where dynamic variables should be discussed.

At first, the energy demand was expressed as a function of each one of the seven variables that define the dynamic thermal properties (Figures 5 and 6). The relation for the periodic thermal transmittance seems linear with two branches, in the same fashion as the U value; such relation is not present for the rest of the variables for both zones, which seems to be quite dispersed. The correlation coefficients confirm that periodic thermal transmittance can accurately predict, until some extent, the total energy demand (Table 7), whereas other parameters alone cannot be used to foresee it.

This difference between variables was also reflected in the correlation coefficients (Table 7). Among correlation coefficients of the periodic thermal transmittance, the time shift, and the decrement factor , the greatest correlation was found for the cooling energy demand. The use of criteria associated with these variables allows therefore the energy demand to be limited. For this reason, the distributions of the total energy demand were analysed by using different groups in each variable.

A deeper analysis shows a correlation between the periodic thermal transmittance and the total energy demand, which also holds true for the time shift and the decrement factor (Figure 7). The relation for the thermal transmittance shows a similar pattern of that from the static U value. Regarding time shift, the lowest demands are achieved if the shift is larger than 15 h. The decrement factor behaves similarly in both zones: The demand is minimum for the lowest values (around 0), then stays constant for intermediate values (between 0.20 and 0.70) and reaches its peak for highest values (over 0.70); however, these data should be handled with caution because there is a disparity between maximum and minimum values.

This issue is discussed separately. If the objective is to minimize the energy demand of the building, special attention should be paid to the time shift periodic thermal transmittance, the decrement factor and the time shift for the internal side of the wall (Table 8). The first one presented the lowest maximum values and the smallest amplitude for both zones; for example, in zone B4, a time shift between 20 and 21 h delivers a maximum energy demand of 10,267.39 kWh, which is

11.44% lower than the lowest demand obtained by limiting the decrement factor, and 26.97% lower than that one obtained by limiting the time shift in the internal side. Similar reductions can be observed in zone E1. The rest of the variables did not show any particular tendency.

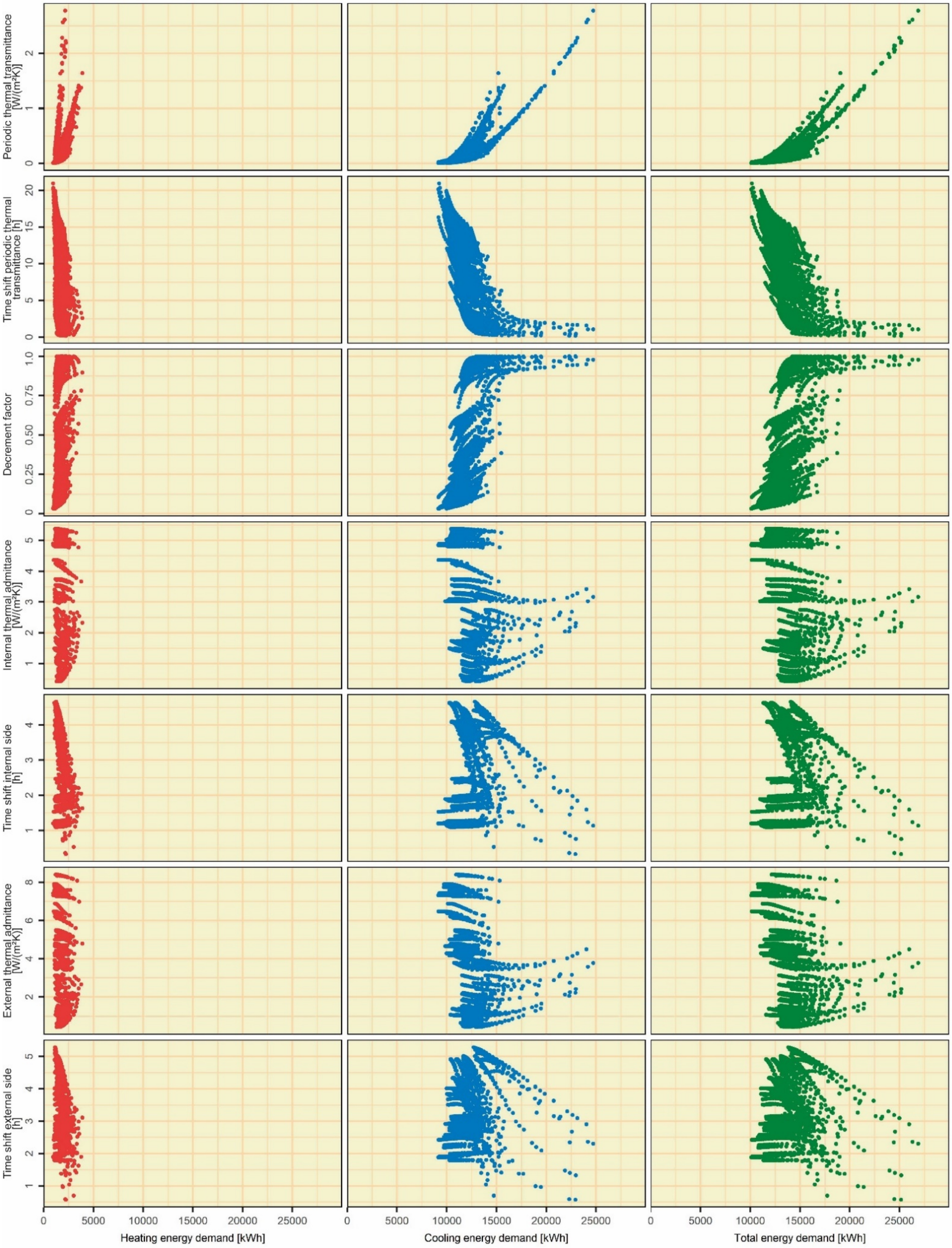


Figure 5. Scatterplot: Energy demand and periodic thermal variables in the zone B4.

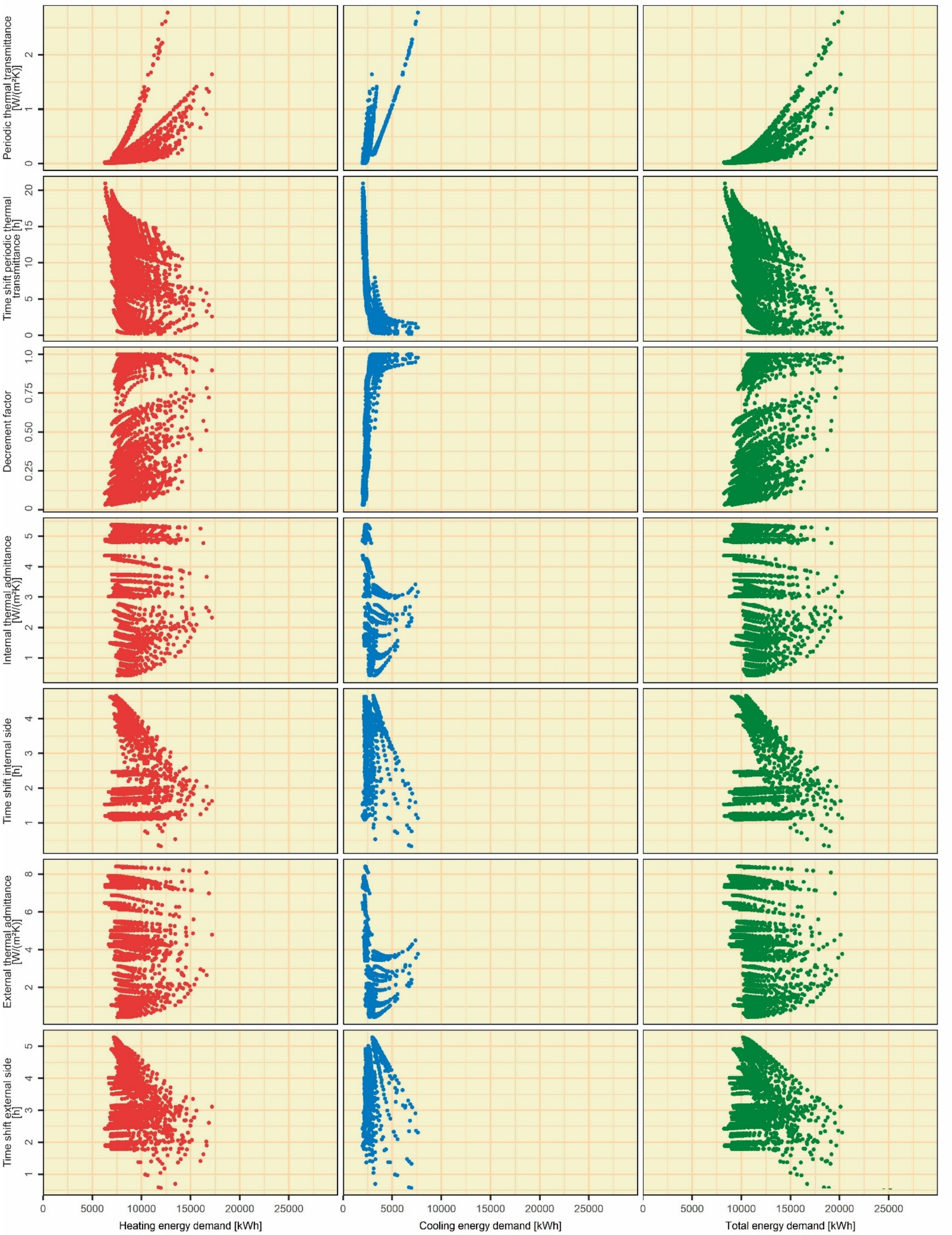


Figure 6. Scatterplot: Energy demand and periodic thermal variables in the zone E1.

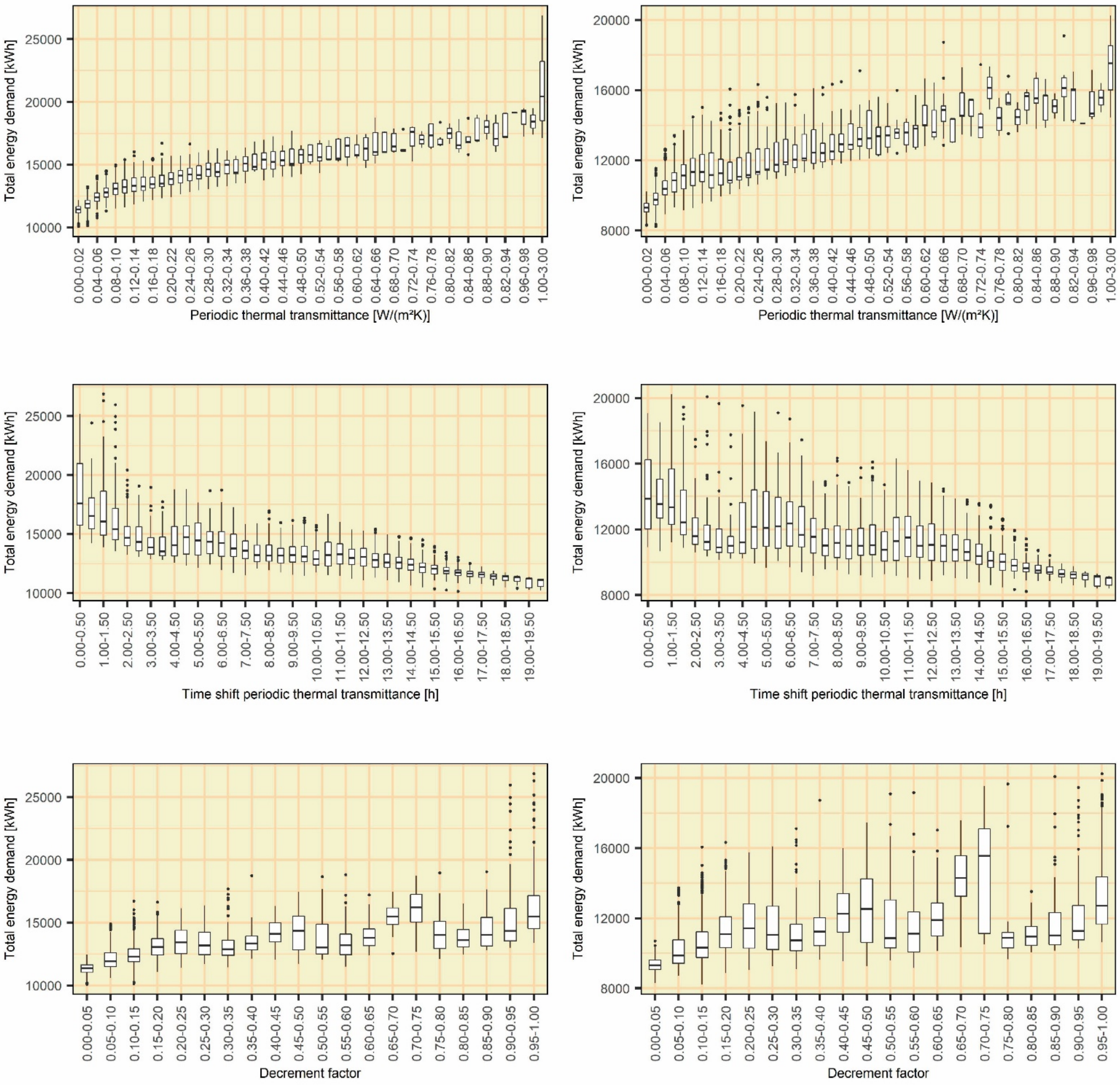
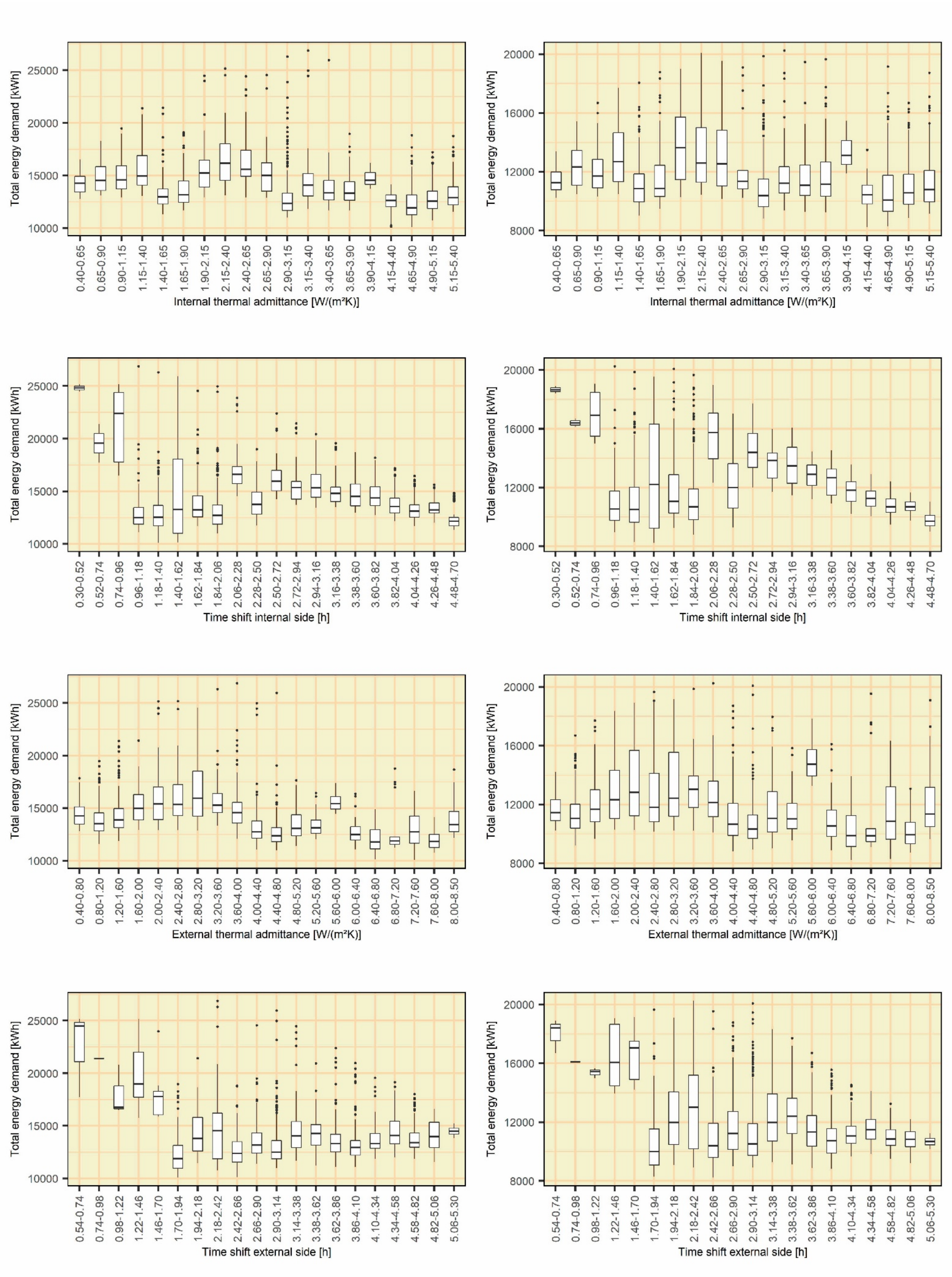


Figure 7. Box-plots of the total energy demand according to the periodic values (periodic thermal transmittance, decrement factor, and time shift periodic thermal transmittance) of the walls analysed: (a) zone B4, and (b) zone E1.



(a) (b)

Figure 8. Box-plots of the total energy demand according to the periodic values (admittances and time shift side) of the walls analysed: (a) zone B4, and (b) zone E1.

Table 7. Correlation coefficient between the periodic thermal variables and the energy demand.

Variable	B4			E1		
	HED	CED	TED	HED	CED	TED
Periodic thermal transmittance	0.59	0.90	0.91	0.61	0.84	0.80
Time shift periodic thermal transmittance	0.42	0.69	0.69	0.39	0.65	0.54
Decrement factor	0.30	0.65	0.63	0.26	0.68	0.44
Internal thermal admittance	0.12	0.30	0.28	0.06	0.34	0.16
Time shift internal side	0.09	0.18	0.14	0.11	0.26	0.02
External thermal admittance	0.19	0.37	0.36	0.10	0.42	0.22
Time shift external side	0.19	0.13	0.08	0.22	0.25	0.12

HED: Heating energy demand; CED: Cooling energy demand; TED: Total energy demand.

Table 8. Influence of the range of values of the most restrictive periodic variables in the total energy demand.

Variable	Range	Total energy demand [kWh]			
		B4		E1	
		Maximum	Minimum	Maximum	Minimum
Time shift periodic thermal transmittance	(18.20, 18.40]	11,594.30	10,489.54	9,585.73	8,588.58
	(18.40, 18.60]	11,489.31	10,607.64	9,453.26	8,681.65
	(18.60, 18.80]	11,461.59	10,377.27	9,431.53	8,482.15
	(18.80, 19.00]	11,370.57	11,244.81	9,312.88	9,147.4
	(19.00, 19.20]	11,344.55	10,273.84	9,292.29	8,390.91
	(19.20, 19.40]	11,234.62	11,185.03	9,185.01	9,107.56
	(19.40, 19.60]	11,197.62	11,155.24	9,164.45	9,088.19
	(19.60, 19.80]	11,125.42	10,194.65	9,069.15	8,389.16
	(19.80, 20.00]	11,095.74	11,095.74	9,050.54	9,050.54
	(20.00, 21.00]	10,267.39	10,091.12	8,380.77	8,297.76
Decrement factor	[0.03, 0.04)	11,594.30	10,091.12	9,585.73	8,297.76
	[0.04, 0.05)	12,466.20	10,273.84	10,695.41	8,390.91
	[0.05, 0.06)	13,067.57	10,607.33	11,462.62	8,711.58
	[0.06, 0.07)	13,865.80	10,750.46	12,541.56	8,729.58
	[0.07, 0.08)	14,476.23	10,788.38	13,369.81	8,813.44
	[0.08, 0.09)	14,633.55	10,902.87	13,535.47	8,886.01

	[0.09, 0.10)	14,892.63	11,012.92	13,727.71	8,999.08
	[0.10, 0.11)	15,405.68	10,146.23	14,471.78	8,229.39
	[0.11, 0.12)	16,023.22	10,251.17	15,021.80	8,340.35
	[0.12, 0.13)	15,064.02	10,483.68	13,994.47	8,599.35
Time shift internal side	(4.00, 4.05]	16,561.77	12,138.37	12,416.07	10,026.11
	(4.05, 4.10]	16,466.19	11,683.00	12,426.14	9,486.06
	(4.10, 4.15]	16,096.83	12,493.36	12,042.12	10,221.97
	(4.15, 4.20]	15,492.24	12,909.18	12,043.48	10,281.68
	(4.20, 4.25]	16,013.12	12,394.28	11,954.1	10,284.16
	(4.25, 4.30]	15,400.20	12,314.45	11,483.82	10,133.84
	(4.30, 4.35]	15,644.41	12,200.07	11,666.62	10,088.91
	(4.35, 4.40]	15,335.34	12,158.00	11,423.38	9,929.84
	(4.40, 4.45]	15,070.11	12,018.38	11,215.88	9,750.65
	(4.45, 4.50]	14,838.13	11,884.90	11,038.88	9,591.54
	(4.50, 4.55]	14,632.04	11,752.25	10,860.63	9,448.75
	(4.55, 4.60]	14,542.86	11,519.55	10,878.45	9,202.76
	(4.60, 4.65]	14,367.23	11,317.43	10,732.36	8,999.78
	(4.65, 4.70]	14,058.21	14,058.21	10,474.42	10,474.42

All together, these data suggest that the periodic thermal transmittance, along with the time shift, deserve special consideration in order to limit the energy demand of buildings located in zones B4 and E1. The next question that arises is, precisely, how these two are related and how future regulations should include them. For this purpose, additional analysis was conducted.

Periodic thermal transmittance and time shift can be combined in order to limit the energy demand of buildings (Figure 9). For lower values of time shift (φ), between 0 and 2 hours, the maximum energy demand depends on the periodic thermal transmittance, and this dependence can be approximated, somehow, by and arctan function, with a maximum over 17.500 kWh; however, it is remarkable that the maximum is not dependant on the transmittance for larger values of φ: the larger the time shift, the sooner the energy demand is decoupled from the periodic thermal transmittance; what is more, large values of φ mean that the maximum energy demand can be drastically reduced, and that periodic thermal transmittance can be disregarded.

On top of that, the periodic thermal transmittance and the time shift periodic transmittance also seem to be related (Figure 10). In general, time shift seems to be strongly dependent on small variations of periodic thermal transmittance for lower values of the latter: When U values are lower than 0.40 W/(m^{2}K), wall configurations have a time shift between 0 and 20 h. For larger values of U, this relation is still significant, but it can be approximated to an exponential decay function in the form of $y=e^{(x)}$. This is even more evident when time shift and periodic thermal transmittance are assessed together to predict the total energy demand in both zones (Figure 11); a negative quasi-linear relationship is found for both of them, and total energy demand reaches a minimum for a combination of low thermal transmittance and large time shift.

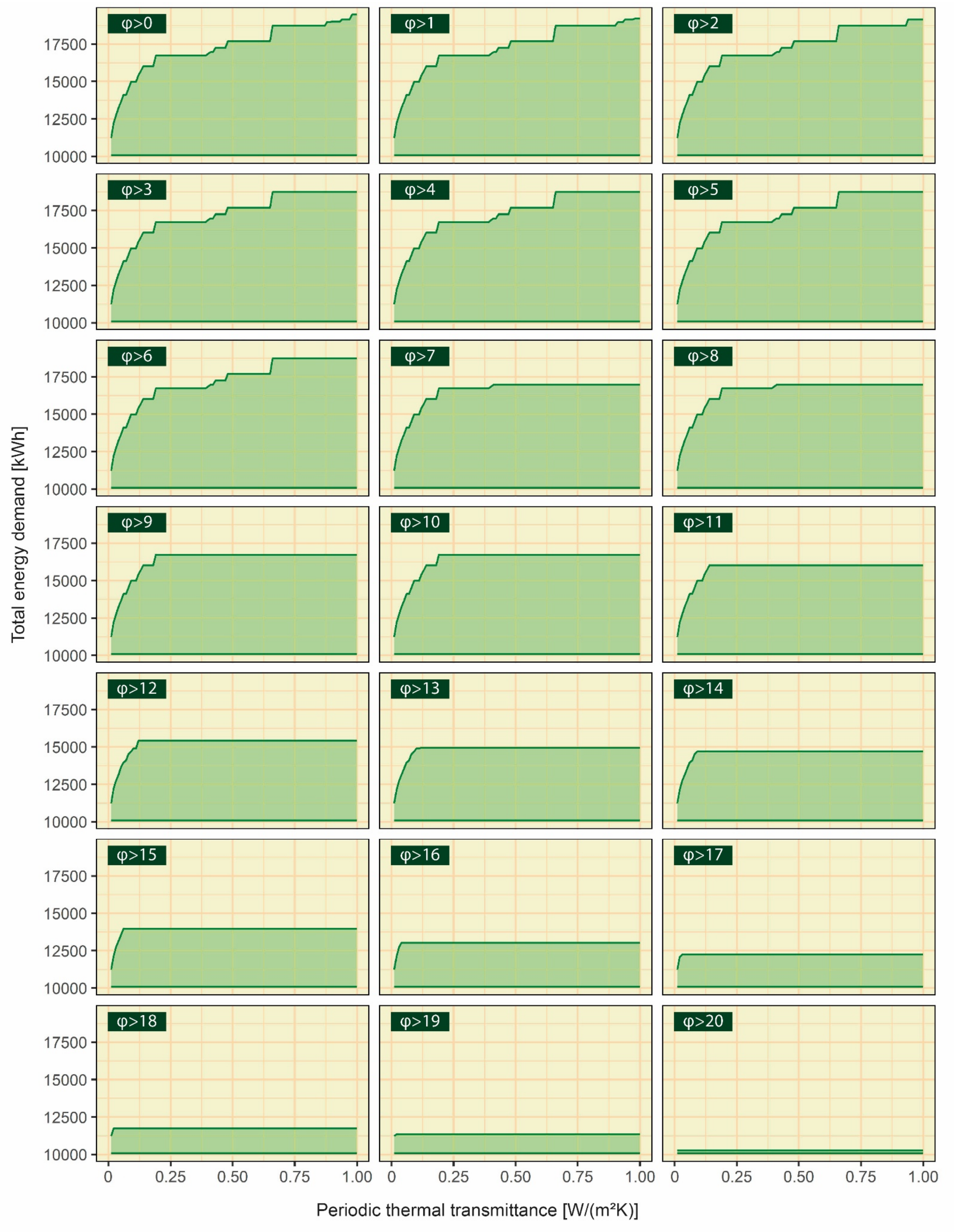


Figure 9. Effect of the application of limitations on the periodic thermal transmittance and its time shift in the zone B4. The lines of the maximum and minimum values of the total energy demand are represented. The shade area corresponds to the range of existing values of energy demand. The axis x represents the upper limit considered in the limitation of the periodic thermal transmittance (e.g., the value of 0.75 corresponds to all values of periodic thermal transmittance between 0 and 0.75).

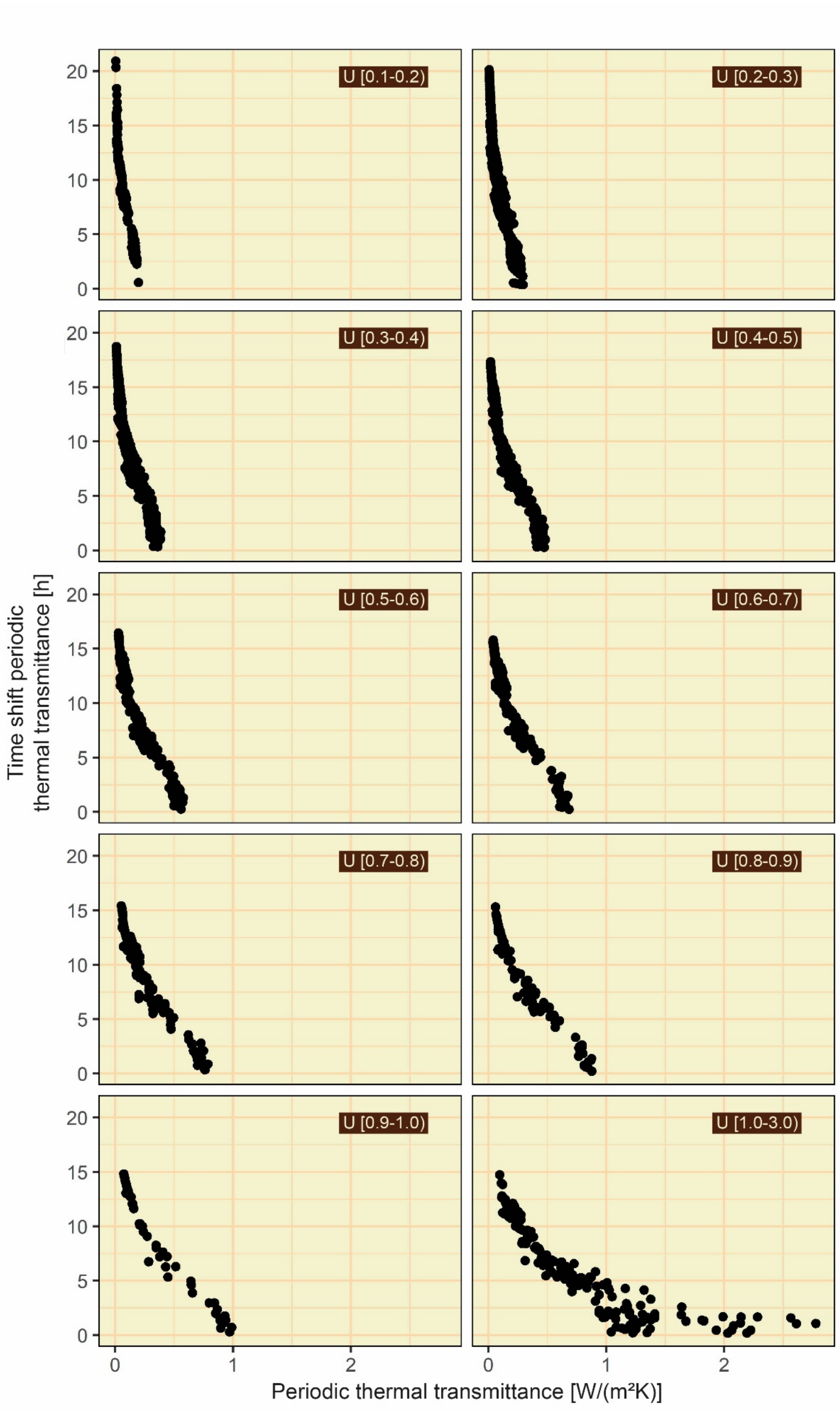


Figure 10. Periodic thermal transmittance and time shift periodic thermal transmittance for various ranges of U-value in the zone B4.

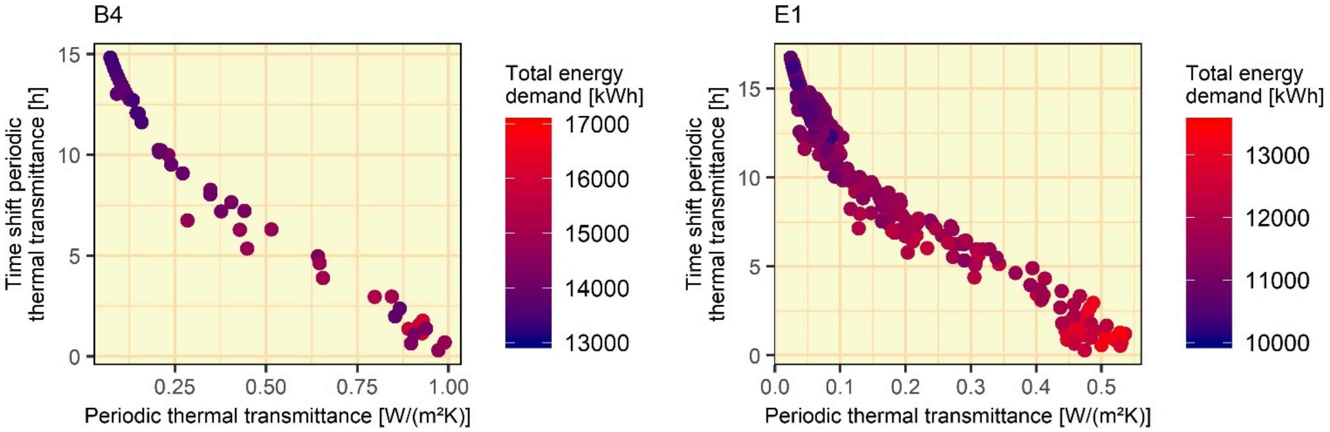


Figure 11. Total energy demand as a function of periodic thermal trannsmittance and time shift for zones B1 and E4

4. Conclusion

This study aimed at clarifying how the recently developed theoretical framework on the periodic thermal properties of building enclosures can find application in the Spanish regulatory framework. For that purpose, simulations have been conducted, using a theoretical prototype located in the coldest and hottest climate zones of Spain. The main results of the study, along with additional considerations, are as follows.

The traditional approach, considering that the energy demand is directly influenced by the U-value of walls, has proven to be inaccurate. Despite it provides with a rather simplistic but effective way to understand the energy performance of buildings, the recent advance in computational capacity has allowed studies like the present one to unveil the complex interplay between several variables. In such way, in the event of an update in the Spanish Building Code, two scenarios can be foreseen.

In a conservative scenario, the Code would still rely on the static approach. In such a case, 3 parameters should be included in the regulation: thermal transmittance, thermal mass and thermal capacity. At least for the 2 climate zones considered in this study, it is concluded that lower U values can minimize the energy demand to a certain extent, but additional limitations for both thermal mass and thermal capacity can greatly help in reducing it even more. As a consequence, the actual limits for the U value (0.55 and 1 W/m^{2}K) should be considered in future revisions of the code, but always together with limitations for the other 2 parameters. In concrete terms, walls with a thermal mass larger than 150 kg/m^2 and a thermal capacity larger than 150 kJ/m^{2}K should prove especially effective in reducing the cooling demand. Therefore, it is suggested that this lower limit should be implemented in future revisions of the code.

In the best-case scenario, periodic thermal properties would be adopted in the regulatory framework and the approach would be totally different. Seven variables come into play, and extreme caution should be exercised before drawing general conclusions. Therefore, this study concludes that periodic thermal transmittance and time shift should be regulated in zone B4 under three conditions. First, periodic thermal transmittance should be limited to 0.50 W/m^{2}K for lightweight construction with a time shift lower than 4 hours; second, in case of walls with a time shift between 4h and 15h, two subcategories can be stablished: If thermal transmittance is below 0.25 W/m^{2}K, substantial energy savings can be expected, if it is greater than this value, any thermal transmittance would be valid; third, for heavyweight construction with time shifts larger than 15 h, thermal transmittance should not be considered in the design of walls. Besides, this study has also proposed that the relation between certain variables should be modelled as mathematical functions, which may find application in the elaboration of future technical standards. Needless to say, these considerations are valid only for this climate zone, and similar analyses should be conducted for other zones to establish such limits. Besides, these results could be extrapolated to other Southern European regions with similar climates [60], amongst which Portugal stands out as a particular case-study, as it has a similar regulation to Spain [61].

Likewise, the findings of this study help solving drawbacks that have been pointed out by other authors, such as Attia et al. [21], who highlighted the differences between climate zones in the same country when drafting a common legislative framework for nZEB 's. This study clarifies that, despite the methodology of analysis may be the same, different parameters should be regulated for each climate. As an example, the Italian regulation limits the periodic thermal transmittance (0.10 W/(m^{2}K)) and the surface mass of walls (230 kg/m^2) [29]; the limitations proposed by this research are different, as the climates are different.

This study also faced several limitations. It only deals with two of the fourteen climate zones as per the Spanish legislation. Further research is required to clarify if the conclusions from this study apply to other zones and, as shown in here, that would require a substantial amount of work. In such way, another contribution from this study is the standardized methodology to clarify how periodic thermal properties could be introduced in future building regulations. At first, all seven variables should be considered, but statistical analysis is necessary to identify those ones crucial for each climate. Besides, the prototype considered in this study is rather a simplification of a real building, so in the future complex structures with different usage profiles and more than on thermal zone should be investigated.

In conclusion, this study provides with information on how a relatively new concept, such as the periodic thermal properties, might be implemented in the Spanish legislation. What is more, the discussion hereby presented is focused on minimising the energy demand of buildings, thus may find application in the development of new technologies such as the nZEB buildings; a multicriteria analysis that considers the complex interplay between the seven variables is deemed crucial to successfully adapt these buildings to a variety of climates. This will be of great help to designers, building engineers, public administrations and stakeholders in order to maximize the economic investment for these low-energy buildings.

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