Title:

Analysing natural ventilation to reduce the cooling energy consumption and the fuel poverty of social dwellings in coastal zones

Abstract:

In southern European countries, summer temperatures could contribute to a high cooling energy consumption. Family units with fewer economic resources living in social dwellings could suffer from fuel poverty if they want to use air conditioning systems. Otherwise, they could face discomfort hours because of a natural ventilation without clear control criteria. This study analyses quantitatively and qualitatively the possibilities of natural ventilation through mixed-mode and the possibility of reducing fuel poverty for family units living in social dwellings. For this purpose, the application of a natural ventilation approach was analysed through an adaptive behaviour based on EN 16798-1: 2019. A case study of 51 social dwellings was analysed by using various operation hypothesis between 2015 and 2019. The results showed the potential of using mixed-mode approaches based on the categories from EN 16798-1:2019 to achieve savings in the energy consumption and to remove cases of fuel poverty in low-income families. Likewise, surveys in which families living in these cities participated reflected the great awareness of the natural ventilation use, although there is not a clear criterion of the need of this ventilation for thermal comfort, as well as the need of a supportive use of air conditioning systems. Finally, the similarity of the climate conditions of the city analysed and the coastal cities from various countries in the south of Europe shows the possibility of using ventilation strategies as energy saving measures in other regions.

Keywords: Mixed-mode; natural ventilation; fuel poverty; social dwellings; south of Spain; cooling energy consumption

1. Introduction

Fuel poverty (FP) is among the problems of today's society. in most European countries. Over 124 million people from the European Union is at FP risk [1]. The governments of each countries are more and more interested in establishing measures to reduce FP cases; however, the lack of a common framework to define the method can make its detection something of a challenge [2]. There are both many definitions for FP and indicators for its quantification [3]. The Spanish Government defined FP as the situation in which a household cannot pay the electricity bill (because of low-incomes), and this situation could be worsened because the dwelling is inefficient in energy [4]. Nevertheless, FP could also be understood as the inability of family units to meet essential heating or cooling energy requirements in their dwellings [5,6]. Likewise, the term energy poverty (EP) is related to the difficulty of family units to access to energy supplies [7] and appropriate installations for dwellings [6], mainly in developing countries [8].

Both FP and EP usually implies that family units deal with many thermal discomfort hours [9], thus causing adverse effects on individuals' physical health [10]. In addition, other factors such as age [11], gender gap [12], mental health [13], emotions [14] or ethnic groups [15] could affect FP. However, FP is also important for environmental purposes because reducing cases of FP could be an opportunity to mitigate climate change. The reason is the potential of reducing greenhouse gas emissions by reducing household energy consumption [16], thus reducing cases of FP [17]. In certain cases, however, the improvement of building energy performance does not remove cases of FP nor lessen climate change because of the rebound effects generated by the saving in the electricity bill (i.e., the new expenses of the family units who live in renovated buildings [18]). A rebound effect could therefore increase heating setpoints [19]. Another interrelated aspect between climate change and FP is increasing taxes of the electric energy consumption from non-renewable sources to favour clean energy consumption. This increase could affect the increase of cases of FP [20].

In recent years, FP has become more important in the policies of European countries. The European Union has recognised FP through the Clean energy for all Europeans package [21]. This plan proposes various measures to protect vulnerable consumers. These measures include energy efficiency measures focused on FP households or the monitoring of the FP situation in European countries through platforms like Energy Poverty Observatory (EPOV). Furthermore, there are policies in each country which define special electricity prices for vulnerable family units [22]. Many studies emphasize that the most appropriate solution to reduce cases of FP is the improvement of building energy efficiency [22]. However, studies conducted in Germany [23], Spain [24] and Switzerland [25] have showed the limitations of the building energy improvement by reducing the energy consumption and the FP risk of family units, although these improvements clearly influence the improvement of occupants' health [26]. This aspect is due to other social and geographic factors related to the concept of FP, such as the gentrification [27] or possible rebound effects [28]. In addition, the geographic component is key in the severity of cases of FP because the climate severity of a region and the cases of FP are related. Besagni and Borgarello [29] found that, in Italy, FP was related to the socio-demographic dimension. However, other geographic factors are related to cases of FP. For instance, Robinson et al. [30] determined that, in England, there were less efficient buildings in rural areas than in urbanized areas. In addition, the economic conditions of a region could contribute to cases of FP. For instance, in the countries in the south of Europe, the income levels of family units are lower than those living in the north, mainly due to the impact of the recent economic crisis in these countries [31]. This crisis, together with the bad thermal quality of the building stock [32] and not very efficient construction codes [10], has contributed to cases of FP. As for Spain, several research studies have analysed the FP risk in the country. The first study was conducted by Tirado Herrero [33], in which the increase of FP in the country was analysed, particularly dwellings where unemployed people lived. One out of three unemployed households (approximately 1.2 million people) spent over 10% of their incomes in domestic energy consumption in 2012, thus increasing the number of households in FP by 142% in a period of 5 years. A more important study was conducted in 2016 at a national level [34]. This study showed that 5.1 million people in Spain (i.e., 11% of households) are not capable of keeping their house adequately warm in winter, thus increasing the number of households in FP by 22% in just two years. The last study was conducted by Castaño-Rosa et al. [35], who analysed the FP risk in 6 dwellings in Seville and the most appropriate modernisation strategies for buildings. Consequently, FP has been recognised by the Spanish Government as an issue to be addressed [36]. Nevertheless, the measures adopted to lessen it, such as social prices for the electricity cost [37], could be inefficient.

One of the main energy consumption in the analysis of the FP risk is usually related to the maintenance of thermal comfort conditions by using heating, ventilation, and air conditioning (HVAC) systems [24]. Acceptable conditions could be ensured in indoor spaces by maintaining thermal comfort, thus guaranteeing users' physical and mental welfare. Appropriate measures should therefore be established to guarantee the thermal comfort of users with fewer economic resources without the risk of being in FP. Many studies have emphasized the importance of improving users' thermal comfort to reduce energy consumption and FP. Vilches et al. [24] proved that users' thermal comfort should be among the aspects considered in the strategies to reduce FP; it is even more important than the improvement of the building. The studies by Hoyt et al. [38] and Parkinson et al. [39] showed the great potential of energy saving obtained by pushing setpoint temperatures to appropriate values for users' thermal comfort.

In the cities in southern Spain, the main type of energy consumption is cooling energy consumption [40]. This aspect is combined with the fact that in these regions there is a greater possibility of ventilating buildings naturally due to their climate conditions [41]. Ventilation is an effective strategy to compensate thermal loads by cooling the building with colder external air, thus reducing active cooling energy consumption [42]. Natural ventilation is a solution which allows indoor spaces to be acclimatized without economic costs [43] as energy consumption is not required [44]. The effectiveness of ventilation depends on various factors, such as climate [20], the thermal transmittance of envelopes [45], the heat storage capacity [46], the height of buildings [47], the regularity of thermal breezes [48] or the effect of the inter-building scale [49]. This is a strategy primarily designed to reduce cooling energy demand [50]. Thus, in cold seasons, it is difficult for users to use natural ventilation to acclimatize the indoor space [51]. Santos and Leal [52] found that the use of natural ventilation in Lisbon, Paris and Helsinki increased heating energy consumption and decreased cooling energy consumption. Likewise, Tong et al. [53] determined that natural ventilation could save between 8 and 78% the cooling energy consumption of office buildings in China. Gil-Báez et al. [54] analysed the use of natural ventilation in school buildings in southern Spain, saving the primary energy consumption between 18 and 33% by using natural ventilation. A similar study by Heracleous and Michael [55] determined that the use of natural ventilation would reduce the risk of overheating in future climate change scenarios. Fernandes et al. [56] analysed the effect of ventilation on the energy consumption of 500 virtual prototypes of buildings located in the Mediterranean, obtaining significant savings in the energy consumption of the virtual prototypes. Furthermore, the authors found that the effectiveness of the energy savings achieved in the warmest region of the Mediterranean did not depend on the shape and orientation of the building. Santamouris et al. [57] determined that the application of night ventilation in residential buildings could reach average decreases of 12 kWh/m2, with maximum values of 40 kWh/m2 in the cooling energy demand. Guarino et al. [58] analysed the energy savings achieved in an Italian residential building, obtaining savings of up to 22% in imported energy. On a larger scale, Oropeza-Pérez and Østergaard [59] noted that the use of natural ventilation obtained energy savings in the Danish residential sector of up to 105 GWh.

The use of natural ventilation requires adequate utilization strategies to be established. In this regard, Schulze and Eicker [60] found that an inadequate ventilation in buildings could generate users' thermal discomfort. This aspect is of great interest because in many occasions users ventilate their dwellings for other reasons than thermal conditioning [61]. Consequently, many studies analyse the aspects that influence the most frequent ventilation patterns of users: (i) Shi et al. [62] determined that the use of natural ventilation in 8 residential buildings in China depended on the outdoor temperature; (ii) a similar study by Andersen et al. [63] determined that the natural ventilation patterns of 15 residential buildings in Denmark depended on both the outdoor temperature and the concentration of carbon dioxide in the indoor space; (iii) Schweriker et al. [64] found that the relationship between the external and internal temperature influenced the opening behaviour of windows; (iv) Jeong et al. [51] determined that the performance of activities at home (e.g., cooking or cleaning) and the outdoor temperature influenced the opening of windows; (v) Ai et al. [65] analysed the most appropriate ventilation strategy in a Hong Kong building to guarantee an adequate indoor air quality. The results of the study only determined a reduction in carbon dioxide and did not assess the possibility of ventilation to reduce energy consumption; and (vi) Chen et al. [66] analysed the effect of natural ventilation on the increase of indoor pollutant rates.

Thus, many studies have stressed the potential of the energy savings achieved with ventilation strategies and its possible implications on indoor air quality. However, previous studies also showed that natural ventilation patterns could vary depending on locations, users and buildings, which can make the establishment of natural ventilation as an energy saving strategy something of a challenge. Furthermore, natural ventilation just does not imply thermal discomfort conditions. For this reason, mixed-mode buildings (i.e., buildings that operate with natural ventilation and air conditioning [67]) guarantee a balance between the maintenance of thermal comfort and an acceptable use of HVAC systems. Some studies have emphasized the possible energy savings obtained by using mixed-mode buildings. Wang and Chen [68] obtained energy savings between 6 and 91% in office buildings in the United States. Barbadilla-Martin et al. [69] evaluated office buildings in southern Spain, obtaining savings of 11.4% in the heating energy consumption and savings of 27.5% in the cooling energy consumption. In a similar study, Hu and Karava [70] analysed mixed-mode predictive control strategies in buildings, obtaining energy savings between 75 and 83% by using mixed-mode cooling strategies.

Most studies have analysed the energy savings achieved in non-residential buildings [71], so there is a knowledge gap regarding residential buildings. Although there are potential energy savings with this strategy, the influence of the mixed-mode on the reduction of the FP in family units with low incomes is an aspect to be studied. Levie et al. [72] found that the characteristics of the dwelling and the income of the family unit influenced the use of natural ventilation. This same aspect is also reflected by Yu et al. al [73], who established that the preference for natural ventilation might depend on users' lifestyle and income levels. However, none of these studies analysed the impact of ventilation strategies on the reduction of the FP risk. Likewise, the application of an adaptive approach (in which users have a broader and more dynamic comfort line depending on the outdoor temperature [74]) would allow an acceptable tool to be constituted to reduce cases of FP. Thus, this study suggests the potential of applying natural ventilation through adaptive approaches to reduce the FP risk in social dwellings. Furthermore, this aspect could ensure a less climatic vulnerability of these dwellings with future climatic variations [75] because of the expected overheating of buildings in southern Europe [76]. For this purpose, the FP risk was analysed in many family units with various incomes who live in a building of 51 social dwellings in Cadiz (Spain). This region is likely to greatly apply natural ventilation. In this regard, the typical years in the region showed an application of ventilation between 3000 and 6000 hours [77]. The analysis was performed in the summer months between 2015 and 2019. The results of this study include several novel aspects: (i) the analysis of the energy savings achieved by using mixed-mode in residential buildings; (ii) the influence of using the adaptive thermal comfort approach from EN 16798-1: 2019; (iii) the use of mixed-mode as a strategy to reduce the FP risk in family units; and (iv) the application of tolerances to the lower limit of the model used for natural ventilation to guarantee "free cooling".

2. Methodology

2.1. Ventilation strategies based on the adaptive thermal comfort model

Adaptive comfort models operate correctly in buildings with natural ventilation, considering the adaptation opportunities with respect to the behaviour and expectations. The European standard that includes the adaptive thermal comfort model is EN 16798-1:2019 [78]. This standard establishes 3 categories of lower and upper limits among which the operative temperature should oscillate, as well as the value of the optimal comfort temperature (see Fig. 1). Each category implies various thermal acceptability levels, so Category I corresponds to users with a lower thermal adaptation than those from Category III, whose limits present a greater thermal gradient. The limit values of both each category and the optimal comfort temperature are obtained through linear correlations with respect to the running mean outdoor temperature (T_{rm}) (see Eqs. (1)-(7)). T_{rm} is obtained through a weighted sum of the daily mean outdoor temperatures of the previous days (see Eq. (8), equation B.2 in Annex B, standard EN 16798-1:2019). T_{rm} is not just useful to obtain the limits of the indoor operative temperature, but also to determine whether the adaptive comfort model from EN 16798-1:2019 could be applied. In this regard, EN 16798-1:2019 establishes that the adaptive comfort model can be applied if T_{rm} is between10 and 30 ºC.

$$Optimal\ comfort\ temperature = 0.33 \cdot T_{rm} + 18.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{1}$$

$$Upper\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 20.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{2}$$

$$Lower\ limit\ (Category\ I) = 0.33 \cdot T_{rm} + 15.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{3}$$

$$Upper\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 21.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{4}$$

$$Lower\ limit\ (Category\ II) = 0.33 \cdot T_{rm} + 14.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{5}$$

$$Upper\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 22.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{6}$$

$$Lower\ limit\ (Category\ III) = 0.33 \cdot T_{rm} + 13.8 \quad [ºC] \quad (10 \leq T_{rm} \leq 30) \tag{7}$$

$$T_{rm} = (T_{ext,d-1} + 0.8T_{ext,d-2} + 0.6T_{ext,d-3} + 0.5T_{ext,d-4} + 0.4T_{ext,d-5} + 0.3T_{ext,d-6} + 0.2T_{ext,d-7})/3.8 \quad [ºC] \tag{8}$$

The adaptive model from EN 16798-1:2019 can be applied in spaces in which occupants have metabolic rates that vary from 1.0 to 1.3. Occupants are free to adapt their clothes to internal and external thermal conditions. Natural ventilation could be controlled by occupants. While a mechanical cooling or heating system in operation. So, EN 16798-1:2019 is not strictly applied in this research because the mixed-mode considers both air conditioning and modes of natural ventilation. To guarantee an appropriate application of the adaptive thermal comfort model in the natural ventilation, indoor spaces are ventilated based on various ventilation approaches. These approaches are based on the natural ventilation when the indoor operative temperature is greater than the optimal comfort temperature and the outdoor temperature is between the optimal comfort temperature and the lower limit of each category (see Fig. 2). If the indoor operative temperature is greater than the upper limit of each category, the air conditioning system is used with a setpoint temperature adjusted to the value of the upper limit. The use of these natural ventilation approaches, together with air conditioning systems, in the hours in which the upper limit is exceeded (using adaptive setpoint temperatures) ensures that the indoor operative temperature is always within the limits of adaptive thermal comfort (i.e., there are no thermal discomfort hours). In addition, comfort conditions also depend on the relation between the demand side (i.e., the occupants and the apartment itself that determines the energy demand) and the supply side (i.e., the HVAC system that generates energy consumption). Thus, the demand side requests for a certain indoor temperature, which depends on the occupants' thermal expectations. The design and size of the apartment coupled with the thermal properties of the envelope and party walls determines the energy required, and the HVAC system is in charge of providing it, thus generating energy (in this case, electricity) consumption. Adaptive setpoint temperatures could be defined as setpoint temperatures that have the value of the upper limit of the category from EN 16798-1:2019 being used, and therefore has a different value each day depending on the daily thermal oscillations of the previous days. Thus, the main advantage of using adaptive setpoint temperatures is the energy saving that can be achieved, since adaptive setpoint temperatures are less restrictive than setpoint temperatures based on the Predictive Mean Vote index, while keeping acceptable adaptive thermal comfort levels.

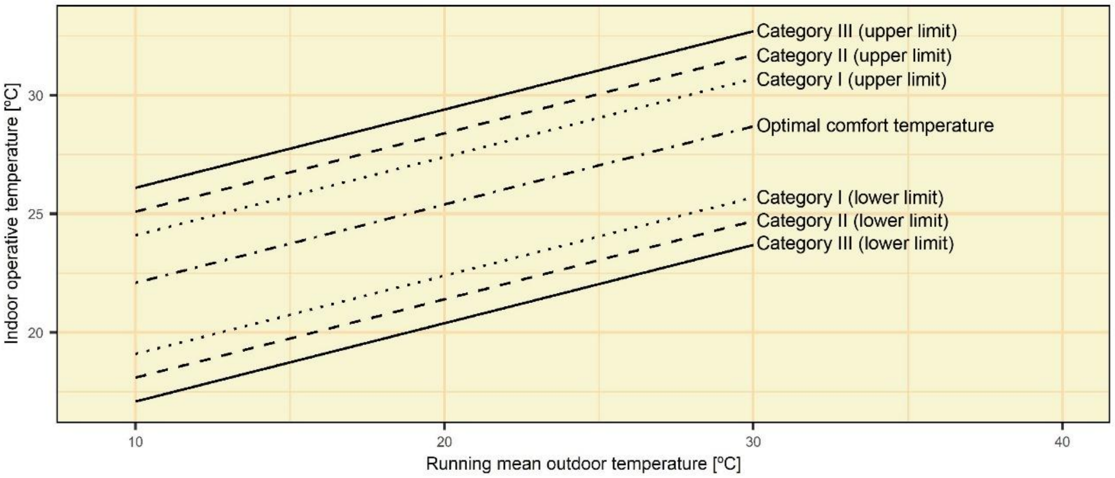


Fig. 1. Limits of the categories from EN 16798-1:2019.

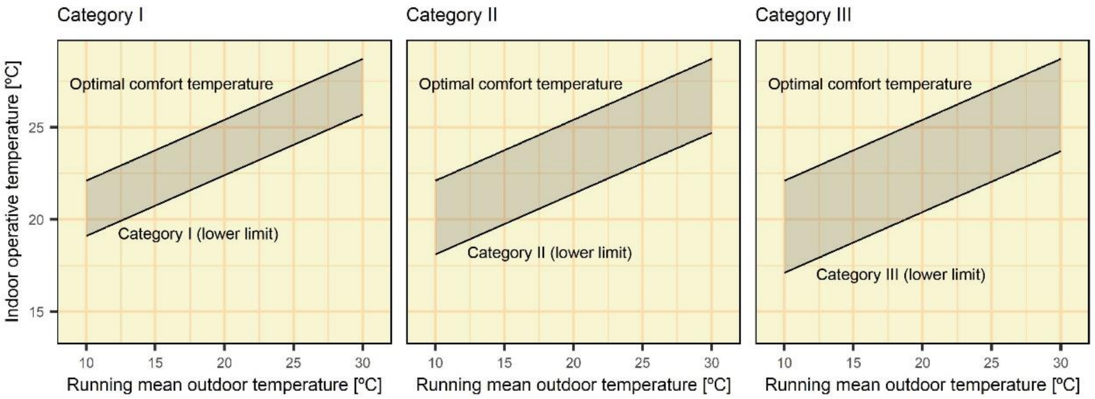


Fig. 2. Range of values among which the outdoor temperature for ventilation should oscillate. The indoor space is naturally ventilated when the indoor operative temperature is greater than the optimal comfort temperature. When natural ventilation could not be used, a cooling adaptive setpoint whose value is obtained from the upper limit of each category is used.

2.2. Case study

A building of social dwellings located in a coastal city (Cadiz) was selected to assess the potential of using natural ventilation strategies (see Fig. 3). It is a right-angled building of parallelepiped configuration, constituted by four floors, with the ground floor having a certain distribution and the remaining floors (first, second, and third) designed according to the typical floor (see Fig. 4). The building was projected and built by the Social Housing Agency in Cadiz (PROCASA in Spanish) in 2004 and according to the Building Technological Standards (NTE in Spanish) because the Spanish Technical Building Code (CTE in Spanish) was not yet into force. Most buildings of the Spanish building stock were built according to the NTE. According to data from the Spanish Institute of Statistics [79], these buildings constitute 37.25% of the building stock. In addition, this building period is when more social dwellings were built in Spain [80]. Dwellings are designed in such a way as the spaces during the day (e.g., living rooms) are placed in the external façade of the block, being ventilated and lighted towards adjoining streets and squares, whereas the private spaces (e.g., bedrooms) and the maximum number of kitchens face the indoor space of the courtyard. The indoor courtyard has the function of distributing the building and provides access to all dwellings through three cores of independent stairs and lifts. Regarding the characteristics of the envelope, the façade is characterized by a design of double-leaf brick with air gap and insulating material (with a thermal transmittance of 0.70 W/(m^{2}K)), and the roof is a traditional design of the region, without insulating material and with a thermal transmittance of 2.19 W/(m^{2}K). The windows of the building are laminated glazing with two glasses of 6 mm of thickness, and their framework is metallic with thermal bridge break.


(a) (b)

Fig. 3. Case study: (a) location in Cadiz; and (b) photograph of the case study.

The building has a total of 51 dwellings (see Table 1). Most dwellings have two bedrooms, except the central dwellings, which have 3 bedrooms and are the dwellings with the greatest surface. All dwellings were analysed.

Table 1. List of dwellings of the building.

Floor	Dwelling	Surface [m^2]	Floor	Dwelling	Surface [m^2]
Ground floor	GF-A	55.80	Second floor	2nd F-D	56.45
	GF-B	59.75		2nd F-E	60.70
	GF-C	66.15		2nd F-F	69.60
	GF-D	66.15		2nd F-G	69.60
	GF-E	67.15		2nd F-H	69.60
	GF-F	67.15		2nd F-I	69.60
	GF-G	54.90		2nd F-J	60.70
	GF-H	53.05		2nd F-K	56.45
	GF-I	54.90		2nd F-L	59.95
First floor	1st F-A	60.70		2nd F-M	56.45
	1st F-B	56.45		2nd F-N	60.70
	1st F-C	59.95	Third floor	3rd F-A	60.70
	1st F-D	56.45		3 rd F -B	56.45
	1st F-E	60.70		3 rd F -C	59.95
	1st F-F	69.60		3 rd F -D	56.45
	1st F-G	69.60		3 rd F -E	60.70
	1st F-H	69.60		3 rd F -F	69.60
	1st F-I	69.60		3 rd F -G	69.60
	1st F-J	60.70		3 rd F -H	69.60
	1st F-K	56.45		3 rd F -I	69.60
	1st F-L	59.95		3 rd F -J	60.70
	1st F-M	56.45		3 rd F -K	56.45
	1st F-N	60.70		3 rd F -L	59.95
Second floor	2nd F-A	60.70		3 rd F -M	56.45
	2 nd F -B	56.45		3 rd F -N	60.70
	2 nd F -C	59.95			

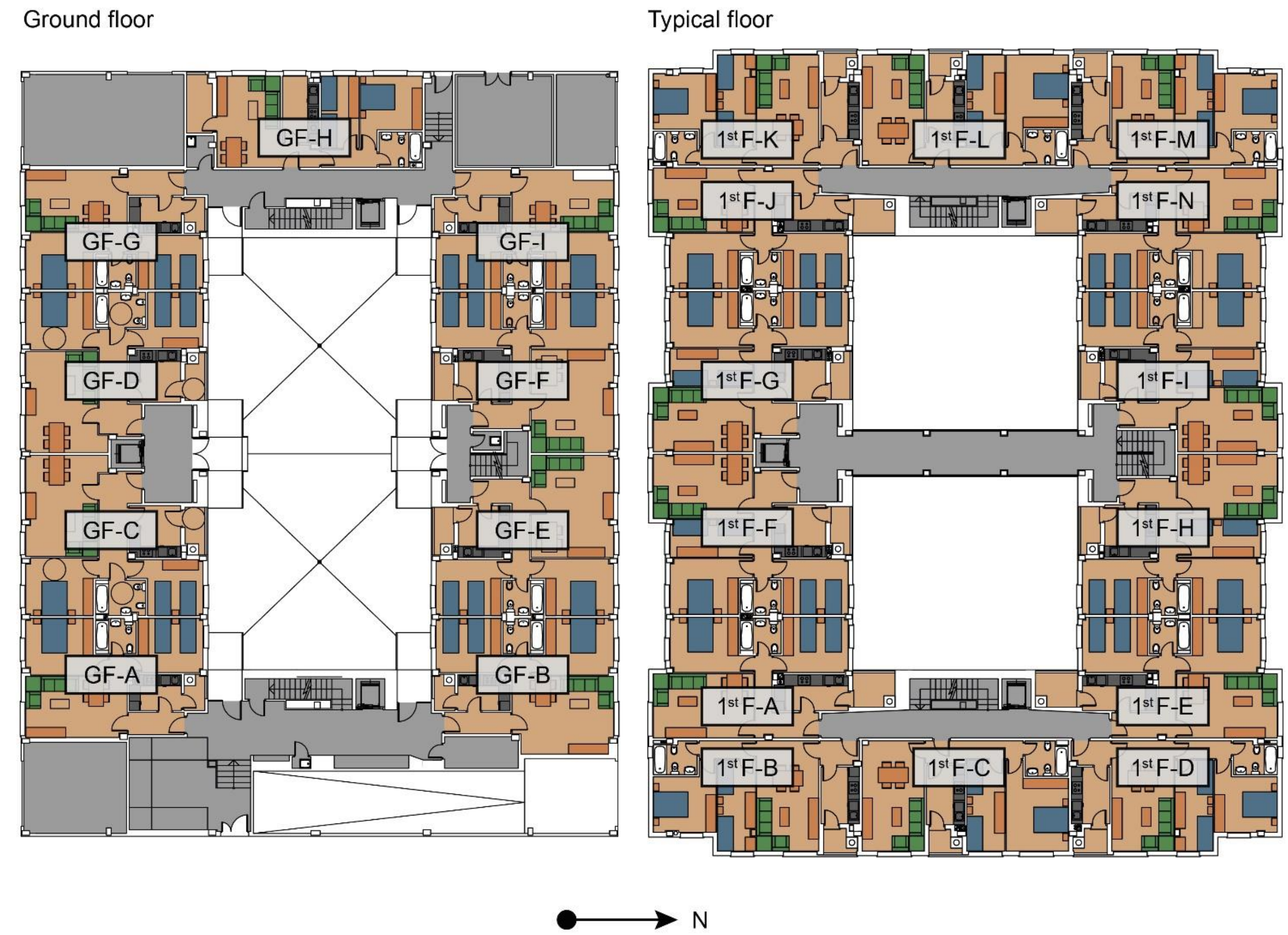


Fig. 4. Planimetry of the ground and typical floor.

2.3. Energy simulation process

The case study was modelled by DesignBuilder to carry out energy simulations with EnergyPlus (see Fig. 5). This model was validated according to ASHRAE Guideline 14-2014 [81]. For this purpose, outdoor and indoor temperatures were measured from 31 May 2018 to 25 November 2018. Measures were performed with a data logger ALMEMO 2590–4AS with thermocouples T 190–2. Probes were placed in the bedrooms of the dwelling 2 ndF -D. In addition, energy consumption data of this dwelling were compiled in the summer months of 2018 and 2019. The data measured were compared to those simulated with the Mean Bias Error (MBE) (Eq. (9)) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) (Eq. (10)). The limit values of the ASHRAE Guideline 14-2014 depend whether the variable analysed has an hourly or monthly scale: the hourly limit values are -10% ≤ MBE ≤ +10% and CV(RMSE) ≤30, and the monthly limit values are -5% ≤ MBE ≤ +5% and CV(RMSE) ≤15. Table 2 indicates the values obtained in the model validation.

$$MBE = \frac{\sum_{i=1}^{n}(y_i - x_i)}{n} \cdot 100 \quad [\%] \tag{9}$$

$$CV(RMSE) = \frac{1}{\bar{y}}\left(\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n-p}\right)^{1/2} \cdot 100 \quad [\%] \tag{10}$$

where y_i is the simulated value, x_i is the actual value, n is the number of measures, $\bar{y}$ is the average of actual values, and p is the number of adjustable model parameters.

Table 2. Results obtained in the model validation.

Variable	MBE [%]	CV(RMSE) [%]
Outdoor temperature	-2.81	17.83
Indoor temperature	-4.01	23.80
Energy consumption	1.12	9.19

The load profile used was that defined in the Spanish regulation for a residential use [82]. This profile is considered representative with the way of using Spanish dwellings. Fig. 6 shows the percentage distribution of loads according to the hour of the day. The occupancy of the case study varied depending on the day, so the occupancy in weekdays depended on the hour of the day, whereas at weekends there was an occupancy of 100% all day. The value of 100% of the occupancy load was 3.51 W/m². The load of devices and equipment showed the same tendency of using all the days of the week. The maximum value of the load for devices and equipment was 4.4 W/m² for each. Regarding the air conditioning system available in dwellings, a heat pump with a performance of 2.10 was considered. At this point, the various operational profiles of air conditioning analysed in the study should be noted: (i) the first one corresponds to a use profile of air conditioning during all the day, with setpoint temperatures of 25 ºC from 7:00 to 23:59 and 27 ºC from 0:00 to 6:59; (ii) the second one corresponds to an analysis of natural ventilation during all the day without any criterion to close windows; and (iii) the third one corresponds to a mixed-mode based on the 3 categories from EN 16798-1: 2019. The mixed-mode was analysed independently of each category and consisted of ventilating the dwelling when the indoor operative temperature was greater than the optimal comfort temperature and when, at the same time, the outdoor temperature was between the optimal comfort temperature and the lower limit of each category. When the indoor operative temperature exceeded the upper limit of each category, an adaptive setpoint temperature whose value is the same value of the upper limit was used.

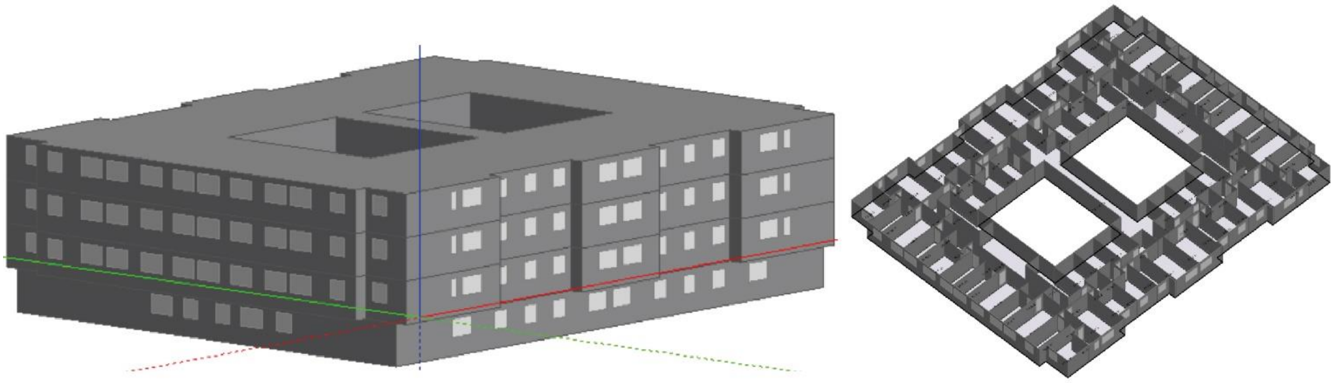


Fig. 5. Model of the case study designed with DesignBuilder.

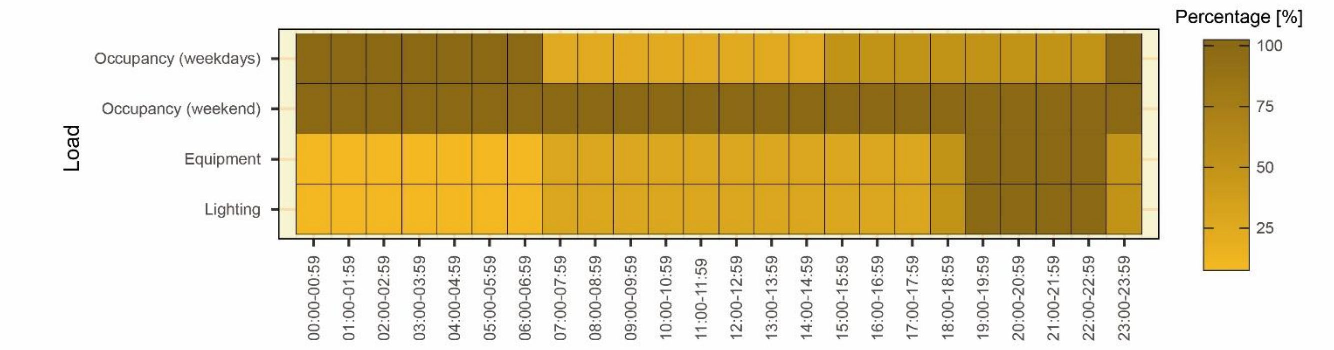


Fig. 6. Hourly distribution of the loads in the case study.

Simulations were performed for the period between 2015 and 2019 inclusive. For this purpose, EnergyPlus Weather (EPW) files were generated with the actual hourly data of temperature, relative humidity and wind speed monitored in Cadiz by the Spanish Meteorological Agency (see Fig. 7). These new EPWs were used to simulate the case study. As the research aimed to analyse the influence of the ventilation strategies on both the cooling energy consumption and the FP risk, the analysis was focused on the 3 months with greater cooling demand: June, July, and August. Although EPW files were not configured by the wind direction, the effect produced by predominant winds in Cadiz was considered. These winds are divided into *Levante* wind and *Poniente* wind [83]. *Levante* winds are winds from the east and are characterized by increasing the temperature and reducing humidity; on the other hand, *Poniente* winds are winds from the Atlantic Ocean and are characterized by lower temperatures. These variations produced by the wind direction were controlled with the values of temperature, relative humidity, and wind direction recorded. The wind direction was not included in the EPW files, but the effects on the climate of the zone due to predominant winds were considered.

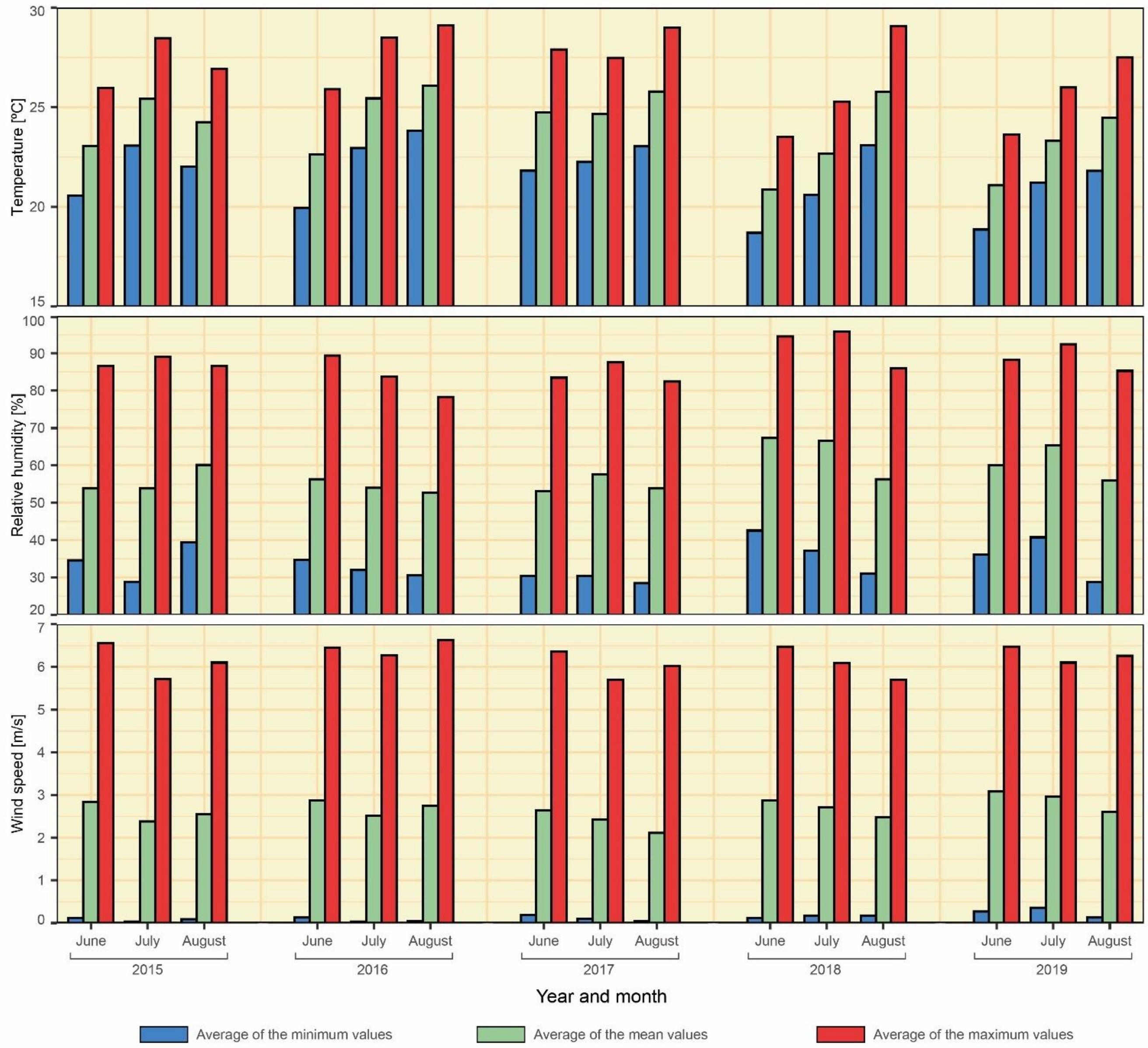


Fig. 7. Average values of the outdoor temperature, relative humidity and wind speed of the summer months in Cadiz between 2015 and 2019.

2.4. Analysis of fuel poverty

The analysis of FP was based on the high share of energy expenditure in income (2M). This indicator is among the 4 indicators used by the EPOV to assess FP and indicates that the family units that spend more than twice the average of energy expenditure at a national level are in FP [84]. Its main advantage is that it is not a static value, and the threshold value of FP can be adapted to the characteristics of each country. As for Spain, a recent study by Sánchez-Guevara Sánchez et al. [85] determined that the value 2M of the country correspond to 10%. Thus, the value of 2M of Spain is coincident with the threshold value of 10% established by the first studies on FP by Boardman [86].

To determine FP, the fuel poverty ratio (FPR) was determined (see Eq. (11)). According to this index, a household is at FP risk when over 10% of their incomes are for the building energy consumption. This study therefore analysed that family units were in FP when over 10% of their incomes is for paying the energy bill (i.e., value of 2M in Spain). As this study aimed to assess the potential of using ventilation strategies to reduce the FP risk of family units, the FPR was analysed independently of the months of June, July and August between 2015 and 2019.

$$\begin{aligned} &FPR = \frac{C}{I} \cdot 100 \quad [\%] \\ &Case\ in\ fuel\ poverty \quad \text{if} \quad FPR \geq 2M\ (10\%) \end{aligned} \tag{11}$$

where FPR is the Fuel Poverty Ratio, C is the monthly cost of the household energy consumption [€], and I is the monthly household income [€].

2.5. Determination of the household energy consumption price

The energy consumption price of a dwelling could be understood as the sum of the various energy consumptions (lighting, equipment, HVAC systems or sanitary hot water) multiplied by the price corresponding to each. The energy consumption of the social dwellings analysed is mainly electricity because the HVAC systems are of heat pump. Regarding the contract of the electricity price, social dwellings have contracted the price regime from the Voluntary Price for the Small Consumer (PVPC in Spanish) without hourly discrimination and with a contracted power of 5.70 kW. Since 2014, it is possible to contract through PVPC, whose electricity price is regulated by the Spanish Government and the price varies according to the hour of the day. The following concepts are included in the monthly energy bill through PVPC (i.e., the value of C):

1. Energy term.
   The energy term is the price applied to each kWh consumed. The energy term is obtained by the sum of the grid access and the cost of production of the electrical energy (see Eq. (12)). This price varies throughout the day, so it is different in each hour of the day. The regulation of the electricity price by the Spanish Government allows users to know beforehand the electricity prices in the 24 hours of both the day of the consultation and the previous days.
   $$ET = EC \cdot ETP \tag{12}$$
   where ET is the energy term [€], EC is the energy consumption of the dwelling [kWh], ETP is the price of the energy term [€/kWh], and n is the number of hours of each month. EC is obtained by simulating the case study, whereas ETP is obtained by the hourly values of the price of PVPC. By way of example, Fig. 8 includes the hourly values of ETP in the summer months of 2015. Each value was multiplied by the hourly values of EC, and the sum of the hourly amounts of each month obtains ET. This process was carried out per dwelling and operational pattern, and values of ET were obtained in each summer month between 2015 and 2019.

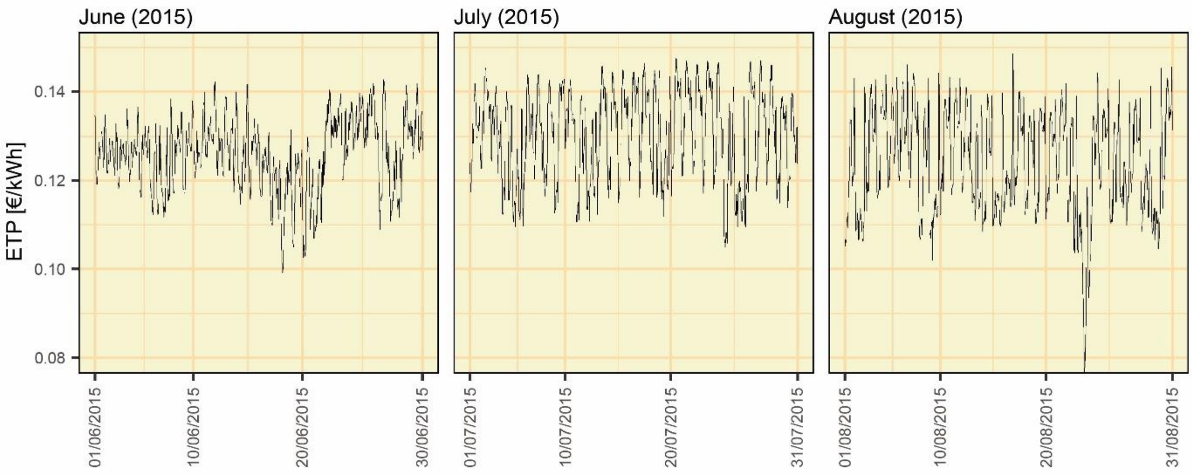


Fig. 8. Values of the price of the energy term during the summer months of 2015.

2. Power term.
   The power term is a fixed price that users should pay because the contracted power is available at all times. This price is obtained by multiplying the contracted power by both the days including the invoicing period and the power term of the PVPC (see Eq. (13)). This power term includes the price of the power term of the grid access (0.104229 €/(kWday)) and the marketing margin (0.010959 €/(kWday)). Dwellings were considered to have a contracted power of 5.7 kW.
   $$PT = 5.7 \cdot ND \cdot (0.104229 + 0.010959) \tag{13}$$
   where PT is the power term [€], and ND is the number of days of the invoicing period. As the summer months (June, July, and August) were analysed, the value of ND is 30 days for June and 31 days for July and August.

3. Electricity tax.
   Another concept included in the price of the bill of the PVPC is the electricity tax (ElT). This tax is applied to the sum of the energy and power terms, with a value of 5.1127% (see Eq. (14).
   $$ElT = 0.051127 \cdot (ET + PT) \tag{14}$$

4. Small expenses and value added tax.
   Finally, the total amount of the electricity bill (i.e., the value of C) that the users of a dwelling should pay is obtained by summing the energy term (ET), the power term (PT), and the electricity tax (ElT), as well as the rent of the electricity meter (EMR) and the value added tax applied (see Eq. (15)). A price of 1.11 €/month was considered for the rent of meters, and the value added tax had a percentage value of 21%.
   $$C = 1.21 \cdot (ET + PT + ElT + EMR) \tag{15}$$

2.6. Income levels of the family units living in social dwellings

The obtaining of a social dwelling by family units depends on their final assessment according to several indicators. One of the most relevant are their incomes as these dwellings aimed at facilitating the obtaining of a dwelling by those family units with very low incomes. To establish both a criterion of the income level of family units and various marks, the Public Income Indicator of Multiple Effects (IPREM in Spanish) is used. IPREM is an index used in Spain since 2004 as a reference to give grants, subventions, and unemployment assistance. IPREM should be understood as an index different from the guaranteed minimum wage which has evolved at a lower speed from its creation to facilitate that the most unfavoured family units are benefited from economic grants. As for social dwellings, family incomes are usually compared with the value of the IPREM. Regarding the social dwellings of the region of Cadiz, the agency responsible for social dwellings establishes a greater mark to access to these dwellings to those family units with incomes lower than two times the IPREM and with a greater mark for those with a monthly income between 0.70 and 1.50 times the IPREM. The value of the IPREM could therefore be used as a reference to analyse the usual income levels of the family units living in social dwellings. This study analysed family units with monthly incomes with variations of 0.1 in the value of the IPREM from 0.5 and 2.0. For example, for a factor of 0.5 and a monthly IPREM of €563.97, it is supposed that the family unit has monthly incomes of €281.98. The proportional part of each month of the annual IPREM with 14 salaries was used as a value to determine the monthly income of the IPREM. Given that the IPREM is related to the gross incomes of the family unit and does not consider their actual income to face various expenses (such as the electricity consumption), a percentage of 10% was applied as regards the taxes deducted from the net income which is finally obtained. So, 90% of the monthly incomes of the IPREM corresponds to the net incomes that the family units can freely spend. As the period from 2015 to 2019 was analysed, the variation presented by the IPREM between 2016 and 2017 was considered: between 2015 and 2016 the annual IPREM with 14 salaries was €7455.14, and €7519.59 from 2017 to 2019. Table 3 summarises the variations of the IPREM and the percentages considered for the family units.

Table 3. Combinations of monthly incomes according to the IPREM.

Years	Annual IPREM (14 salaries) [€]	Monthly IPREM [€]	Monthly IPREM (net income) [€]	Factors applied to the IPREM in the hypothesis analysis of family unit's incomes
2015, 2016, and 2017	7,519.59	626.63	563.97	0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, and 2.0
2018 and 2019	7,455.14	621.26	559.14	

2.7. Climate analysis

Finally, this study performed a climate analysis to assess the similarity of the conditions of application of the adaptive thermal comfort models in the summer months (June, July, and August) in the coastal cities of the countries in southern Spain. For this purpose, the hourly temperature data from the coastal cities of Spain, France, Portugal, Italy, Croatia, Albania, Montenegro, and Greece were obtained. A total of 3,047 climate data were analysed, which corresponded to various cities of these countries. Climate data were obtained with the METEONORM software. The analysis of the conditions to apply the adaptive thermal comfort model was based on the possibility of application in the summer months according to T_{rm}. As indicated in Section 2.1, the adaptive model could be applied if T_{rm} are between 10 and 30 ºC. Therefore, the percentage of days of the summer when the adaptive model is applied will be determined according to the following rule:

$$
\begin{aligned}
&PDAAM = \frac{\sum_{i=1}^{n_{DS}} d_i}{n_{DS}} \\
&d_i = 1 \quad if\ 30 \geq T_{rm} \geq 10 \\
&d_i = 0 \quad if\ T_{rm} > 30 \\
&d_i = 0 \quad if\ T_{rm} < 10
\end{aligned}
\qquad (16)
$$

where $PDAAM$ is the percentage of days to apply the adaptive thermal comfort model during the summer months [%], d_i is a value assigned to each day of the summer through the rules established for T_{rm}, and n_{DS} is the total number of days of the summer months.

Moreover, the possibility of applying natural ventilation was determined with a rule like that for applying the adaptive model. However, several modifications were made. First, the analysis was performed at an hourly scale due to the modifications presented by the possibility of using natural ventilation throughout the day. Second, the analysis was independently performed for each category of EN 16798-1:2019. The application of the adaptive thermal comfort model was independent of the category analysed and therefore there were no distinction per category in Eq. (16). Eqs. (17)-(19) show the rules to determine the possibility of applying natural ventilation.

$$
\begin{aligned}
&PHNV_{\ cat1} = \frac{\sum_{i=1}^{n_{HS}} h_{cat1,i}}{n_{HS}} \\
&h_{cat1,i} = 1 \quad if\ Optimal\ comfort\ temperature \geq T_{ext,i} \geq Lower\ limit\ (Category\ I) \\
&h_{cat1,i} = 0 \quad if\ T_{ext,i} > Optimal\ comfort\ temperature \\
&h_{cat1,i} = 0 \quad if\ T_{ext,i} < Lower\ limit\ (Category\ I)
\end{aligned}
\qquad (17)
$$

$$PHNV_{\ cat2} = \frac{\sum_{i=1}^{n_{HS}} h_{cat2,i}}{n_{HS}}$$
$$\begin{aligned} h_{cat2,i} &= 1 \quad if\ Optimal\ comfort\ temperature \geq T_{ext,i} \geq Lower\ limit\ (Category\ II) \\ h_{cat2,i} &= 0 \quad if\ T_{ext,i} > Optimal\ comfort\ temperature \\ h_{cat2,i} &= 0 \quad if\ T_{ext,i} < Lower\ limit\ (Category\ II) \end{aligned} \tag{18}$$

$$PHNV_{\ cat3} = \frac{\sum_{i=1}^{n_{HS}} h_{cat3,i}}{n_{HS}}$$
$$\begin{aligned} h_{cat3,i} &= 1 \quad if\ Optimal\ comfort\ temperature \geq T_{ext,i} \geq Lower\ limit\ (Category\ III) \\ h_{cat3,i} &= 0 \quad if\ T_{ext,i} > Optimal\ comfort\ temperature \\ h_{cat3,i} &= 0 \quad if\ T_{ext,i} < Lower\ limit\ (Category\ III) \end{aligned} \tag{19}$$

where $PHNV$ is the percentage of hours in which the adaptive natural ventilation strategies are applicable in the summer months [%],h_i is a value assigned to each hour of the year through the rules established for $T_{ext,i}$, and n_{HS} is the total number of hours of the summer months.

To analyse the similarity among the coastal cities, unidimensional cluster analyses were performed [87]. For this purpose, k-means was used; this is an iterative resignation algorithm based on the centroid concept of clusters of observations [88]. The k-value indicates the number of clusters created. Determining the k-value is therefore essential in the analysis. For this purpose, the optimal number of k was determined through the Elbow method [89], and in the silhouette index [90]. The Elbow method determines k by reducing the total within-cluster sum of squares (see Eq. (20)). The graphic representation of the curve of the total within-cluster sum of squares determines the elbow in which the optimal number of k is located. However, the code cannot be precisely determined in some cases, so the analysis should be complemented with an additional indicator [89]. Thus, the silhouette index was used ($s(i)$). This index determined the similarity of each observation to the remaining observations of a same cluster (see Eq. (21)), thus assessing the quality of the clusters obtained. Likewise, $s(i)$ obtains values between -1 y 1. A value between 0 and 1 implies that individuals are in the correct cluster, unlike a value between -1 and 0.

$$WSS = \sum_{k=1}^{K} \sum_{i \in S_k} \sum_{j=1}^{p} \left(x_{ij} - \bar{x}_{kj}\right)^2 \tag{20}$$

$$s(i) = \frac{b(i) - a(i)}{max\{a(i), b(i)\}} \tag{21}$$

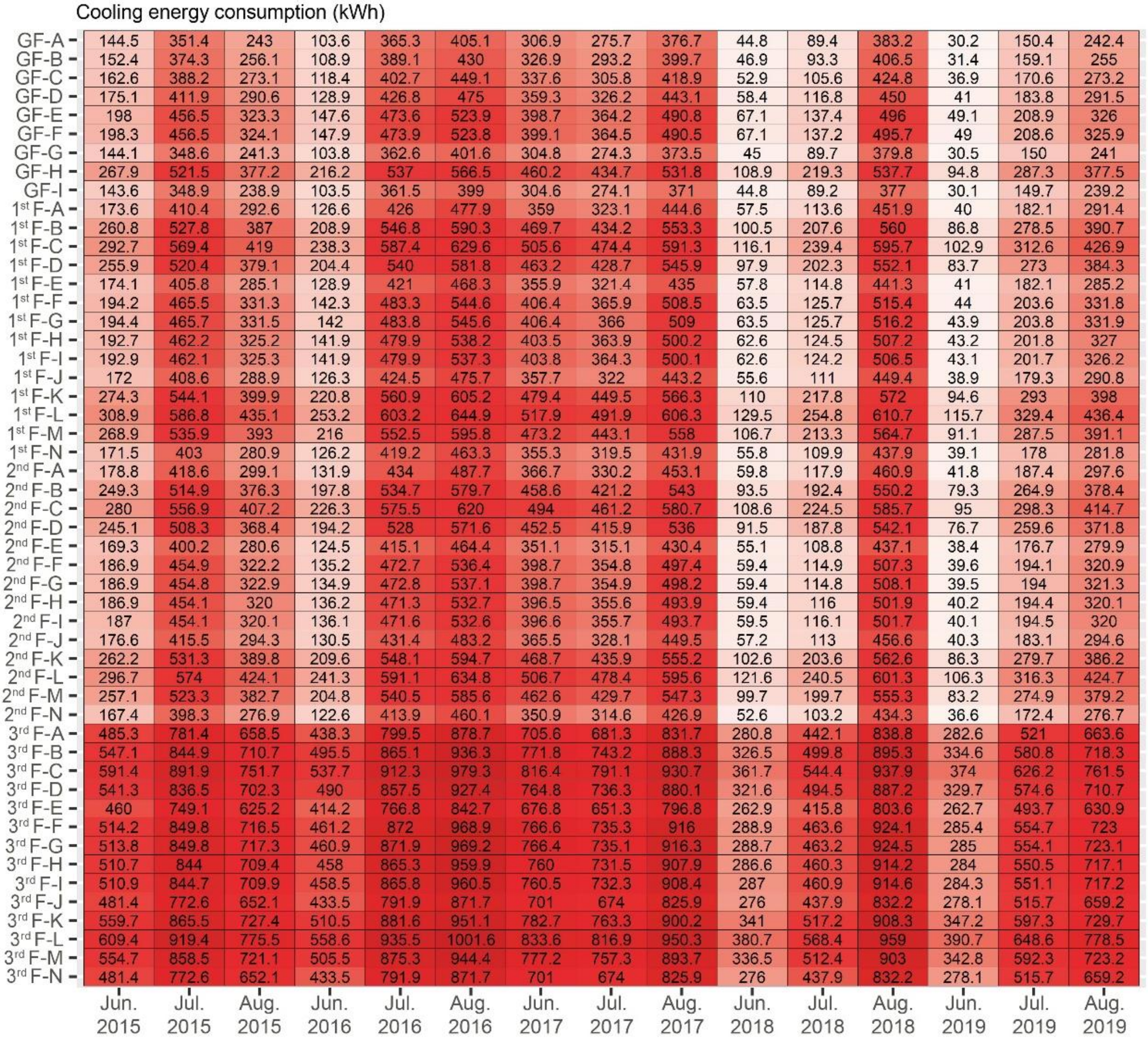
where WSS is the total within-cluster sum of squares; $\bar{x}_{kj}$ is the j-th centroid for the k-th cluster, S_k is the set of instances grouped in each cluster, $a(i)$ is the mean distance between the instance (i) and the rest of the cluster, and $b(i)$ is the minimal mean distance between the instance (i) and the other clusters.

3. Results and discussion

3.1. The impact of static use patterns on the fuel poverty risk of social dwellings

First, the effect of some patterns to use air conditioning systems without adopting adaptive ventilation strategies (i.e., through static behaviour patterns) was analysed, as well as the potential of using ventilation strategies. This subsection discusses the results obtained by using static setpoint temperatures in the dwellings analysed. Fig. 9 includes the results of the cooling energy consumption in the 5 years analysed. This energy consumption presented a variable tendency in the last 5 years. The month with the greatest severity was different in each year: July in 2015 and August in 2016 and 2019. Moreover, cooling energy consumption could be possible in the other month analysed (June) as there were high cooling energy consumptions, such as June in 2017, with a greater consumption than in July. Likewise, the values in each dwelling usually had a same pattern: the dwellings on the highest floor recorded greater energy consumption values (with a maximum value of 1001.6 kWh in August 2016,), and the dwellings on the ground floor had a lower energy consumption. As expected, the dwellings with a greater envelope surface influenced by solar radiation presented a greater cooling energy demand than those on intermediate floors.

There was a climate variability in the cooling energy consumption according to the climate oscillations presented by the summer season. However, the analysis of the FP risk did not only depend on the cooling energy consumption, but also on the variability of the price of the energy term in the PVPC. Although August 2016 obtained the greatest cooling energy consumption, this month did not present a greater FP risk. This aspect is shown in Fig. 10, which represents the distributions of the values of FPR obtained in each dwelling and according to the level of household incomes in relation to the IPREM. The tendencies of energy consumption were not directly related to the FP risk due to the variability of the price of the energy term (see Fig. 11). In the case of August, there was an increase tendency of the quartile values of the distributions between 0.01 and 0.09 in the value of FPR, with values of greater risk recorded in August 2018. By comparing the results with the energy consumption values, the energy consumption in August 2016 was greater than in August 2018 (with differences between 21.8 and 45.9 kWh). However, the values of FPR increased between 0.01 and 0.11 in comparison to 2016. This same behaviour took place in July 2015 and 2016: although the energy consumption was greater in 2016, greater values of FPR were obtained in 2015. Regarding the analysis of the number of cases at FP risk according to the level of monthly incomes with respect to the IPREM, the combination of households with lower incomes presented many cases at FP risk. In this regard, the increase of monthly incomes by 0.1 times the value of the IPREM implied an average decrease in the value of FPR of 0.02 in the first and second quartile of the distributions, and 0.03 in the third quartile. A greater level of family incomes allowed therefore the risk of being in FP to be reduced. However, the usual low-income levels of the family units that live in social dwellings showed the ease with which households are in FP. In addition, there were cases of FP in the assumptions of family units with more incomes (i.e., monthly incomes with a value of 2 with respect to the IPREM): (i) in 2015, there were 14, 48, and 24 dwellings at FP risk in June, July, and August, respectively; (ii) in 2016, there were 35 and 39 dwellings at FP risk in July and August; (iii) in 2017, there were 27 dwellings at FP risk in June, 19 in July, and 42 in August; (iv) in 2018, all dwellings were at FP risk in August; and (v) 2019 was the year with a lower number of dwellings at FP risk, with a total of 14 cases in July and August. Thus, family units could be at FP risk even in households with high incomes. There is a great relationship between the FP risk of family units and the fact of living in a dwelling on the highest floor (see Fig. 12). The dwellings on the third floor of the building under study (i.e., the dwellings on the highest floor) were characterized by presenting greater values of FPR than the dwellings on the other floors, particularly on the ground floor which obtained the lowest values of FPR. This aspect suggested that an intelligent allocation of family units in the dwellings of a social building according to the values of their incomes according to the IPREM would allow the energy vulnerability to be controlled in the months with greater energy consumption. Recent studies conducted in Chilean social dwellings [91] have developed methodologies to assess the possible FP risk of the family units allocated to social dwellings according to their level of incomes and of constructive parameters of the dwelling (including the roof surface). Nonetheless, the results included in Fig. 12 show a tendency of the FP risk according to the floor of the dwelling; however, having greater information on it should be required for a more effective allocation, but this is not the objective of this research.


Cooling energy consumption (kWh)

	Jun. 2015	Jul. 2015	Aug. 2015	Jun. 2016	Jul. 2016	Aug. 2016	Jun. 2017	Jul. 2017	Aug. 2017	Jun. 2018	Jul. 2018	Aug. 2018	Jun. 2019	Jul. 2019	Aug. 2019
GF-A	144.5	351.4	243	103.6	365.3	405.1	306.9	275.7	376.7	44.8	89.4	383.2	30.2	150.4	242.4
GF-B	152.4	374.3	256.1	108.9	389.1	430	326.9	293.2	399.7	46.9	93.3	406.5	31.4	159.1	255
GF-C	162.6	388.2	273.1	118.4	402.7	449.1	337.6	305.8	418.9	52.9	105.6	424.8	36.9	170.6	273.2
GF-D	175.1	411.9	290.6	128.9	426.8	475	359.3	326.2	443.1	58.4	116.8	450	41	183.8	291.5
GF-E	198	456.5	323.3	147.6	473.6	523.9	398.7	364.2	490.8	67.1	137.4	496	49.1	208.9	326
GF-F	198.3	456.5	324.1	147.9	473.9	523.8	399.1	364.5	490.5	67.1	137.2	495.7	49	208.6	325.9
GF-G	144.1	348.6	241.3	103.8	362.6	401.6	304.8	274.3	373.5	45	89.7	379.8	30.5	150	241
GF-H	267.9	521.5	377.2	216.2	537	566.5	460.2	434.7	531.8	108.9	219.3	537.7	94.8	287.3	377.5
GF-I	143.6	348.9	238.9	103.5	361.5	399	304.6	274.1	371	44.8	89.2	377	30.1	149.7	239.2
1st F-A	173.6	410.4	292.6	126.6	426	477.9	359	323.1	444.6	57.5	113.6	451.9	40	182.1	291.4
1st F-B	260.8	527.8	387	208.9	546.8	590.3	469.7	434.2	553.3	100.5	207.6	560	86.8	278.5	390.7
1st F-C	292.7	569.4	419	238.3	587.4	629.6	505.6	474.4	591.3	116.1	239.4	595.7	102.9	312.6	426.9
1st F-D	255.9	520.4	379.1	204.4	540	581.8	463.2	428.7	545.9	97.9	202.3	552.1	83.7	273	384.3
1st F-E	174.1	405.8	285.1	128.9	421	468.3	355.9	321.4	435	57.8	114.8	441.3	41	182.1	285.2
1st F-F	194.2	465.5	331.3	142.3	483.3	544.6	406.4	365.9	508.5	63.5	125.7	515.4	44	203.6	331.8
1st F-G	194.4	465.7	331.5	142	483.8	545.6	406.4	366	509	63.5	125.7	516.2	43.9	203.8	331.9
1st F-H	192.7	462.2	325.2	141.9	479.9	538.2	403.5	363.9	500.2	62.6	124.5	507.2	43.2	201.8	327
1st F-I	192.9	462.1	325.3	141.9	479.9	537.3	403.8	364.3	500.1	62.6	124.2	506.5	43.1	201.7	326.2
1st F-J	172	408.6	288.9	126.3	424.5	475.7	357.7	322	443.2	55.6	111	449.4	38.9	179.3	290.8
1st F-K	274.3	544.1	399.9	220.8	560.9	605.2	479.4	449.5	566.3	110	217.8	572	94.6	293	398
1st F-L	308.9	586.8	435.1	253.2	603.2	644.9	517.9	491.9	606.3	129.5	254.8	610.7	115.7	329.4	436.4
1st F-M	268.9	535.9	393	216	552.5	595.8	473.2	443.1	558	106.7	213.3	564.7	91.1	287.5	391.1
1st F-N	171.5	403	280.9	126.2	419.2	463.3	355.3	319.5	431.9	55.8	109.9	437.9	39.1	178	281.8
2nd F-A	178.8	418.6	299.1	131.9	434	487.7	366.7	330.2	453.1	59.8	117.9	460.9	41.8	187.4	297.6
2nd F-B	249.3	514.9	376.3	197.8	534.7	579.7	458.6	421.2	543	93.5	192.4	550.2	79.3	264.9	378.4
2nd F-C	280	556.9	407.2	226.3	575.5	620	494	461.2	580.7	108.6	224.5	585.7	95	298.3	414.7
2nd F-D	245.1	508.3	368.4	194.2	528	571.6	452.5	415.9	536	91.5	187.8	542.1	76.7	259.6	371.8
2nd F-E	169.3	400.2	280.6	124.5	415.1	464.4	351.1	315.1	430.4	55.1	108.8	437.1	38.4	176.7	279.9
2nd F-F	186.9	454.9	322.2	135.2	472.7	536.4	398.7	354.8	497.4	59.4	114.9	507.3	39.6	194.1	320.9
2nd F-G	186.9	454.8	322.9	134.9	472.8	537.1	398.7	354.9	498.2	59.4	114.8	508.1	39.5	194	321.3
2nd F-H	186.9	454.1	320	136.2	471.3	532.7	396.5	355.6	493.9	59.4	116	501.9	40.2	194.4	320.1
2nd F-I	187	454.1	320.1	136.1	471.6	532.6	396.6	355.7	493.7	59.5	116.1	501.7	40.1	194.5	320
2nd F-J	176.6	415.5	294.3	130.5	431.4	483.2	365.5	328.1	449.5	57.2	113	456.6	40.3	183.1	294.6
2nd F-K	262.2	531.3	389.8	209.6	548.1	594.7	468.7	435.9	555.2	102.6	203.6	562.6	86.3	279.7	386.2
2nd F-L	296.7	574	424.1	241.3	591.1	634.8	506.7	478.4	595.6	121.6	240.5	601.3	106.3	316.3	424.7
2nd F-M	257.1	523.3	382.7	204.8	540.5	585.6	462.6	429.7	547.3	99.7	199.7	555.3	83.2	274.9	379.2
2nd F-N	167.4	398.3	276.9	122.6	413.9	460.1	350.9	314.6	426.9	52.6	103.2	434.3	36.6	172.4	276.7
3rd F-A	485.3	781.4	658.5	438.3	799.5	878.7	705.6	681.3	831.7	280.8	442.1	838.8	282.6	521	663.6
3rd F-B	547.1	844.9	710.7	495.5	865.1	936.3	771.8	743.2	888.3	326.5	499.8	895.3	334.6	580.8	718.3
3rd F-C	591.4	891.9	751.7	537.7	912.3	979.3	816.4	791.1	930.7	361.7	544.4	937.9	374	626.2	761.5
3rd F-D	541.3	836.5	702.3	490	857.5	927.4	764.8	736.3	880.1	321.6	494.5	887.2	329.7	574.6	710.7
3rd F-E	460	749.1	625.2	414.2	766.8	842.7	676.8	651.3	796.8	262.9	415.8	803.6	262.7	493.7	630.9
3rd F-F	514.2	849.8	716.5	461.2	872	968.9	766.6	735.3	916	288.9	463.6	924.1	285.4	554.7	723
3rd F-G	513.8	849.8	717.3	460.9	871.9	969.2	766.4	735.1	916.3	288.7	463.2	924.5	285	554.1	723.1
3rd F-H	510.7	844	709.4	458	865.3	959.9	760	731.5	907.9	286.6	460.3	914.2	284	550.5	717.1
3rd F-I	510.9	844.7	709.9	458.5	865.8	960.5	760.5	732.3	908.4	287	460.9	914.6	284.3	551.1	717.2
3rd F-J	481.4	772.6	652.1	433.5	791.9	871.7	701	674	825.9	276	437.9	832.2	278.1	515.7	659.2
3rd F-K	559.7	865.5	727.4	510.5	881.6	951.1	782.7	763.3	900.2	341	517.2	908.3	347.2	597.3	729.7
3rd F-L	609.4	919.4	775.5	558.6	935.5	1001.6	833.6	816.9	950.3	380.7	568.4	959	390.7	648.6	778.5
3rd F-M	554.7	858.5	721.1	505.5	875.3	944.4	777.2	757.3	893.7	336.5	512.4	903	342.8	592.3	723.2
3rd F-N	481.4	772.6	652.1	433.5	791.9	871.7	701	674	825.9	276	437.9	832.2	278.1	515.7	659.2

Fig. 9. Cooling energy consumption using the static behaviour patterns obtained in the case studies in the 5 years analysed.

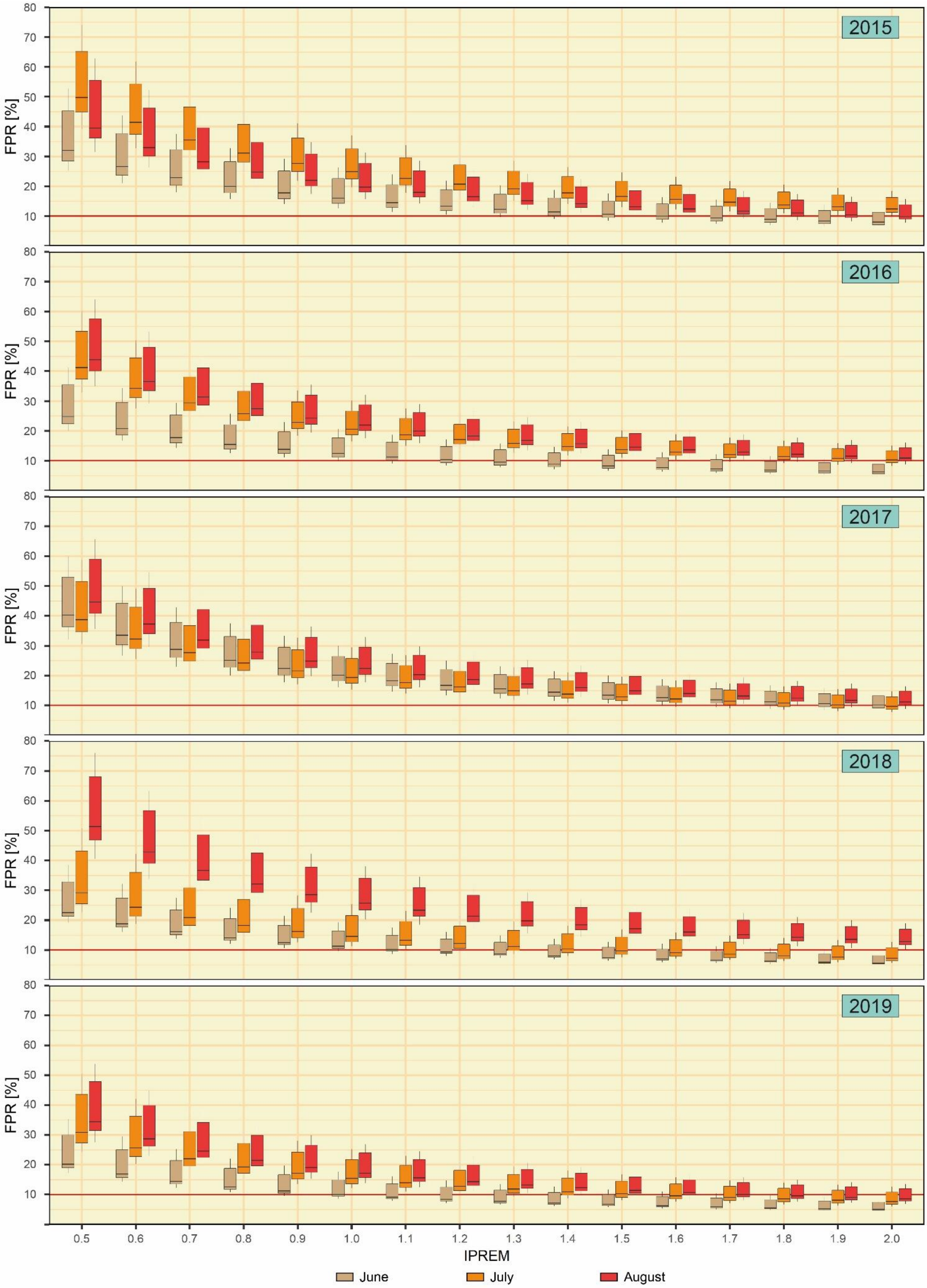


Fig. 10. Distributions of the values of BI by values of incomes according to the IPREM using the static behaviour patterns. The red line represents the line of 10%.

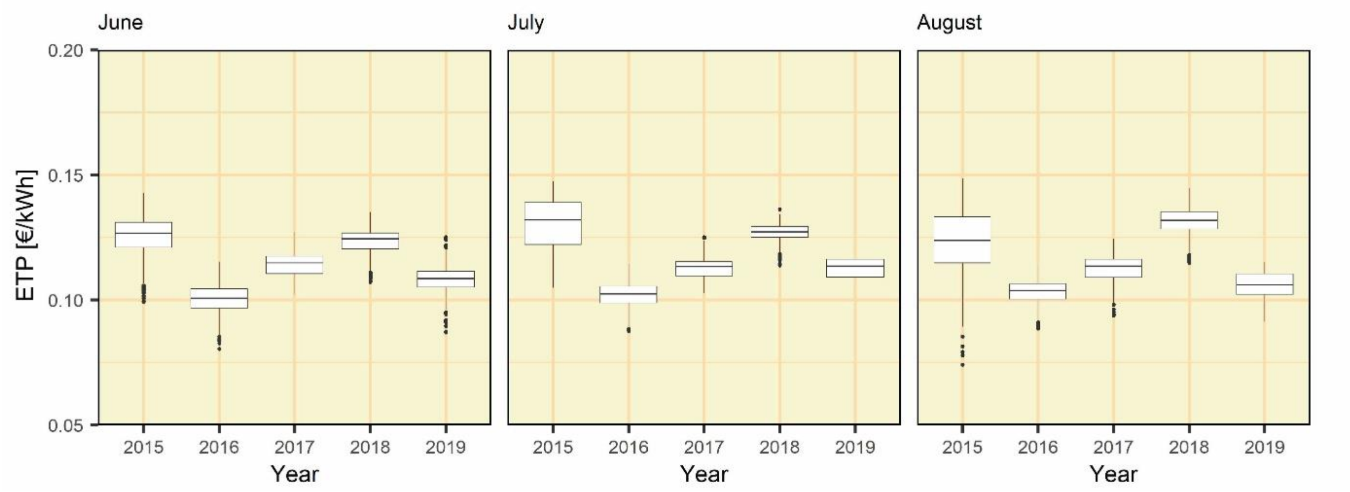


Fig. 11. Distributions of the values of ETP.

Fig. 12. Comparison of the influence of the floor analysed on the values of BI using the static behaviour patterns. The red line represents the line of 10%.

3.2. Effective ventilation strategies to reduce fuel poverty risk

The conditioning of indoor spaces of social dwellings in coastal zones by using air conditioning and based on static setpoints leads to a high FP risk, which could be reduced by natural ventilation. However, natural ventilation strategies should be adequately applied. A common practice in the summer months in coastal zones are the opening of windows throughout the day to acclimatize the indoor space, thus implying that the indoor operative temperature reaches values of thermal discomfort. To prove this aspect, the dwellings of the case study were assessed with natural ventilation patterns during all days of the summer months, and the number of hours in thermal discomfort was determined with respect to the upper limit of the categories of adaptive thermal comfort from EN 16798-1:2019. Fig. 13 shows the distributions of the thermal discomfort hours obtained in the bedrooms and living rooms of each dwelling. A natural ventilation throughout the day implied many thermal discomfort hours. In this regard, Category I (the category with greater thermal expectations on the part of users) obtained high values of thermal discomfort hours. Regardless of the outliers found in the distributions reaching values of 300 thermal discomfort hours in a month, the values of the third quartile of distributions oscillated between 46 and 122 h in the months that recorded a greater cooling energy consumption (see Fig. 9). There were therefore high values of thermal discomfort hours for users with a lower thermal adaptability. In the other categories of adaptive thermal comfort (Categories II and III) that increased the upper limit and therefore involved a greater adaptation of users, there were some hours with thermal discomfort, thus implying a risk in users' health because users could live in extreme situations that lead to heatstrokes, thermal stress, and even the death of weak people. Although natural ventilation reduces the energy consumption of dwellings, an effective natural ventilation strategies is required. For this reason, 3 natural ventilation patterns based on the categories of adaptive thermal comfort from EN 16798-1:2019 were analysed.

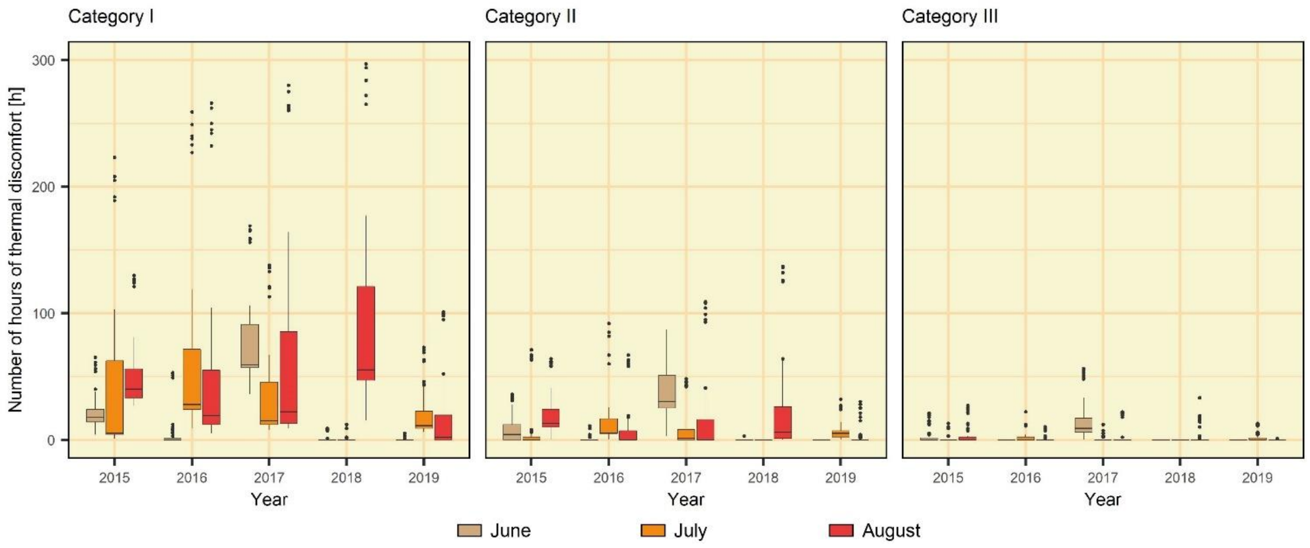


Fig. 13. Distributions of the thermal discomfort hours according to the upper limit values of the categories from EN 16798-1:2019 with natural ventilation patterns during all day of the summer months by users.

Moreover, the cooling energy consumption was reduced by applying both natural ventilation and air conditioning based on adaptive thermal comfort models (see Fig. 14). Unlike the use of adaptive setpoint temperatures (in which correlations are linear in comparison to the use of static setpoint temperatures [92]), the energy consumption based on mixed-mode presented a polynomial correlation with respect to the static setpoint temperatures. These polynomial correlations were from the second to the sixth degree in the various months analysed (see Table 4). This aspect means that, with energy consumption values with static setpoints of up to 250 kWh, the cooling energy consumption in the dwelling can be removed, and from values greater than 250 kWh, the cooling energy consumption can be 0 kWh depending on the conditions of the outdoor temperature and users' thermal expectations. The application of the mixed-mode based on the Category III from EN 16798-1:2019 practically removed the energy consumption in all case studies and months, with cooling energy consumption values being sometimes not greater than 115 kWh. A greater users' thermal expectation (such as the case of Categories I and II) implies a greater energy consumption as the possibilities of ventilation are lower because of the narrowing of the thermal gradient between the optimal comfort temperature and the lower limit. Thus, the potential of energy saving of natural ventilation strategies mainly depends on users' adaptation capacities.

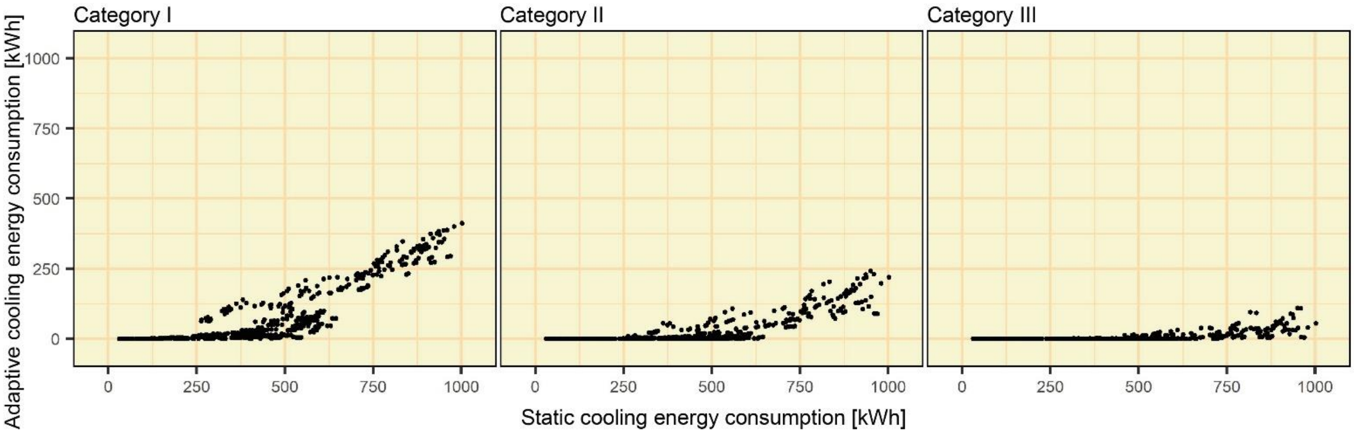


Fig. 14. Dispersion diagrams between the monthly energy consumption obtained with adaptive behaviour patterns (mixed-mode) and static behaviour patterns (only air conditioning).

Table 4. Polynomial correlations between the adaptive and static energy consumption values.

Year/	Category I		Category II		Category III	
month	R2	Equation	R2	Equation	R2	Equation
2015						
Jun.	0.99	$y = 0.001x^2 - 0.366x + 33.3$	0.99	$y = 0.0005x^2 - 0.215x + 21.17$	0.98	$y = 0.0002x^2 - 0.092x + 9.963$
Jul.	0.98	$y = 0.001x^2 - 0.65x + 101.2$	0.94	$y = 10^{-6}x^3 - 0.0019x^2$	0.86	$y = 4 \cdot 10^{-9}x^4 - 9 \cdot 10^{-6}x^3 + 0.0075x^2 - 2.6514x + 345.38$
Aug.	0.98	$y = 0.0009x^2 - 0.405x + 52.4$	0.94	$y = 10^{-7}x^3 - 0.0008x^2 + 0.306x - 39$	0.90	$y = 3 \cdot 10^{-9}x^4 - 5 \cdot 10^{-6}x^3 + 0.0033x^2 - 0.93x + 94.65$
2016						
Jun.	0.99	$y = 0.001x^2 - 0.343x + 21.9$	0.95	$y = 0.0008x^2 - 0.3364x + 31.014$	0.96	$y = 8 \cdot 10^{-12}x^5 - 10^{-8}x^4 + 4 \cdot 10^{-6}x^3 - 0.001x^2 + 0.094x + 3.4$
Jul.	0.98	$y = 0.0008x^2 - 0.326x + 4.84$	0.95	$y = 6 \cdot 10^{-7}x^3 - 0.0002x^2 - 0.1393x + 52.682$	0.91	$y = 5 \cdot 10^{-11}x^5 - 10^{-7}x^4 + 0.0002x^3 - 0.0984x^2 + 27.396x + 2979.3$
Aug.	0.97	$y = 0.001x^2 - 0.706x + 114.66$	0.90	$y = 3 \cdot 10^{-9}x^4 - 7 \cdot 10^{-6}x^3 + 0.0069x^2 - 3.177x + 532.6$	0.68	$y = 10^{-13}x^6 - 4 \cdot 10^{-10}x^5 + 6 \cdot 10^{-7}x^4 - 5 \cdot 10^{-3}x^3 + 0.26x^2 - 64.86x + 6583.7$
2017						
Jun.	0.99	$y = 0.0009x^2 - 0.389x + 43.182$	0.97	$y = 0.0008x^2 - 0.5409x + 95.747$	0.95	$y = 7 \cdot 10^{-9}x^4 - 10^{-5}x^3 + 0.0111x^2 - 3.7501x + 460.55$
Jul.	0.98	$y = 0.0011x^2 - 0.601x + 84.91$	0.93	$y = 2 \cdot 10^{-6}x^3 - 0.0029x^2 + 1.235x - 170.53$	0.95	$y = 2 \cdot 10^{-11}x^5 - 6 \cdot 10^{-8}x^4 + 5 \cdot 10^{-5}x^3 - 0.0247x^2 + 5.5427x - 480.7$
Aug.	0.98	$y = 0.0008x^2 - 0.3668x + 19.659$	0.96	$y = 10^{-10}x^5 - 3 \cdot 10^{-7}x^4 + 4 \cdot 10^{-4}x^3 - 0.26x^2 + 76.6x - 8743.8$	0.89	$y = 3 \cdot 10^{-13}x^6 - 10^{-9}x^5 + 2 \cdot 10^{-6}x^4 - 0.0014x^3 + 0.6318x^2 - 145.22x + 13628$
2018						
Jun.	0.99	$y = 0.0014x^2 - 0.1653x + 4.0286$	0.96	$y = 5 \cdot 10^{-6}x^3 - 0.0022x^2 + 0.2459x - 7.9344$	0.97	$y = 4 \cdot 10^{-9}x^4 - 4 \cdot 10^{-6}x^3 + 0.0008x^2 - 0.0695x + 1.9875$
Jul.	0.96	$y = 0.0012x^2 - 0.4582x + 37.818$	0.92	$y = 10^{-6}x^3 - 0.0011x^2 + 0.2351x - 14.623$	1.00	$y = 0$
Aug.	0.97	$y = 0.0006x^2 - 0.2027x - 24.145$	0.97	$y = 9 \cdot 10^{-11}x^5 - 3 \cdot 10^{-7}x^4 + 4 \cdot 10^{-3}x^3 - 0.242x^2 + 72.218x - 8344.7$	0.91	$y = 3 \cdot 10^{-14}x^6 - 6 \cdot 10^{-11}x^5 + 5 \cdot 10^{-8}x^4 - 2 \cdot 10^{-5}x^3 + 0.0011x^2 + 0.4324x - 65.736$
2019						
Jun.	0.99	$y = 0.0011x^2 - 0.0774x + 0.5732$	0.97	$y = 3 \cdot 10^{-6}x^3 - 0.0009x^2 + 0.0836x - 2.034$	0.82	$y = 2 \cdot 10^{-9}x^4 - 2 \cdot 10^{-6}x^3 + 0.0004x^2 - 0.0317x + 0.7259$
Jul.	0.97	$y = 0.0011x^2 - 0.5107x + 60.184$	0.96	$y = 2 \cdot 10^{-6}x^3 - 0.0014x^2 + 0.4106x - 38.009$	0.98	$y = 6 \cdot 10^{-12}x^5 - 10^{-8}x^4 + 9 \cdot 10^{-6}x^3 - 0.0028x^2 + 0.4096x - 22.38$
Aug.	0.98	$y = 0.0011x^2 - 0.6131x + 83.598$	0.95	$y = 10^{-10}x^5 - 2 \cdot 10^{-7}x^4 + 2 \cdot 10^{-4}x^3 - 0.098x^2 + 20.386x - 1631.5$	0.8678	$y = 3 \cdot 10^{-14}x^6 - 6 \cdot 10^{-11}x^5 + 5 \cdot 10^{-8}x^4 - 2 \cdot 10^{-5}x^3 + 0.0011x^2 + 0.4324x - 65.736$

However, the saving in the energy consumption may not modify the number of FP cases of the family units of social dwellings due to the relation presented by FPR with respect to the incomes of the family unit and the energy price. For this reason, the variation presented in the FP cases in the dwellings analysed between the use patterns of air conditioning during all the day and the ventilation patterns through adaptive strategies was analysed (the ventilation during all the day was not considered as it is an hypothesis which would not imply cooling energy consumption, although it implies a risk in thermal discomfort hours). Fig. 15 shows the distributions of the FP cases in the various months analysed. The use of mixed-mode significantly reduced these cases. Category I (that with the lowest thermal adaptation) reduced the number of dwellings in FP between 13 and 16 for those family units with monthly incomes between 1 and 1.2 times the IPREM. Income values greater than 1.2 times the IPREM allowed the number of FP cases to be progressively reduced with Category I until almost reaching null values. The use of Categories II and III reduced more significantly the cases at FP risk, emphasizing Category III which for family units with incomes greater than 0.9 times the IPREM, FP cases were almost removed. These results showed the huge potential of using adaptive strategies in a thermal conditioning based on the exclusive use of air conditioning. The values of FP by using air conditioning contributed to more FP cases. However, the number of cases between the adaptive strategies and the exclusive use of air conditioning were coincident in the family units with incomes lower than 0.8 times the IPREM. In these cases, although the use of adaptive strategies reduced the energy consumption in comparison to the exclusive use of air conditioning, the monthly low income generated that the electricity bill exceeded the proportion of 10%. These family units would therefore face a situation of energy vulnerability even by using effective strategies of thermal conditioning during the summer months. To address this aspect, the use of financing strategies by social work bodies would be required to face the payment of the electricity bill. Regarding the relationship between the impact of the rook and the FP risk of adaptive strategies, the family units on ground floors presented a lower FP risk than those on the highest floor (see Fig. 16). In this regard, the family units on the highest floor are the reason of FP cases found in Categories II and III for family units with monthly incomes greater than 0.9 times the IPREM. The importance of an effective allocation of family units in dwellings is again emphasized, so family units with lower incomes are allocated on ground floors.

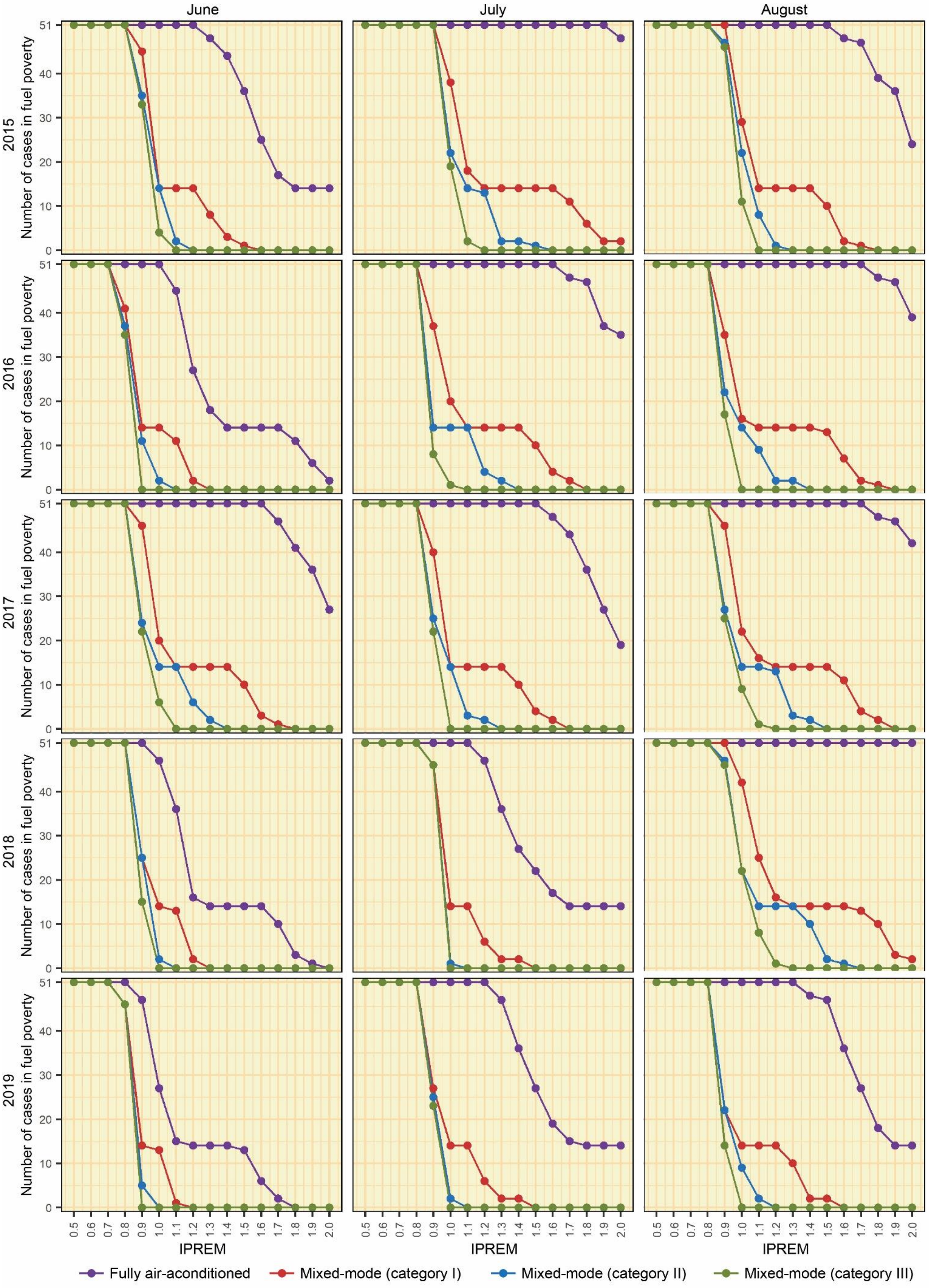


Fig. 15. Number of cases in fuel poverty risk according to the users' behaviour patterns and level of incomes. The value 51 corresponds to the total of dwellings analysed.

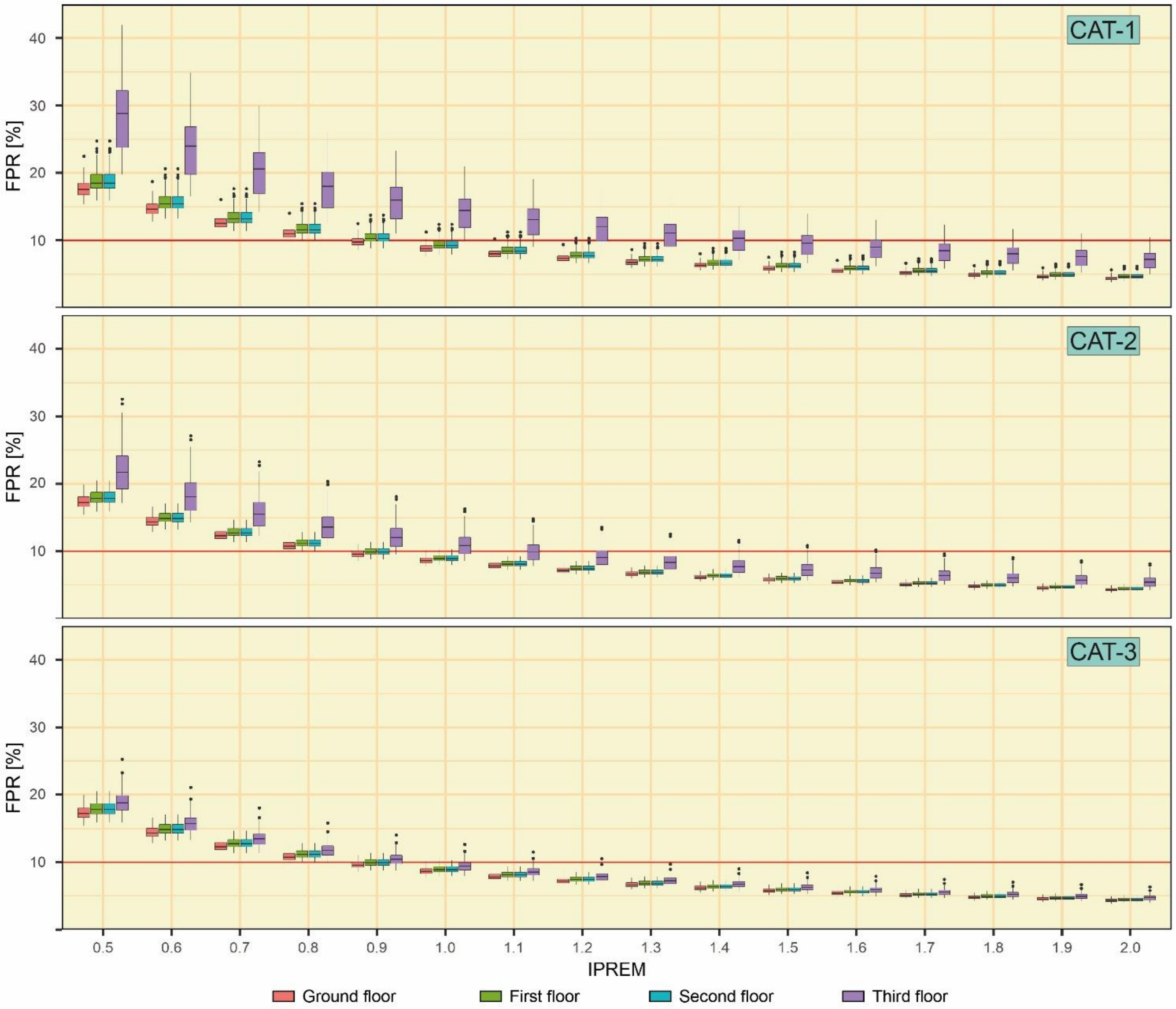


Fig. 16. Distribution of the values of fuel poverty ratio obtained by applying the mixed-mode based on adaptive thermal comfort models and organised per floors. The distributions grouped the results of June, July, and August in the 5 years analysed. The red line represents the line of 10%.

3.3 Possibilities of modifying the ventilation lines through tolerances

Ventilation strategies are useful to significantly reduce energy consumption and the value of FPR, so these strategies could improve the conditions of the family units with lower economic resources. However, ventilation strategies could be more developed in summer with outdoor temperatures lower than the lower limit of each adaptive thermal comfort model. For this reason, the effect of applying tolerances of 1, 2, and 3 ºC to the lower limit of each category was analysed (see Fig. 17). The application of tolerances to the lower limit of Categories I and II coincides with the lower limits of the upper categories. However, the upper limit to use cooling systems was not modified. This analysis therefore aims to show the effect of having a greater tolerance on the lower limit in the summer months to naturally ventilate the dwelling as it is possible to ventilate the dwellings when the outdoor temperature was below the lower limits. In this period (the summer months), the running mean outdoor temperature was always greater than 20 ºC, so the values of the lower limit were never lower than 17.5 ºC. Fig. 18 shows the point clouds between the energy consumption of the models without tolerance and that of the models with the lower limit increased. The distributions of the point clouds were practically coincident due to a minimum reduction of the energy consumption, although there was a greater effect of the increase of the lower limit on Category I. In this regard, the modification of the lower limit of the category implied an average decrease of 6.21, 10.59, and 14.66 kWh for the tolerances 1, 2, and 3 ºC, respectively, whereas in Categories II and III there were average decreases between 2.87 and 4.31 and between 0.27 and 0.31 kWh, respectively. Thus, users with a lower thermal adaptation could apply tolerances to the lower limit of thermal comfort for the natural ventilation of indoor spaces to decrease the cooling energy consumption. Regarding the influence of these tolerances on the FP cases, the reduction of cases was low (see Fig. 19). Category I recorded a greater decrease in the FP cases with values of up to 14 for the tolerance of 3 ºC, whereas in Category II, the greater number of cases was 10, and in Category II, 4. Likewise, in Category III, the application of a tolerance of 1 ºC achieved the greatest values of decrease, and the increase of the tolerance did not reduce the FP risk. Tolerances would therefore reduce the FP risk of family units. The implications of these tolerances could be hugely used in actual applications. According to users' thermal acceptability level, the application of these tolerances could significantly reduce the FP risk. Thus, family units with a lower thermal adaptation in summer because of the use of air conditioning systems could reduce the risk of being in FP by applying tolerances to the lower limit for the natural ventilation. Although the upper limit is more restrictive (e.g., Category I), the greatest ventilation produced by the tolerances in the lower limit would reduce the cooling energy demand of dwellings due to the free cooling.

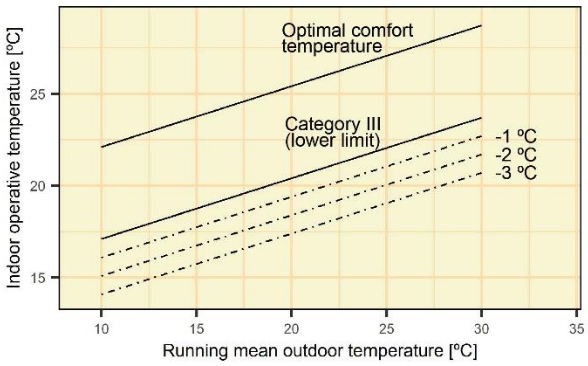


Fig. 17. Tolerances analysed regarding the lower limit for the natural ventilation of indoor spaces. The graph represents the example of Category III.

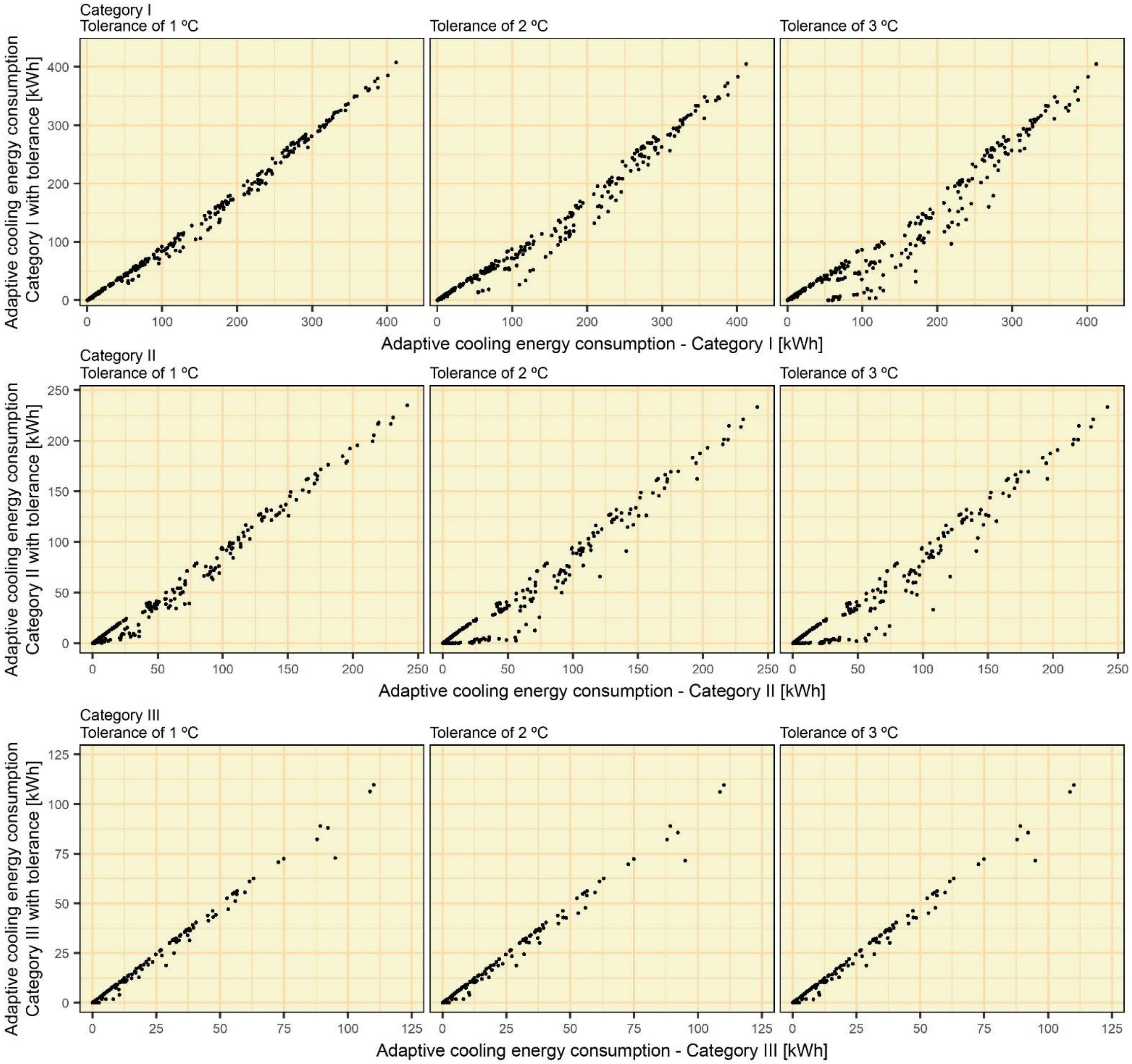
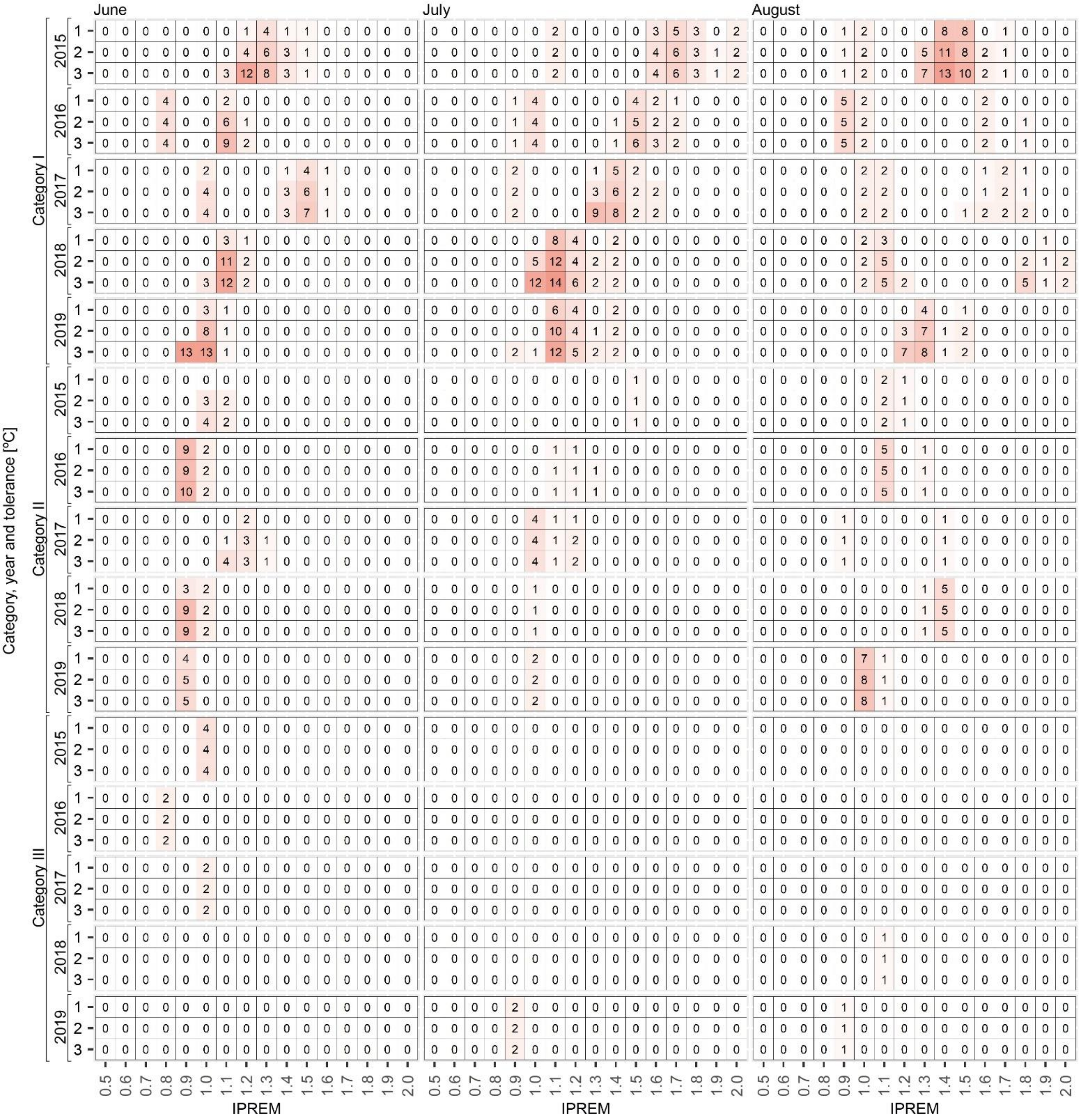


Fig. 18. Dispersion diagrams comparing the effect of increasing the lower limit by 1, 2 or 3 ºC in comparison to the ventilation approach based on both the optimal comfort temperature and the lower limit of each category.



June

Category	Year	Tolerance [ºC]	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Category I	2015	1	0	0	0	0	0	0	0	1	4	1	1	0	0	0	0	0
		2	0	0	0	0	0	0	0	4	6	3	1	0	0	0	0	0
		3	0	0	0	0	0	0	3	12	8	3	1	0	0	0	0	0
	2016	1	0	0	0	4	0	0	2	0	0	0	0	0	0	0	0	0
		2	0	0	0	4	0	0	6	1	0	0	0	0	0	0	0	0
		3	0	0	0	4	0	0	9	2	0	0	0	0	0	0	0	0
	2017	1	0	0	0	0	0	2	0	0	0	1	4	1	0	0	0	0
		2	0	0	0	0	0	4	0	0	0	3	6	1	0	0	0	0
		3	0	0	0	0	0	4	0	0	0	3	7	1	0	0	0	0
	2018	1	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	11	2	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	3	12	2	0	0	0	0	0	0	0	0
	2019	1	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	8	1	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	13	13	1	0	0	0	0	0	0	0	0	0
Category II	2015	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	4	2	0	0	0	0	0	0	0	0	0
	2016	1	0	0	0	0	9	2	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	9	2	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	10	2	0	0	0	0	0	0	0	0	0	0
	2017	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	1	3	1	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	4	3	1	0	0	0	0	0	0	0
	2018	1	0	0	0	0	3	2	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	9	2	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	9	2	0	0	0	0	0	0	0	0	0	0
	2019	1	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0
Category III	2015	1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0
	2016	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
	2017	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
	2018	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2019	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

July

Category	Year	Tolerance [ºC]	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Category I	2015	1	0	0	0	0	0	0	2	0	0	0	0	3	5	3	0	2
		2	0	0	0	0	0	0	2	0	0	0	0	4	6	3	1	2
		3	0	0	0	0	0	0	2	0	0	0	0	4	6	3	1	2
	2016	1	0	0	0	0	1	4	0	0	0	0	4	2	1	0	0	0
		2	0	0	0	0	1	4	0	0	0	1	5	2	2	0	0	0
		3	0	0	0	0	1	4	0	0	0	1	6	3	2	0	0	0
	2017	1	0	0	0	0	2	0	0	0	1	5	2	0	0	0	0	0
		2	0	0	0	0	2	0	0	0	3	6	2	2	0	0	0	0
		3	0	0	0	0	2	0	0	0	9	8	2	2	0	0	0	0
	2018	1	0	0	0	0	0	0	8	4	0	2	0	0	0	0	0	0
		2	0	0	0	0	0	5	12	4	2	2	0	0	0	0	0	0
		3	0	0	0	0	0	12	14	6	2	2	0	0	0	0	0	0
	2019	1	0	0	0	0	0	0	6	4	0	2	0	0	0	0	0	0
		2	0	0	0	0	0	0	10	4	1	2	0	0	0	0	0	0
		3	0	0	0	0	2	1	12	5	2	2	0	0	0	0	0	0
Category II	2015	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	2016	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
	2017	1	0	0	0	0	0	4	1	1	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	4	1	2	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	4	1	2	0	0	0	0	0	0	0	0
	2018	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	2019	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Category III	2015	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2016	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2017	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2018	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2019	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0

August

Category	Year	Tolerance [ºC]	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
Category I	2015	1	0	0	0	0	1	2	0	0	0	8	8	0	1	0	0	0
		2	0	0	0	0	1	2	0	0	5	11	8	2	1	0	0	0
		3	0	0	0	0	1	2	0	0	7	13	10	2	1	0	0	0
	2016	1	0	0	0	0	5	2	0	0	0	0	0	2	0	0	0	0
		2	0	0	0	0	5	2	0	0	0	0	0	2	0	1	0	0
		3	0	0	0	0	5	2	0	0	0	0	0	2	0	1	0	0
	2017	1	0	0	0	0	0	2	2	0	0	0	0	1	2	1	0	0
		2	0	0	0	0	0	2	2	0	0	0	0	1	2	1	0	0
		3	0	0	0	0	0	2	2	0	0	0	1	2	2	2	0	0
	2018	1	0	0	0	0	0	2	3	0	0	0	0	0	0	0	1	0
		2	0	0	0	0	0	2	5	0	0	0	0	0	0	2	1	2
		3	0	0	0	0	0	2	5	2	0	0	0	0	0	5	1	2
	2019	1	0	0	0	0	0	0	0	0	4	0	1	0	0	0	0	0
		2	0	0	0	0	0	0	0	3	7	1	2	0	0	0	0	0
		3	0	0	0	0	0	0	0	7	8	1	2	0	0	0	0	0
Category II	2015	1	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
	2016	1	0	0	0	0	0	0	5	0	1	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	5	0	1	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	5	0	1	0	0	0	0	0	0	0
	2017	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
		2	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
		3	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
	2018	1	0	0	0	0	0	0	0	0	1	5	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	1	5	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	1	5	0	0	0	0	0	0
	2019	1	0	0	0	0	0	7	1	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	8	1	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	8	1	0	0	0	0	0	0	0	0	0
Category III	2015	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2016	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2017	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2018	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	2019	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		3	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

Fig. 19. Heatmap with the number of cases of fuel poverty risk obtained with the various natural ventilation approaches according to Category III from EN 16798-1:2019.

3.4 The perception of the ventilation strategies by family units living in coastal cities of southern Spain

Natural ventilation strategies are an opportunity to improve the energy performance of the dwellings in coastal zones of southern Spain and to reduce the FP risk of the family units with lower resources. However, the perception of the natural ventilation and the use of air conditioning should be analysed. A total of 541 family units that live in the coastal zones of southern Spain were surveyed. The survey was composed by 6 simple questions to assess their strategies to acclimatize the indoor space and their perception of the need for using air conditioning (see Fig. 20). There was a greater predominance of family units with air conditioning (57%) than those without air conditioning (43%). However, their use was limited to certain hours of the day so as not to excessively use it. In this regard, users tended to use air conditioning mainly during the hottest hours of the day (65%), whereas the remaining 35% increased their use also at night. Users were therefore aware of the need of using air conditioning in a limited way to reduce the energy consumption of their dwelling.

Regarding the ventilation strategies, there was a huge practice of natural ventilation as 98% of those polled usually open the windows to ventilate their dwellings. However, the criterion to ventilate them was not always associated with the thermal conditioning, since 17% of users ventilated their dwelling to improve the air quality and to avoid moistures (due to the many cases of condensations in the dwellings of these regions), whereas the remaining 83% also included the perception of improving thermal comfort by this strategy. None of users considered that the only criterion to ventilate the dwelling was due to thermal comfort, as other aspects were also considered important for ventilation, such as the air quality. In view of the use of natural ventilation, the perception of the possible need of users without air conditioning of not investing in an air conditioning system could be emphasized. In this regard, 59% considered not necessary to buy an air conditioning system, and 63% considered that, with natural ventilation and the use of adaptive techniques such as electric ventilators, they could take heat adequately without using air conditioning. However, a full natural ventilation during all the summer months could achieve many thermal discomfort hours, which should be treated by the complementary use of air conditioning systems. Although 59% of those polled did not consider necessary to buy an air conditioning system maybe because their thermal expectations are very similar to Category III, other factors such as habits or daily rules could be the reason as they contributed to a lower perception of the need for using air conditioning. In the coastal zones, beaches could contribute to the fact that users occupy their dwellings during a lower number of hours in these periods. However, recent confinement events, such as the case of the coronavirus pandemic, have shown that lower use patterns of the dwelling do not guarantee that family units are in lower energy vulnerability as they should occupy their dwelling more time under these circumstances. The results of the surveys also showed the possible variability presented by FP in coastal zones and the strategies of energy analysis usually used, as the actual use of air conditioning systems could be different due to the possible resilient strategies of users or to the fact of not having heating or cooling systems. In these cases, the use of operational profiles of air conditioning systems, such as the residential profile used in the energy certification tools or to justify the energy regulation in Spain, did not constitute the most appropriate profile to assess the FP cases in these regions. Nonetheless, ventilation strategies do not guarantee an appropriate thermal comfort of indoor spaces, so it could be a risk for health. The combination of natural ventilation strategies with a low use of air conditioning systems (based on adaptive setpoint temperatures) ensured a low impact of the cooling energy consumption on FP cases. In this manner, those users with a greater need for using air conditioning systems used them effectively. The profiles of operational conditions of air conditioning systems during all day analysed in this study used effective static setpoint temperatures (25 and 27 ºC according to the hour of the day). However, these setpoint temperatures could not be always used by users, thus using lower setpoint temperatures that generated a greater energy consumption. In addition, an intelligent allocation of the family units with lower resources on the lower floor could ensure a lower number of FP cases.

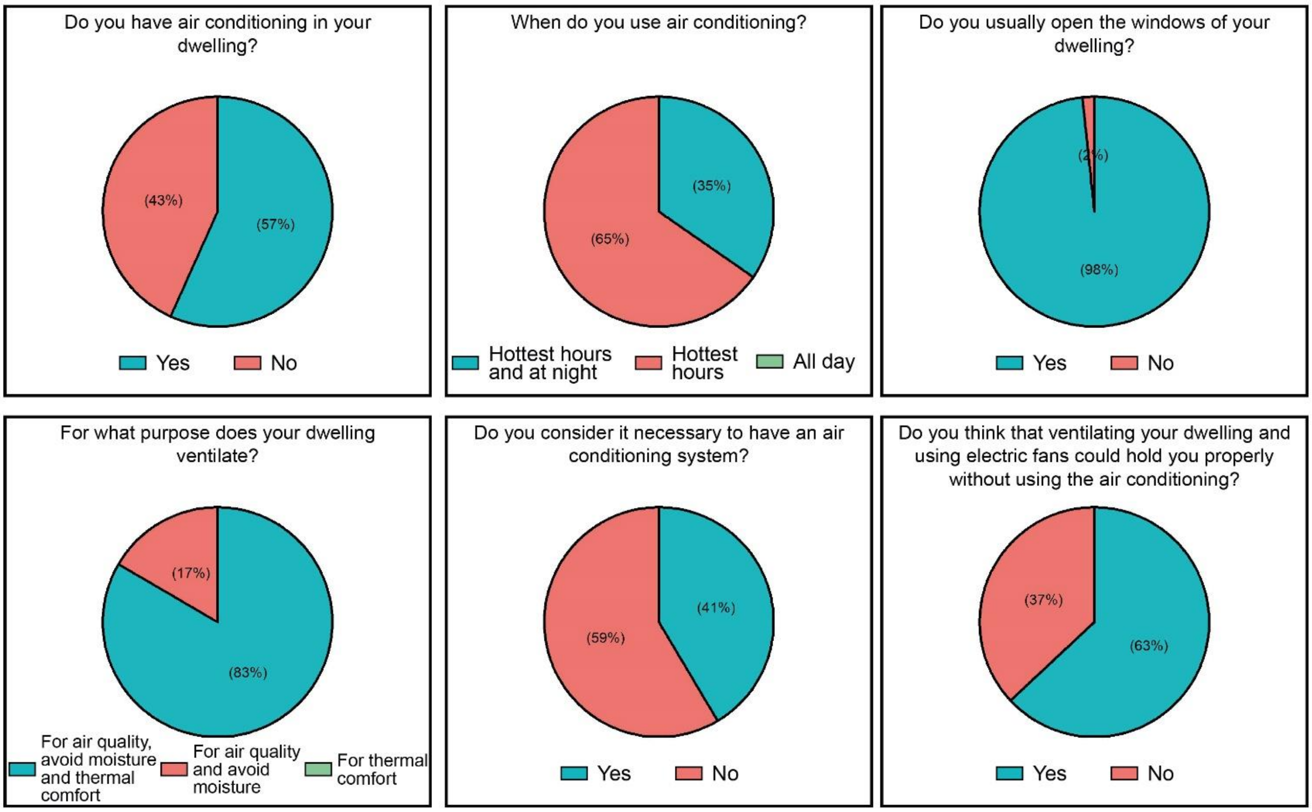


Fig. 20. Results of the survey for users of dwellings located in coastal cities of the south of Spain.

3.5. Natural ventilation strategies to reduce the cooling energy consumption in countries in southern Europe

The international context of the results was analysed. This analysis was based on the similarity of the climate conditions of coastal zones to the application of the adaptive thermal comfort models, thus determining the similarity of the climate conditions of the city analysed (Cadiz) to other coastal cities. However, these similarity patterns would show the potential of energy saving obtained in the research, whereas the reduction of cases of FP (as other factors such as the level of incomes or the energy prices of each region could be involved) could show differences

Fig. 21 summarizes the results obtained in the climate analysis process. The four variables to apply the adaptive thermal comfort models could be classified into three clusters. The city of Cadiz was included in the clusterswith a larger number of cities in most variables. Only in the case of natural ventilation of category III, the city was grouped in a cluster with a lower number of cities. In the case of the percentage of days in which the adaptive model could be applied, most coastal cities had similar and coincident percentages of application to the city of Cadiz, thus implying that the percentages of application of the adaptive model were greater than 90% of the days of the summer months. However, the similarity among countries was less homogeneous in the case of the possibility of applying natural ventilation. In this case, three clusterswere created in the coastal cities. Cadiz was grouped in the densest clustersof categories I and II. These clusters comprised cities from all the countries considered in the climate analysis. Thus, these zones would meet similar conditions to apply adaptive thermal comfort models according to that analysed in the research. In addition, greater savings could be obtained in other regions because the centroid of the clusters of Cadiz did not have the greatest value of application of natural ventilation: (i) as for category I, the cluster of Cadiz had a centroid of 22.8%, and cluster 2 had a centroid of 30.35% of the hours of summer; (ii) as for category II, the cluster of Cadiz had a centroid of 32.80%, and cluster 3 had a value of 41.72%; and (iii) as for category III, the cluster of Cadiz had a centroid of 42.59%, and cluster 2 had a centroid of 53.58%. A greater application of natural ventilation would therefore be possible in these other clusters, thus achieving a greater saving in the building energy consumption.

Thus, the international character of the results was notable. The similarity between the possibility of application of the adaptive thermal comfort model from EN 16798-1:2019 of the study zone (Cadiz) to many coastal cities of the countries in southern Europe would allow natural ventilation to be considered to reduce building energy consumption. Several studies have showed both the possible limitations related to the implementation of nearly zero energy consumption buildings in the countries in southern Europe [93] and the possible vulnerability in these regions due to the progressive increase of the outdoor temperature because of climate change [94]. The possibility of implementing the natural ventilation strategy to acclimatize indoor spaces would reduce the energy consumption in the existing buildings of the coastal zones from these countries and ensure a greater resilience of users. In addition, these strategies would reduce one of the variables considered in the FP risk of family units: energy consumption. Thus, these strategies could be an actual opportunity to establish policies and measures to reduce cases of FP, although these measures also depend on the economic and cultural characteristics of each countries and on the evolution of the energy prices. Finally, the use of automation processes and the development of applications would allow natural ventilation strategies to be more and correctly applied in existing buildings.

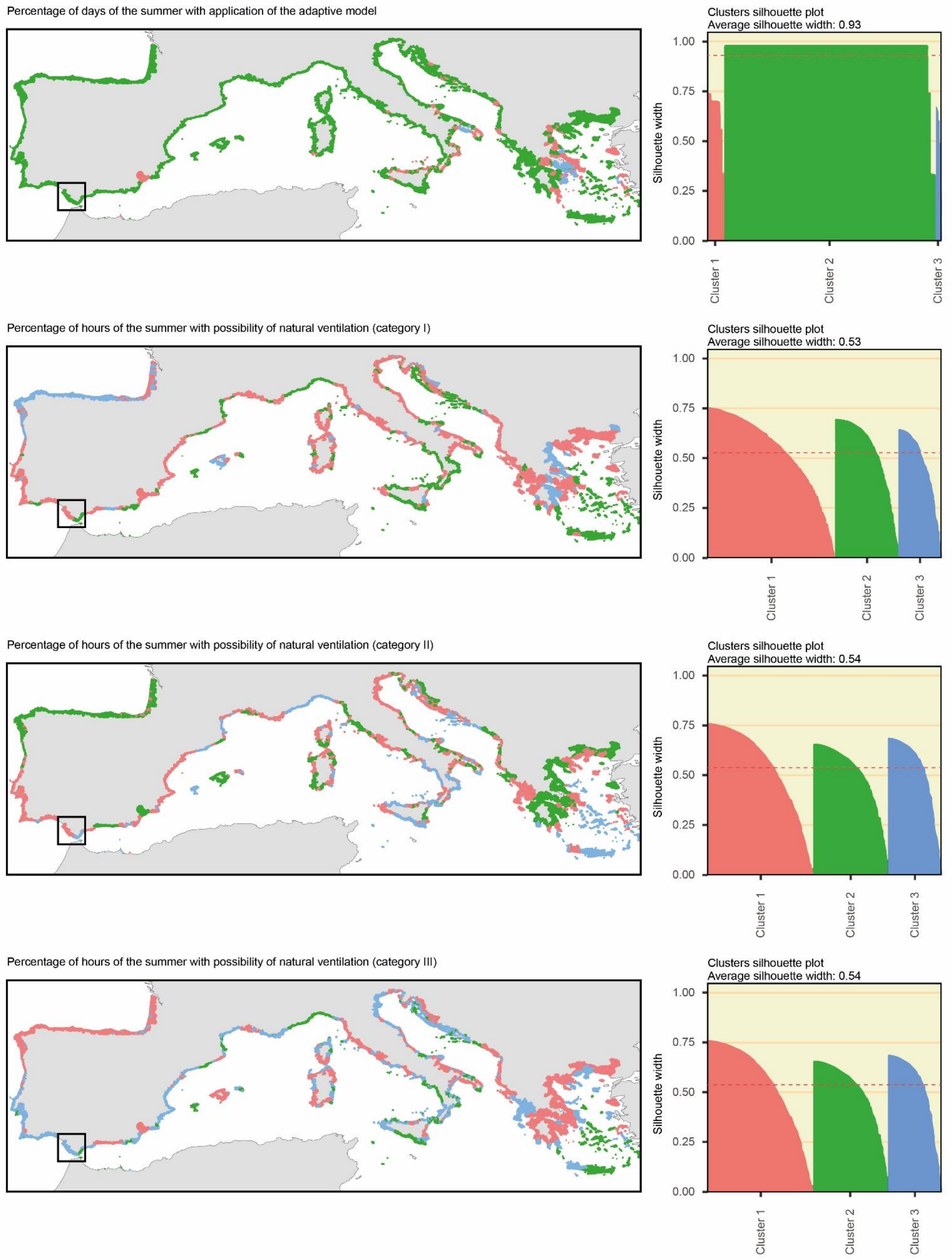


Fig. 21. Clusters in the coastal cities of the countries in southern Europe according to the application of the adaptive thermal comfort models and the natural ventilation strategies of the categories from EN 16798-1:2019. The spatial distribution of clusters is shown on the left, and the values of the silhouette index on the right.

4. Conclusions

The fuel poverty is recognised by official bodies in Spain as a social issue to be addressed. However, the great variability of factors among regions differentiating them (economic, social, and climate factors, among others) makes the development of detailed analyses and the establishment of corrective measures something of a challenge. The use of natural ventilation strategies in summer could present a greater potential of use in coastal than in internal zones [41]. For this reason, this research analyses quantitatively and qualitatively the impact of the natural ventilation on the decrease of the fuel poverty of family units living social dwellings located in the coastal zones of the South of Spain. The analyses were performed by using an actual case study of 51 social dwellings. The effect of considering three behaviour patterns by users in the summer months was analysed: (i) the exclusive use of air conditioning, (ii) natural ventilation during all day; and (iii) mixed-mode based on the categories from EN 16798-1:2019. The results showed that a thermal conditioning based on the exclusive use of air conditioning, despite guaranteeing 100% of the thermal comfort hours in the summer months, increased the amount of the electricity bill which is unacceptable by most family units living in social dwellings. Likewise, the use of a natural ventilation during all day, despite eliminating the energy consumption of air conditioning systems, implied a number of thermal discomfort hours which could be high if users have a low thermal adaptation. The balance between 100% of thermal comfort hours and a low amount of the electricity bill is by using the mixed-mode based on the three categories included in the European standard. The use of these strategies significantly reduces the cases of fuel poverty with respect to the static use patterns of air conditioning systems.

Unlike other behaviour strategies by the users of the dwellings, such as the modification of setpoint temperatures, natural ventilation is a strategy of which users are aware. However, the criteria for the need of this ventilation were not always related to the thermal comfort, since in many cases users perceived that the criterion to ventilate their dwelling was to guarantee a better indoor air quality. Likewise, the low perception of the importance of using air conditioning could be based on social criteria or habits, such as occupying their dwelling a lower number of hours. However, in confinement events forcing them to stay a greater number of hours in their dwelling lead to an inappropriate use of it and in turn a greater number of thermal discomfort hours. Through the effective ventilation strategies analysed in this research, it could be guaranteed that users condition correctly the indoor spaces of their dwelling with a minimum use of air conditioning.

Likewise, the results of energy saving obtained could be extrapolated to other coastal zones of the countries in the south of Europe. The climate analysis by applying the adaptive thermal comfort model verified that the climate conditions of the zone analysed were grouped with a high percentage of cities in the coastal zones of Portugal, France, Spain, Italy, Greece, Croatia, Albania, and Montenegro. This extrapolation of results to other regions is in relation to the saving in the energy consumption because the reduction of the fuel poverty risk will depend on other factors such as the sociocultural factors of each region, the richness level of family units, and the price of the electricity bill.

To conclude, the results are also useful to show the possible limitations of the analysis of fuel poverty by operational patterns of the use of standardized air conditioning systems and the need for including in these analyses the possible resilient capacities of the most vulnerable family units. Nonetheless, the results did not consider the possible influence of the sociocultural characteristics of the family units of social dwellings and the possible differences among regions. Although it is clear that the acclimatization with mixed-mode could generate a lower number of cases of fuel poverty, the development of various profiles of occupancy and development of limits of adaptive thermal comfort adapted to the users of these dwellings would allow the efficiency of ventilation strategies to be more accurately analysed.

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