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# Development of climate-based thermal comfort ranges from existing data: Analysis of the Smart Controls and thermal comfort (SCATS) database

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ABSTRACT

Despite the multifaceted nature of notion of thermal comfort, designers have embraced a very strict definition of it, which consists of very tight and static environments, were transition and stimuli are not admitted, and with very narrow ranges of microclimatic parameters required equally for all the subjects. This neglects all the potential implications related to different users. However, when it comes to thermal comfort, the long-term history of subjects and their climatic background play a pivotal role towards their own thermal sensations and preferences. In this work, to address these diversities, the authors analysed the existing database of the Smart Controls and Thermal Comfort (SCATS) project, which was built from monitoring and survey campaigns conducted in the late 90s in five different European countries. Data were studied by means of statistical techniques to grasp and define the potential combined influence of climatic location, seasonal variations, subjective variables and ventilation modes on the occupants' thermal feeling and preference. Different scenarios recommended by standard EN 16798 were tested to address the differences in the thermal feelings of users living in different European countries. Finally, country-based operative temperatures that optimize users' thermal feeling and preference were determined. Results highlight that users in different countries differently evaluate indoor thermal parameters both in terms of thermal feeling and thermal preferences. This results in differences among countries for acceptability levels associated with standardised indoor conditions. Furthermore, the results highlight the importance of air movement to improve acceptability at higher indoor temperatures for all the countries.

## 1. Introduction

The term "comfort", according to ASHRAE Standard 55 [1], indicates that "condition of mind that expresses satisfaction with the thermal environment". Linking the definition to a "state of mind" already implies a certain degree of complexity, which is just the tip of an iceberg constituted of multidisciplinary aspects that include engineering, architecture and building physics, social sciences, psychology, physiology, and anthropology. Due to this polyhedric nature, the very notion of comfort has evolved through time and history, being the result of various cultural, social, technological, and economic changes and influences. Focusing on thermal comfort, which together with air quality is considered to be the most significant contributor to the overall user satisfaction in indoor environments [2], it is codified in standards by zones characterized by strict ideal conditions (thermal and personal parameters) that should match with a condition of neutrality equal for all the users. Of course, standards must deal with controllable or predictable parameters, but nevertheless subjects are intrinsically different, flexible, with a background of preferences and habits that result in a far more complex situation: indoor environments can be richer experiences than merely neutrality, providing valuable sensory stimulations to users. On the contrary, as stated by Brager and de Dear [3], the engineering ideal notion of comfort implies an absence of sensation, striving to create indoor environments that never vary over time or space, purposely creating a "sensationless, thermal Nirvana" [4]. This misconception has eventually led to the current common notion of indoor environment for air-conditioned buildings: very tight and static environments, where transition and stimuli are not admitted, with very narrow ranges of microclimatic parameters to be maintained equally for all the subjects. This despite that the desired sensation of users in buildings is often other than 'neutral' [5].

As explained by Brager and de Dear [3], when it comes to users'

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adaptation three main mechanisms are key: i) physiological acclimatization, namely changes in physiological responses, physiological set points and gains for controlling shivering, skin blood flow and sweating; ii) psychological adaptation, i.e. changes in one's perception and reaction to sensory information; iii) behavioural adjustment, which is all the conscious actions taken by the user such as altering clothing, eating cold or hot food, and using fans.

If we consider the adaptation mechanisms as a set of strategies implemented, consciously or not, by the user to improve the thermal experience, we must then include the concept of user's expectation as a key parameter toward thermal acceptability and satisfaction. Another work from the authors [6] highlights by means of a literature review all the factors that contribute to subjects' adaptation and expectation in the indoor environment. Defined by P.O. Fanger as the 7th parameter in the heat balance model of thermal comfort [7], expectation is a complex combination of many factors like one's climate history, social understanding, cultural differences, demographics, education, economic level, and others. This parameter has so far been completely neglected in the design of buildings, construction, and operation: in the general strain for energy efficiency, functionality and overall Indoor Environmental Quality (IEQ), thermal imperceptibility is targeted, and the absence of any perceptible stimuli is demanded, aiming to an ideal repeatable standardized format. However, this has demonstrated not to be the optimal solution. In the work by Arens et al. [8], it is highlighted how with this standard of indoor environments there has not actually been a commensurate increase on building occupants' thermal satisfaction, and moreover it takes more energy to maintain a narrow indoor temperature range than a broader one. Thermal acceptability is a relative judgment, and results presented by Maohui Luo et al. and by Humphreys and Hancock [9,5] show how it does not necessarily occur at "neutral" thermal sensations. In addition to this, findings from other works [9–13] suggest that thermal comfort perception is closely related to peoples' long-term thermal history and that residents from different climates are likely to adapt over time to the thermal conditions in their new environment. Users' background can shape their expectations and attitudes through time and space, shaping their judgement and acceptation over the thermal indoor environment, and comfort temperatures are likely to be influenced by recently experienced climate conditions [14]. Residents moving into different climates are likely to adapt over time however, comfort expectations do not have symmetric dynamics and it is easier to lift building occupants' expectations than lower them [12]. Moreover, a prolonged exposure to air-conditioned environments and to static and narrow ranges of indoor microclimatic parameters may weaken people's physiological adaptability and their natural ability to deal with climatic changes, affecting the ability of the thermoregulatory system [10].

All these aspects are often neglected, and users' diversities, specificities and needs related to their climatic and socio-cultural background are usually not accounted for.

According to thermal comfort theories, two main comfort approaches are internationally well known and accepted for assessing indoor conditions: i) the adaptive model and ii) the PMV/PPD model. The latter, developed by P.O. Fanger and based on the heat balance of the human body, is meant for air-conditioned indoor environments and implies a very strict control of thermal parameters, with narrow and constant conditions that do not reflect the variability in users' perception, it is regardless of the external climate diversities and does not account for adaptation mechanisms. On the other side, the adaptive model is meant for naturally ventilated buildings, and it is based on the outdoor running mean temperature. It considers users' adaptability to various environments, accounting for transient and dynamic indoor conditions and attempts to address diversities in users' interactions.

But when it comes to design, inputs and operation requirements prescribed by standards and guidelines, both at European, U.S. and international level, do not account for climatic differences neither other diversity factors, limiting the actual significance and usability of the proposed criteria and requirements. This subsists for all the four aspects of comfort (thermal, visual, acoustic, and air quality), but it is much more evident on the thermal environment, where users' preferences (linked to expectation) are demonstrated to be strongly affected by users habits, climate, and most implemented technologies [6].

In this work, the aim was to investigate and prove the existence of potential differences in users' subjective sensations, needs and preferences, for what concerns the thermal environment, accounting for their geographical and thus climatic location, and long-term habituation mechanisms. The driver hypothesis was that users, accustomed to living in a context with a specific climate, have different heterogeneous sensations, preferences and expectations, which cannot be matched with unique neutral indoor temperature. In addition, they get the habit of a specific way to control the indoor environment, so their expectations usually tend towards that specific condition or better. In this perspective, a statistical analysis was conducted on the Smart Controls and Thermal Comfort (SCATS) database [15], which was built and used for the development of the Adaptive Control Algorithm (ACA).

Following section **1. Introduction**, where an overview of the state-of-the-art is offered together with the premises and assumptions for this work, in section **2. Dataset**, the dataset used for this work is presented and described. In section **3. Statistical methodology**, an overview of the statistical model implemented for the analysis is offered. In section **4. Results and discussion**, the outcomes of this analysis are shown for the various research questions addressed by this work, together with the assistance of dedicated tables and figures. Finally, in section **5. Conclusions**, the major outcomes of this work are outlined, with some insights and recommendations for further research in this field.

## 2. Dataset

As mentioned, this work is based on the analysis of the SCATS database, which is the analytical base of the adaptive comfort model developed by Nicol and Humphreys [16]. Nicol and Humphreys, in the early 1970s, challenged the 'steady-state' notion of comfort with the introduction of the adaptive comfort theory [17]. According to the adaptive principles, building occupants are likely to adapt to their environment either by adjusting clothing, controls or location, so as that they could tolerate environmental conditions outside those recommended by 'steady-state' theories, and hence the current common thermal comfort standards [18]. According to Nicol and Humphreys, adaptation to the thermal environment is a key factor in the interpretation of thermal comfort data from users. The mechanisms of adaptation create a self-regulating system which tends to produce a condition of thermal comfort [17].

The Smart Controls and Thermal Comfort project [15] was conducted from December 1997 to December 2000, and it was designed around the adaptive assumption of thermal comfort. As it is stated in the project's final report [19], the driving goal of the task was to reduce energy consumption in air-conditioned buildings and to encourage the implementation of naturally ventilated ones through the development of control systems for indoor temperature accounting for the adaptive effect. For the scope, microclimatic monitoring campaigns and subjective surveys were conducted in both "Air Conditioned" and "Naturally Ventilated" buildings, between five and six buildings for each involved country. Overall, about 850 subjects were involved over the 12 months of surveys. The five assessed countries consist of Greece and Portugal in

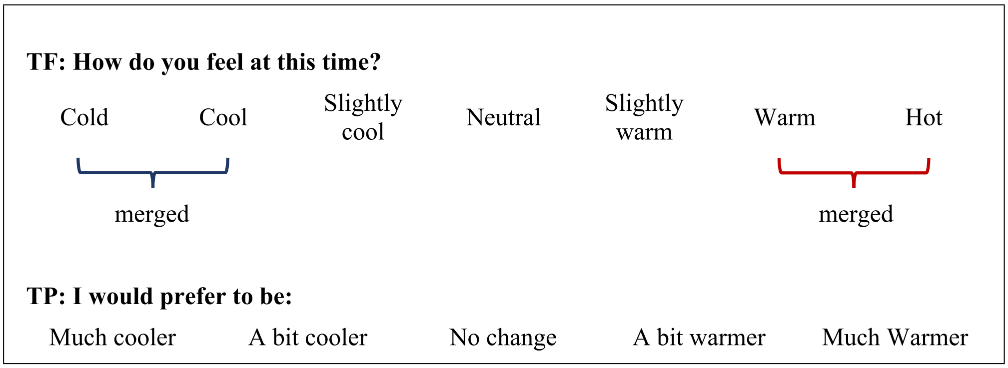


**Fig. 1.** Thermal Feeling (TF) and Thermal Preference evaluation scales used in the SCATs database project's survey. Braces indicate the votes merged for the analysis of this paper.

the Mediterranean Climate with 5 buildings each, France and United Kingdom in the Oceanic climate with 5 and 6 buildings respectively, and Sweden in the Sub-arctic with 5 buildings, for a total number of 26 surveyed facilities.

### *2.1. Dataset for the analysis*

Buildings were categorized according to their ventilation mode, namely NV = naturally ventilated (heating in winter, free-running - no cooling or mechanical ventilation - in summer), AC = centrally air conditioned, (heating and cooling), MV = mechanically ventilated (no cooling in summer: this was excluded in our analysis due to the peculiarity of the system and to the small sample), MM = mixed mode (Heating in winter, cooling when needed in summer), PP = a mixture of AC and NV in the same building. To better frame our analysis in a contest of users accustomed to similar indoor conditions, we categorized the building systems according to the summer cooling mode: on one side AC, MM, and PP buildings were merged in a unique category, i.e., MC as for Mechanically Conditioned, on the other side NV ones constituted separately the Naturally Ventilated set (i.e., NV). Users in MM buildings may experience slightly different thermal feelings compare to users in either AC or NV buildings [20–22], but since we do not have information on the control logics driving the mechanical cooling operation, and since both ASHRAE Standard 55 and EN 16798-1 [23] make a clear distinction between building with and without mechanical cooling for the application of the adaptive model, in line with the scope of this work, we decided to put answers coming from MM buildings together with AC and PP.

Finally, to achieve higher accuracy in the results, data have been limited to summer and winter seasons.

For the scope of this work, measured parameters for the indoor environment included air temperature ($t_{ai}$, °C), calculated operative temperature ($t_{op}$, °C), relative humidity (RH, %), air velocity ($v_{air}$, m/s), and personal parameters as the metabolic rate (MET) and the clothing level (CLO). For what concerns the latter two personal parameters, MET and CLO were assessed by the authors of the SCATS database by means of self-reported checklist and self-reported amount of time per listed activities, respectively. Due to the wide range of MET values in the sample, it was decided to limit the analysis to $0.8 \leq \text{MET} \leq 1.5$, to avoid higher rates that could strongly affect the reliability of the thermal comfort analysis.

Regarding the subjective responses, the ones coming from the SCATS transverse survey [24] were used for this analysis since, compared to the longitudinal one, this data collection is the most complete in terms of questions and measured parameters. Questionnaires were conducted from June 1998 to September 1999. Considering the research aim, from the sample of questions the two regarding the Thermal Feeling (TF) and Thermal Preference (TP) were used. The TF and TP votes are assessed in the SCATS questionnaire by means of a 7-points scale (1-Cold to 7-Hot, 4-Neutral) and a 5-points scale (1-Much warmer to 5-Much cooler, 3-No change), respectively, as shown in Fig. 1. However, regarding the TF votes, due to the small number of votes on the extreme poles of the scale, it was considered statistically appropriate (see section 3) to merge the votes Cold and Cool, and Warm and Hot.

The final dataset of subjective responses is summarized in Table 1.

Considering the final dataset, the aim of the analysis conducted in this work was to firstly investigate the potential existing connections between indoor microclimatic measures and point-in-time subjective responses, in order to point out the potential combined effect of the climatic location, seasonal variation, ventilation mode, air motion, metabolic and clothing patterns on the occupants' subjective thermal feeling and preferences, according to their geo-climatic background.

Secondly, the TF and TP of users were assessed for what concerns indoor operative temperature inputs as implemented by the EN 16798 [23]. As a final goal, the indoor operative temperature values that optimize the TF and TP of users were predicted by the model, opening for subjects' climatic background as an additional parameter affecting comfort expectations and perception.

In order to do this, a statistical model was specifically elaborated for this work and trained using R Software [25], as explained in the following section.

Using ERA5 data, we summarize the mean monthly temperatures over the period 1991–2020 in the five investigated countries (see appendix A).

## 3. Statistical methodology

Thermal Feeling and Thermal Preference are modelled in the subsequent sections with cumulative logistic regression [26]. Before giving a brief description of this popular class of statistical models, it is important to highlight how the simplistic practice of giving numerical scores to the levels of an ordinal response and then use linear regression

**Table 1**
Final dataset used for statistical analysis.

| Variable | | Number of responses | Share of the overall sample |
|---|---|---|---|
| Country | France | 108 | 8% |
| | Greece | 58 | 4% |
| | Portugal | 471 | 36% |
| | Sweden | 229 | 17% |
| | UK | 454 | 34% |
| **Season** | Winter | 687 | 52% |
| | Summer | 633 | 48% |
| **Ventilation mode** | MC | 951 | 69% |
| | NV | 434 | 31% |
| **Gender** | Male | 753 | 57% |
| | Female | 567 | 43% |

has various serious drawbacks that are well-known in statistical literature.

In his popular reference textbook about ordinal categorical data, Agresti [26] identifies four recommended reasons against the use of linear regression for ordinal response scores. The first drawback is that the results of linear regression depend on the choice of the numerical scores. Very often the numerical scores are based on some untestable assumption of equal distance between the levels. In this case, the same "distance" is assumed between the scores used for thermal feelings "neutral" and "slightly cool" and between the scores for thermal feelings "slightly cool" and "cool", resulting in coding thermal feeling levels with scores $-2; -1; 0; 1; 2$. However, when this assumption is wrong, it might yield misleading statistical conclusions. A second drawback is that linear regression does not give estimated probabilities for the response levels as a function of the covariates. The third drawback is lack of guarantee that fitted or predicted values could be above the highest level of the response or below the lowest one. The last drawback is that linear regression assumes that the variability of the responses is constant whereas there is typically little variability at the levels that are observed with higher probability and large variability at the levels that are less frequently observed. This strong homogeneity assumption is also a source of misleading statistical conclusions. Agresti [26] gives a numerical illustration of the incorrect results that can be obtained using linear regression with ordinal response scores.

Proper statistical analysis of ordinal response variables requires methodology designed for responses measured on an ordinal scale. Cumulative link models are perhaps the most popular statistical approach for studying the relationship between an ordinal response variable and a set of covariates. Cumulative link models also use numerical scores for the ordinal response levels, but the statistical results are invariant with respect to the specification of the scores (as long as the numerical scores are ordered). Furthermore, cumulative link models naturally consider the different amount of variability in the response levels.

Let us denote with Y the numerical score of an ordinal response and with $x_1, \cdots, x_p$ the covariates. As usual, the categorical covariates with n levels are coded using n-1 binary variables. Without loss of generality, Y assumes values in the set {1, 2, …, k}, where k is the number of levels (in our application we have k = 5 for both Thermal Feeling and Thermal Preference). Proportional-odds cumulative logit models assume that the cumulated probabilities are

$$g\{\Pr(Y \leq r)\} = \alpha_r - \beta_1 x_1 - \cdots - \beta_p x_p, r = 1, \cdots, k-1$$

where $\alpha_1 \leq \alpha_2 \leq \cdots \leq \alpha_{r-1}$ is a sequence of ordered level-specific intercepts, $\beta_1, \cdots, \beta_p$ are the regression coefficients and $g(x) = \log[x/(1-x)]$ is the logistic function. The model is specified for the first r-1 levels of Y: the last level is obtained from the condition that the probabilities must sum to one. The regression coefficient $\beta_j$ describes the effect of the covariate $x_j$: positive values for $\beta_j$ indicate that an increase of covariate $x_j$ is associated with an increase of the probability of higher levels for the response y, negative values are vice versa associated with an increase of the probability of lower levels for the response y. See Agresti [26] for technical details and references about cumulative logit models. In our analyses discussed in the next section, the vector of model parameters $\theta = (\alpha_1, \cdots, \alpha_{r-1}, \beta_1, \cdots, \beta_p)$ is estimated using the method of maximum likelihood as implemented in function polr of the R [27] package MASS [28].

## 4. Results and discussion

The analysis was conducted with a stepwise approach, aiming at multiple research goals: i) identifying a potential difference in terms of users' Thermal Feeling and Thermal Preference between different countries; ii) testing operative temperature design inputs recommended by standard EN 16798 [23] for the four IEQ categories in mechanically and naturally ventilated buildings, both in summer and winter conditions, and calculating the users' acceptability rate for each country; iii)

**Table 2**
Statistical analysis of the covariates of occupants' Thermal Feeling.

***t* test of coefficients for Thermal Feeling (TF)**

| **Covariates** | | **Summer season** | | | **Winter season** | | |
|---|---|---|---|---|---|---|---|
| | | **Estimate** | ***p*-value** | **Signif.** | **Estimate** | ***p*-value** | **Signif.** |
| $t_{op}$ | | 0.791 | <0.001 | *** | 0.367 | <0.001 | *** |
| **Country** | Greece | −1.961 | <0.001 | *** | −2.154 | 0.003 | ** |
| | Portugal | −0.260 | 0.356 | | −0.070 | 0.829 | |
| | Sweden | 0.845 | 0.021 | * | −0.647 | 0.036 | * |
| | UK | 0.647 | 0.069 | . | 0.669 | 0.040 | * |
| **Ventilation mode** | MC | 0.220 | 0.329 | | 0.157 | 0.379 | |
| **RH** | | −0.020 | 0.154 | | −0.008 | 0.393 | |
| **CLO** | | −0.339 | 0.650 | | −0.041 | 0.934 | |
| **Vair** | | −2.633 | 0.002 | ** | −0.678 | 0.382 | |

Significance codes: *** represents $P < 0.001$, ** represents $P < 0.01$, * represents $P < 0.05$, "." represents $P < 0.1$, ns represents $P > 0.1$.

**Table 3**
Statistical analysis of the covariates of occupants' Thermal Preference.

***t* test of coefficients for Thermal Preference (TP)**

| **Covariates** | | **Summer season** | | | **Winter season** | | |
|---|---|---|---|---|---|---|---|
| | | **Estimate** | ***p*-value** | **Signif.** | **Estimate** | ***p*-value** | **Signif.** |
| $t_{op}$ | | −0.778 | <0.001 | *** | −0.387 | <0.001 | *** |
| **Country** | Greece | 0.487 | 0.400 | | 1.303 | 0.128 | |
| | Portugal | 0.067 | 0.831 | | −0.001 | 0.995 | |
| | Sweden | −1.126 | 0.004 | ** | 0.497 | 0.128 | |
| | UK | −0.956 | 0.015 | * | −0.432 | 0.205 | |
| **Ventilation mode** | MC | −0.284 | 0.229 | | −0.308 | 0.114 | |
| **RH** | | 0.010 | 0.491 | | 0.001 | 0.955 | |
| **CLO** | | 2.479 | 0.003 | ** | 0.780 | 0.125 | |
| **Vair** | | 2.352 | 0.004 | ** | −0.073 | 0.910 | |

Significance codes: "***" represents $P < 0.001$, "**" represents $P < 0.01$, "*" represents $P < 0.05$, "." represents $P < 0.1$, ns represents $P > 0.1$.

**Table 4**
Scenarios elaborated from Standard UNI EN 16798–2 and tested in the statistical analysis.

| **Mechanically ventilated buildings** | | | | |
|---|---|---|---|---|
| **Scenario 1 Winter (MVw):** MET = 1.2; CLO = 1; RH = 50%; $v_{air} < 0.1$ m s$^{-1}$ | | | | |
| **$t_{op}$ per IEQ category** | IV = 16 °C | III = 18 °C | II = 20 °C | I = 21 °C |
| **Scenario 2 Summer (MVs):** MET = 1.2; CLO = 0.5; RH = 50% | | | | |
| **$t_{op}$ per IEQ category** | IV = 28 °C | III = 27 °C | II = 26 °C | I = 25.5 °C |
| **Four $v_{air}$ considered**: <0.1 m s$^{-1}$; 0.6 m s$^{-1}$; 0.9 m s$^{-1}$; 1.2 m s$^{-1}$ | | | | |
| **Naturally ventilated buildings** | | | | |
| **Scenario 3 Winter (NVw):** MET = 1.2; CLO = 1.0; RH = 40%; $v_{air} < 0.1$ m s$^{-1}$ | | | | |
| **$t_{op}$ per IEQ category** | IV = 17—25 °C | III = 18—25 °C | II = 20—25 °C | I = 21—25 °C |
| **Scenario 4 Summer (NVs):** MET = 1.2; CLO = 0.5; RH = 60% | | | | |
| **$t_{op}$ per IEQ category** | IV = 21—28 °C | III = 22—27 °C | II = 23—26 °C | I = 23.5—25.5 °C |
| **Four $v_{air}$ considered**: <0.1 m s$^{-1}$; 0.6 m s$^{-1}$; 0.9 m s$^{-1}$; 1.2 m s$^{-1}$ | | | | |

predicting the operative temperature values that optimize users' TF and TP for each country in mechanically and naturally ventilated buildings, both in summer and winter conditions.

### *4.1. Difference in terms of users' thermal feeling*

Tables 2 and 3 summarize the results for the first analysis. Two main seasonal periods have been taken in consideration, winter (December, January, and February) and summer (June, July, and August) respectively. The implemented cumulative logistic regression model takes as reference level the users' response in France in NV buildings. With respect to the statistical model explained, TF and TP were used as responses in the model. The tables report the estimated regression coefficients that describe the effect of the covariate on the response. Positive values for the estimates indicate that an increase of a specific covariate is associated with an increase of the probability of higher levels in the TF and TP scales, on the contrary negative values are associated with an increase of the probability of lower levels of TF and TP votes. Specifically, regarding the Thermal Feeling, Table 2 describes how the Thermal Feeling (TF) varies with reference to the operative temperature ($t_{op}$), country, ventilation mode, RH, CLO, and $v_{air}$. MET was excluded from the analysis due to its very limited variability, especially in summer. In fact, looking at the data for both summer and winter, almost 75% of MET observations fall in the range 1.2–1.3 MET with a median of 1.2 MET, with the 60% of the self-reported values equal to 1.2. Consequently, after a preliminary test, MET was considered not relevant for the model and thus to make any generalization.

As it can be seen in Table 2, both for summer and winter season, the estimated effect of a covariate (in the column "Estimate") is positive when an increase of the later implies an highly probability to report a Thermal Feeling tending to the "Warm" to "Hot" side of the scale, on the contrary a negative effect is associated to a TF tending towards "Cold" when the variable increases. This means that the probability of a user responding between "Warm" to "Hot" increases with temperatures, but less rapidly in winter compared to summer. Among the analysed countries, in summer Greece significantly differs from France, Portugal and UK, due to a lower tendency for users to vote towards the "Warm" side of the scale. On the contrary, Sweden users have a higher tendency to vote

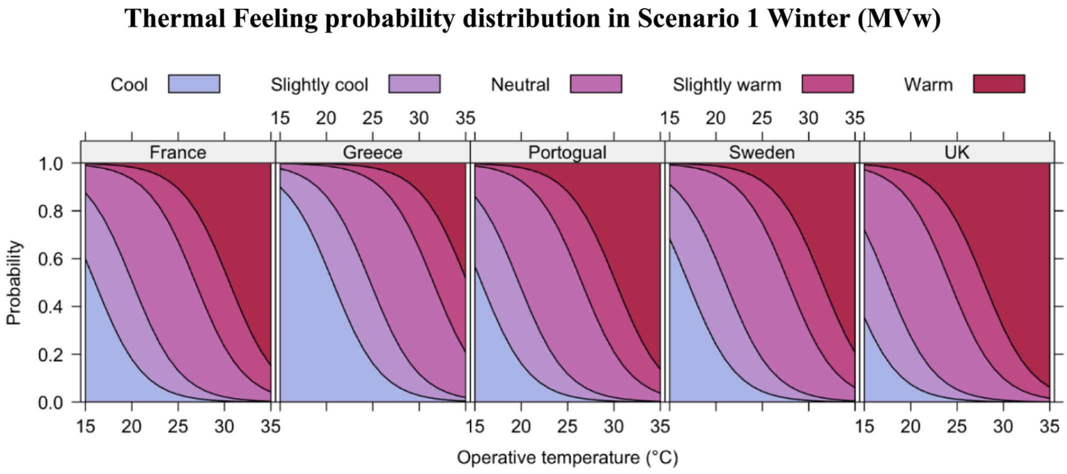
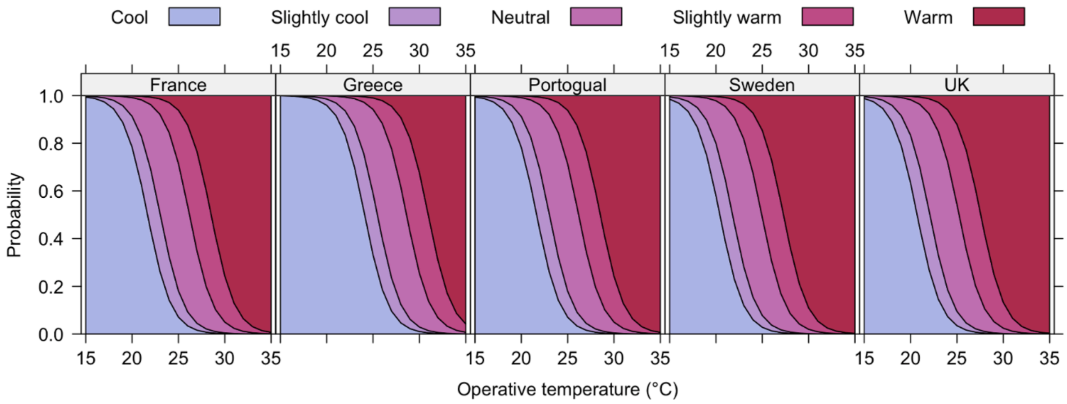


**Fig. 2.** Estimated Thermal Feeling probability distribution, according to environmental and personal parameters of Scenario 1 Winter (MVw) from Table 4.

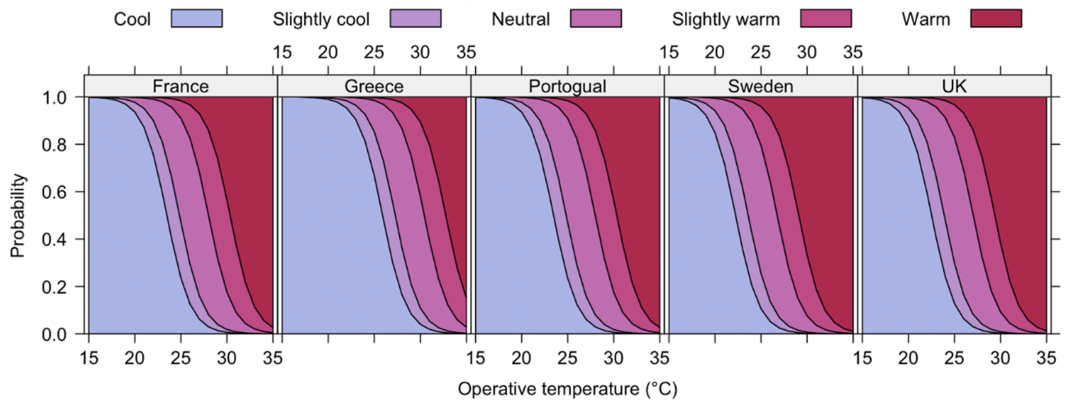
**Table 5**
Acceptability rates for each country for each IEQ Category, i.e., the % of users voting in the range Slightly cool – Neutral – Slightly warm. In green, the rates ≥ 80%, as prescribed by ANSI/ASHRAE Standard 55.

| **Acceptability rate [%]** | | **Scenario 1 Winter (MVw)** | | | |
|---|---|---|---|---|---|
| | | **I CAT**<br>**$t_{op}$ = 21°C** | **II CAT**<br>**$t_{op}$ = 20°C** | **III CAT**<br>**$t_{op}$ = 18°C** | **IV CAT**<br>**$t_{op}$ = 16°C** |
| **Countries** | **France** | 84% | 81% | 67% | 49% |
| | **Greece** | 52% | 43% | 25% | 14% |
| | **Portugal** | 86% | 82% | 70% | 52% |
| | **Sweden** | 81% | 75% | 59% | 41% |
| | **UK** | 88% | 88% | 83% | 72% |

Thermal Feeling probability distribution in Scenario 2 Summer (MVs) - $v_{air} < 0.1$ m $s^{-1}$



Thermal Feeling probability distribution in Scenario 2 Summer (MVs) - $v_{air} = 0.6$ m $s^{-1}$



Thermal Feeling probability distribution in Scenario 2 Summer (MVs) - $v_{air} = 0.9$ m $s^{-1}$

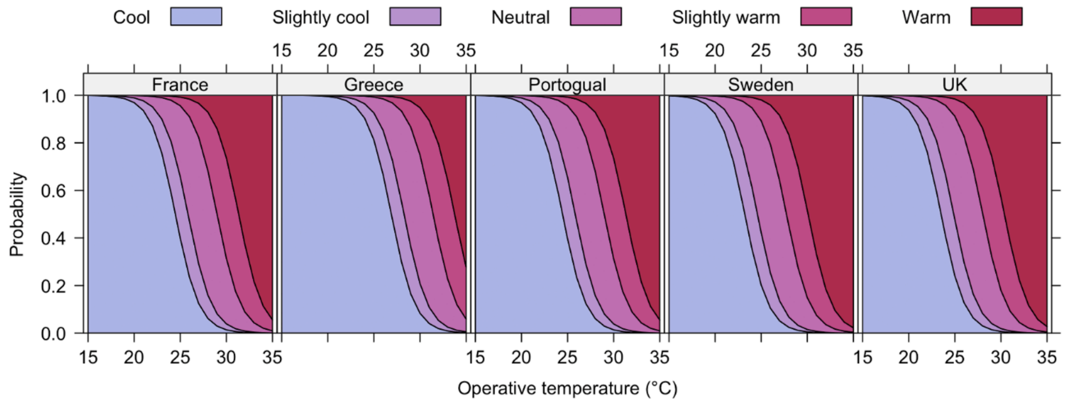


**Fig. 3–6.** Estimated Thermal Feeling probability distribution, according to environmental and personal parameters of Scenario 2 Summer (MVs) and increased Vair values from Table 4.

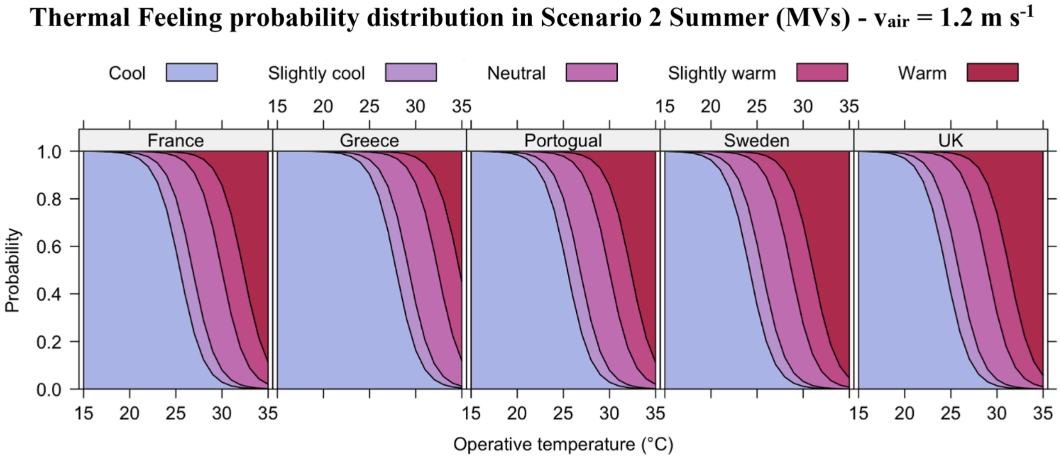


**Fig. 3–6.** (*continued*).

in the “Warm” range of the scale with respect to French, Portuguese and UK users. In the winter period, Greece, Sweden and United Kingdom show a significant difference from France and Portugal. The first two countries show a negative estimated effect that points at a tendency of users to vote on the “Cold” side of the scale. Contrarily, UK has an estimated positive effect, meaning a higher tendency of users to vote towards the warmer side of the TF scale. Air velocity has a significant effect over the TF in the summer period, which means that an increase in the Vair leads to an increase in the votes in the “Cold” side of the TF scale. CLO and other variables do not account for significance in the model. No statistically significant effect associated to the ventilation mode was found.

### 4.2. *Difference in terms of users’ thermal preference*

The same analysis has been performed according to the users’ Thermal Preference (TP) for the summer and winter season. Table 3 reports how the TP varies with reference to the operative temperature ($t_{op}$), country, ventilation mode, RH, CLO, MET and $v_{air}$.

Observing the results, the estimated effects are positive if the considered covariate and the Thermal Preference change in the same direction, vice versa when the estimate is negative (i.e., $t_{op}$ increases and TP tends toward cooler). Looking at the results in Table 3, this means that an increase in the operative temperature values lead the users to prefer cooler temperatures and vice versa. Thus, both in summer and winter, the increase in the $t_{op}$ leads to an increased tendency of users to vote towards cooler TP. In winter, no significant country-effect is found. In summer, Sweden and UK differ from France, Greece, and Portugal, with a higher tendency to lower values of TP. In summer, the clothing level and the air speed have a significant association with TP. An increase in the clothing level can be read as a consequence of users responding with the desire of having warmer temperatures, also considering this action as the easiest adaptation method in office environments. An increase in the $v_{air}$ values, parameter over which the user has not control in these measurements, is also a cause for warmer TP votes. This should not be read as a mere increase of probably toward a warmer TP due to the localized discomfort given by too high air movement values or draughts, but it could be also due to the fact that for the same values of warm indoor temperatures, a user that without air movement would have answered ‘Much cooler’, with some air movement may answer “A bit cooler’ or ‘No change’.

Similar to what observed for the TF, also the TP seems to be not impacted by the ventilation mode, or more specifically in this case, by the presence or not of mechanical cooling. This is a result that seems in contrast with the use of two different thermal comfort models, one for mechanically cooled buildings and one, the adaptive, for naturally ventilated buildings. An explanation for this may be found in the very same idea of adaptive model, which implies a higher ability of adaptation for users in NV buildings. One of the main ways to implement this adaptation is adjusting the clothing. So, the change from NV to MC may impact the CLO values at similar temperatures and so the TP. Although the covariate “Ventilation mode” was considered in our models, a full assessment of its impact on TF and TP would require an experiment in which user behavior is controlled in a way that avoids clothing adjustments that mask potential effects of ventilation.

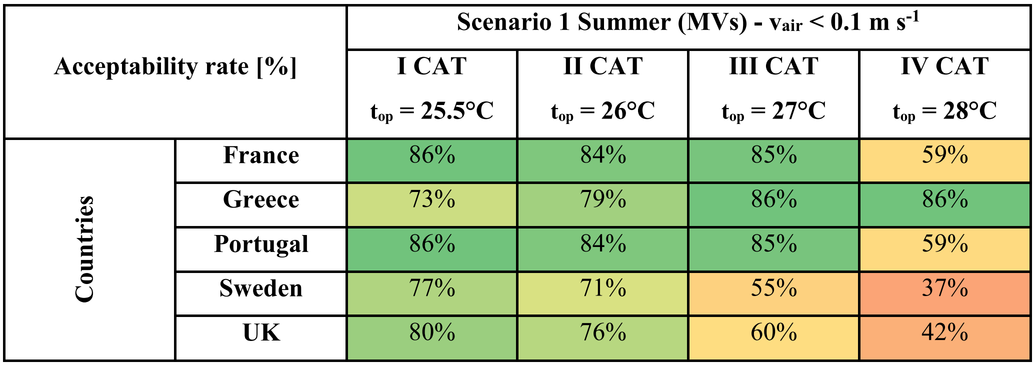
### 4.3. *Analysis of users’ TF in different countries, with reference to design inputs scenarios by EN 16798 for MV and NV buildings*

With these premises, the second step of the analysis has focused on extrapolating the potential differences in terms of TF and TP, assuming as constraints the operative temperature design inputs recommended in the Standard EN 16798-2 [23] for the four Indoor Environmental Quality (IEQ) categories. In this direction, specific scenarios have been identified including the indoor environmental input parameters for design and assessment of energy performance of buildings, addressing specifically the thermal environment. Different conditions were specified for the mechanically and the naturally ventilated buildings, both in summer and in winter, and they are summarized in Table 4. Besides the microclimatic parameters, some personal inputs have been considered, namely MET and CLO levels. Each scenario is indicated with and ID (e.g., MVw), where MV stands for Mechanically Ventilated and NV for Naturally Ventilated buildings, and w/s means winter or summer.

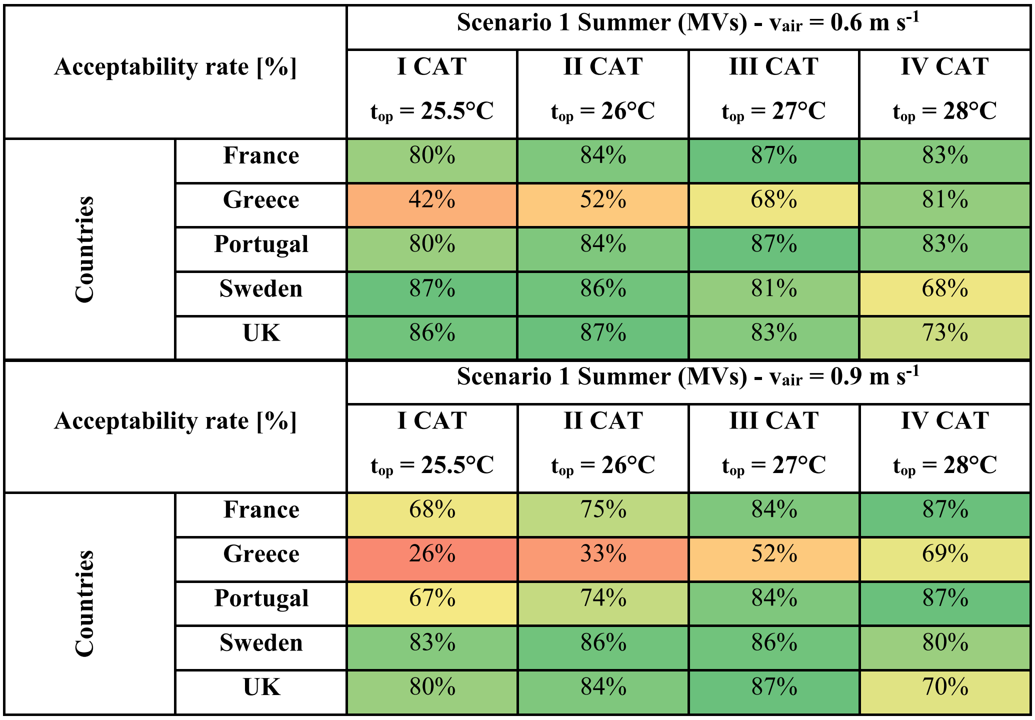
The results are presented hereafter. For each scenario, there is a vector of plots that display the estimated probability that the user expresses a specific TF vote as a function of the operative temperature design values of the four different IEQ Categories prescribed by EN 16798 [23]. In the Tables, acceptability rates for each country for each IEQ Category are provided, i.e., the percentage of users voting in the range Slightly cool – Neutral – Slightly warm. In green, the rates $\geq$ 80%, as prescribed by ASHRAE Standard 55 for an acceptable thermal environment [1].

**Table 6–9**

Acceptability rates for each country for each IEQ Category, i.e., the % of users voting in the range Slightly cool – Neutral – Slightly warm. In green, the rates ≥ 80%, as prescribed by ANSI/ASHRAE Standard 55.

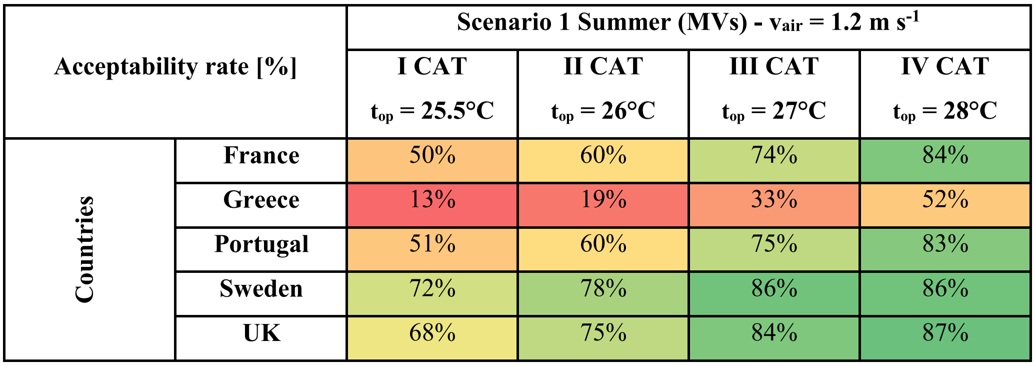


| Acceptability rate [%] | | Scenario 1 Summer (MVs) - $v_{air} < 0.1$ m s$^{-1}$ | | | |
|---|---|---|---|---|---|
| | | I CAT<br>$t_{op}$ = 25.5°C | II CAT<br>$t_{op}$ = 26°C | III CAT<br>$t_{op}$ = 27°C | IV CAT<br>$t_{op}$ = 28°C |
| Countries | **France** | 86% | 84% | 85% | 59% |
| | **Greece** | 73% | 79% | 86% | 86% |
| | **Portugal** | 86% | 84% | 85% | 59% |
| | **Sweden** | 77% | 71% | 55% | 37% |
| | **UK** | 80% | 76% | 60% | 42% |



| Acceptability rate [%] | | Scenario 1 Summer (MVs) - $v_{air} = 0.6$ m s$^{-1}$ | | | |
|---|---|---|---|---|---|
| | | I CAT<br>$t_{op}$ = 25.5°C | II CAT<br>$t_{op}$ = 26°C | III CAT<br>$t_{op}$ = 27°C | IV CAT<br>$t_{op}$ = 28°C |
| Countries | **France** | 80% | 84% | 87% | 83% |
| | **Greece** | 42% | 52% | 68% | 81% |
| | **Portugal** | 80% | 84% | 87% | 83% |
| | **Sweden** | 87% | 86% | 81% | 68% |
| | **UK** | 86% | 87% | 83% | 73% |

| Acceptability rate [%] | | Scenario 1 Summer (MVs) - $v_{air} = 0.9$ m s$^{-1}$ | | | |
|---|---|---|---|---|---|
| | | I CAT<br>$t_{op}$ = 25.5°C | II CAT<br>$t_{op}$ = 26°C | III CAT<br>$t_{op}$ = 27°C | IV CAT<br>$t_{op}$ = 28°C |
| Countries | **France** | 68% | 75% | 84% | 87% |
| | **Greece** | 26% | 33% | 52% | 69% |
| | **Portugal** | 67% | 74% | 84% | 87% |
| | **Sweden** | 83% | 86% | 86% | 80% |
| | **UK** | 80% | 84% | 87% | 70% |



| Acceptability rate [%] | | Scenario 1 Summer (MVs) - $v_{air} = 1.2$ m s$^{-1}$ | | | |
|---|---|---|---|---|---|
| | | I CAT<br>$t_{op}$ = 25.5°C | II CAT<br>$t_{op}$ = 26°C | III CAT<br>$t_{op}$ = 27°C | IV CAT<br>$t_{op}$ = 28°C |
| Countries | **France** | 50% | 60% | 74% | 84% |
| | **Greece** | 13% | 19% | 33% | 52% |
| | **Portugal** | 51% | 60% | 75% | 83% |
| | **Sweden** | 72% | 78% | 86% | 86% |
| | **UK** | 68% | 75% | 84% | 87% |

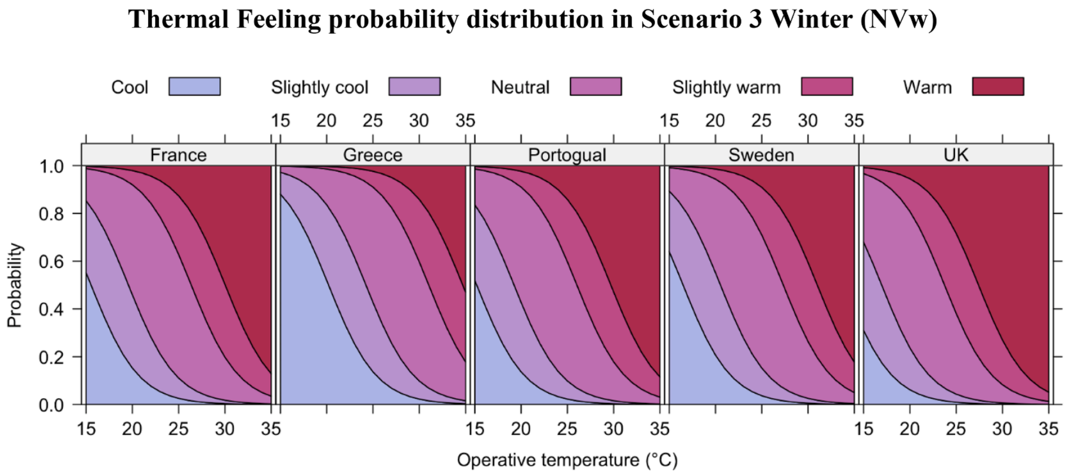


**Fig. 7.** Estimated Thermal Feeling probability distribution, according to environmental and personal parameters of Scenario 3 Winter (NVw) from Table 4.

**Table 10**
Acceptability rates for each country for each IEQ Category, i.e., the % of users voting in the range Slightly cool – Neutral – Slightly warm. In green, the rates ≥ 80%, as prescribed by ANSI/ASHRAE Standard 55.

| Acceptability rate [%] | | Scenario 1 Winter (NVw) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I CAT<br>$t_{op}$ = 21-25 °C | | | II CAT<br>$t_{op}$ = 20-25 °C | | | III CAT<br>$t_{op}$ = 18-25 °C | | | IV CAT<br>$t_{op}$ = 17-25 °C | | |
| Countries | France | 86% | - | 85% | 83% | - | 85% | 71% | - | 85% | 63% | - | 85% |
| | Greece | 57% | - | 84% | 48% | - | 84% | 31% | - | 84% | 22% | - | 84% |
| | Portugal | 87% | - | 84% | 84% | - | 84% | 73% | - | 84% | 66% | - | 84% |
| | Sweden | 83% | - | 88% | 77% | - | 88% | 64% | - | 88% | 54% | - | 88% |
| | UK | 88% | - | 71% | 89% | - | 71% | 85% | - | 71% | 80% | - | 71% |

### 4.3.1. *Mechanically ventilated buildings*

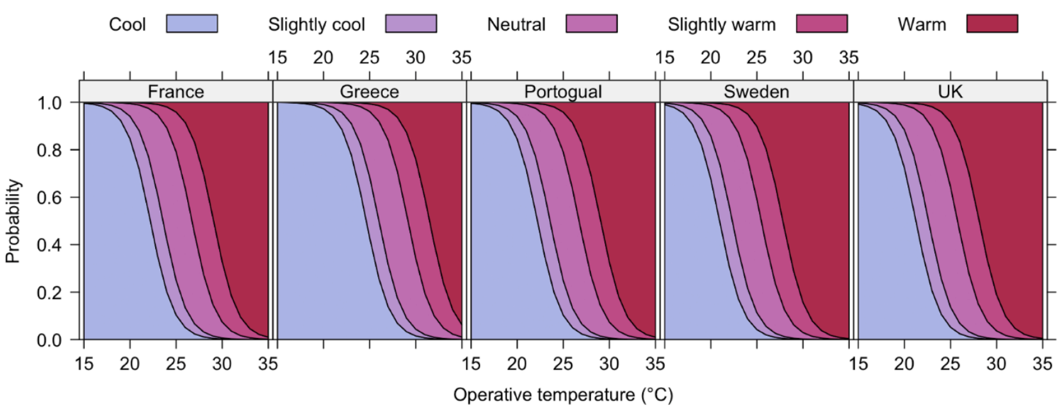
Observing the results reported in Fig. 2 and Table 5, it was possible to confirm that users from Greece are the ones who mainly differ in terms of thermal sensation. In fact, even in the I category of comfort, they generally have a feeling towards cool and an acceptability rate around 50%, whereas in the other countries the TF appears to be less extreme, with a major share of neutral sensations tending to slightly cool at the most. Moreover, the estimated probabilities of answering in the cool-discomfort side of the scale clearly increases with a decrease in the operative temperature values. This increment is less significant in the other countries, and in the UK the odds mainly remain in the range from neutral to slightly cool even at 16 °C (IV Category) showing a clear difference with the other countries. Regarding France, Portugal and Sweden, they appear to have a good acceptability rate until the II Category of IEQ, value that appears to drop in the III and IV Categories.

In the summer season (Figs. 3–6), Greece again appears to work differently from the other countries. In fact, the probability of a slightly cool TF is higher with respect to the others. TF for Greek users improves with an increase in the operative temperature, whereas it worsens with an increase in the air velocity values (Table 6–9). On the contrary, Sweden and UK are the countries with the highest increase of slightly warm to warm TFs, moving towards the III and IV categories of comfort. As it can be seen from the tables, for these countries the acceptability of occupants increases with the increase in air velocity. This trend partially changes when the air velocity values are in the higher ranges (0.9–1.2 ms$^{-1}$). In these cases, it positively impacts acceptability, and so TF, only at higher operative temperatures, while it has a negative impact at lower temperatures. The same is observed in the analysis of results for France and Portugal. France and Portugal show again a similar behaviour, with a generally good acceptability rate through the four IEQ categories with a $v_{air} < 0.1$ m s$^{-1}$. With an increase in the $v_{air}$, users' acceptability increases for higher $t_{op}$. In Table 11, $v_{air} = 1.2$ m s$^{-1}$ seems to be too elevated for all the users in the four countries, with the acceptability rates increasingly shifting to even higher $t_{op}$ values. These results highlight the potential differences in the users' thermal sensations across different EU countries, especially moving from a Mediterranean to a continental / sub-arctic climate. In addition, it is evident the key role that air velocity plays in the summer period, allowing the building's occupants to tolerate higher and wider ranges of indoor temperatures. In fact, increments of the air velocity values bring additional comfort to the users, increasing the probability of a neutral to slightly cool TF up to $v_{air} = 0.9$ m s$^{-1}$. This means that, maintaining higher air movement in the environment, can enable to achieve higher temperatures, ensuring the thermal comfort of occupants avoiding a massive use of air conditioning. At the same time, it is clear how the differences in perception among countries may lead to unwanted cooling associated with elevated air movements.

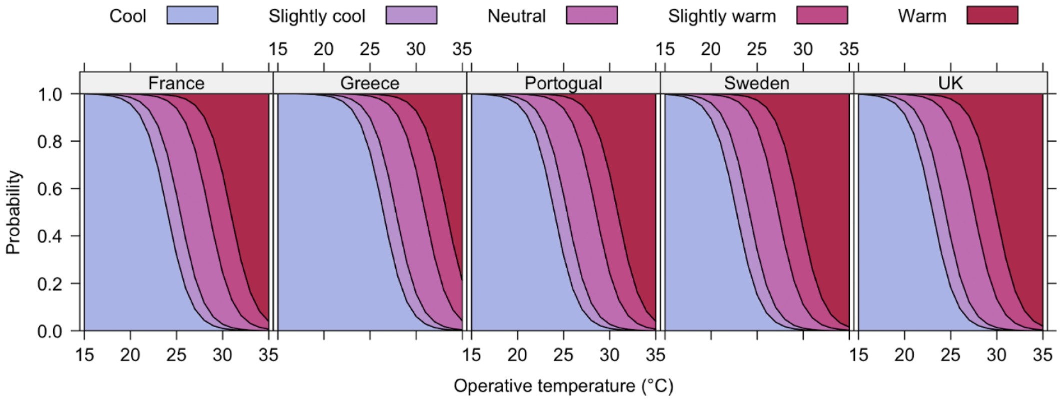
### 4.3.2. *Naturally ventilated buildings*

The same investigations were conducted focusing on the data

Thermal Feeling probability distribution in Scenario 4 Summer (NVs) - $v_{air} < 0.1\ m\ s^{-1}$



Thermal Feeling probability distribution in Scenario 4 Summer (NVs) - $v_{air} = 0.6\ m\ s^{-1}$



Thermal Feeling probability distribution in Scenario 4 Summer (NVs) - $v_{air} = 0.9\ m\ s^{-1}$

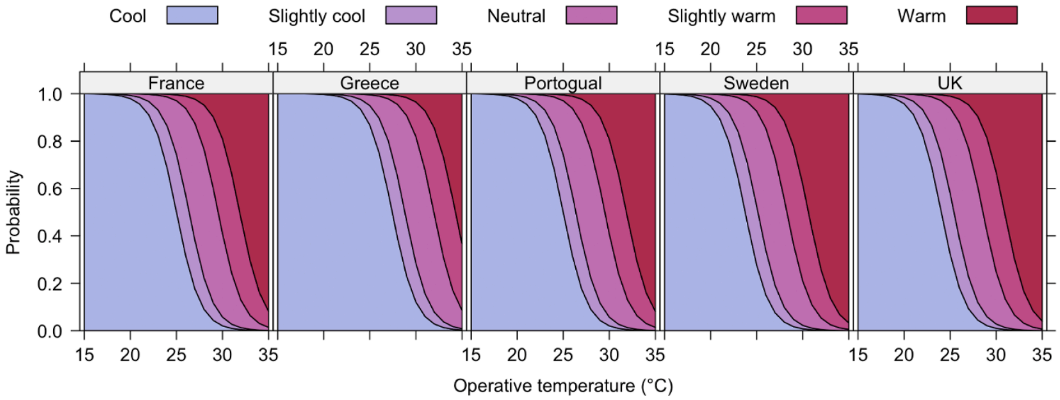


**Fig. 8–11.** Estimated Thermal Feeling probability distribution, according to environmental and personal parameters of Scenario 4 Summer (NVs) and increased $v_{air}$ values from Table 4.

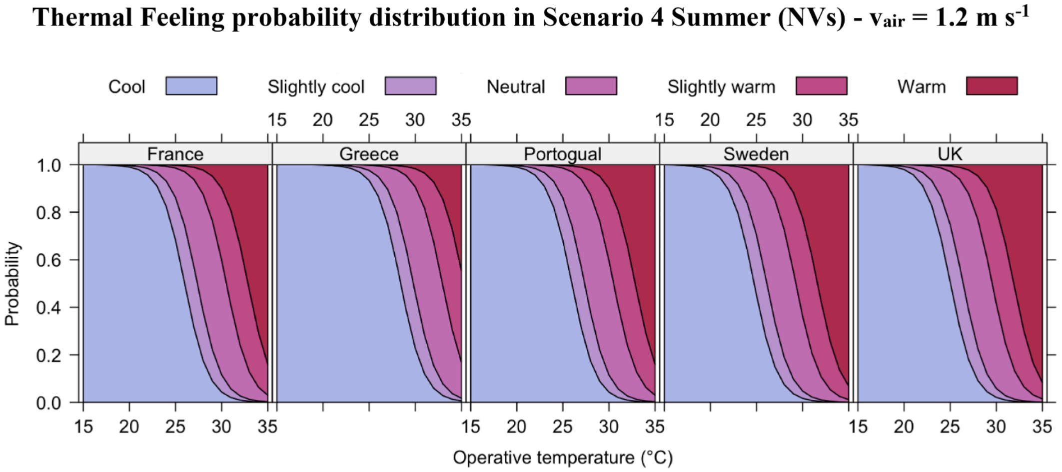


**Fig. 8–11.** (*continued*).

gathered from occupants of naturally ventilated buildings. In this case, scenarios have been selected according to the input parameters ranges given by Standard EN 16798-2 [23] specifically for Naturally Ventilated buildings. It is key to remember that the ranges in this standard are developed from a model built on this very same dataset. In fact, the adaptive thermal comfort models in ASHRAE 55 with respect to ISO and EN standards are based on different initial datasets [29]: ASHRAE 55 is developed from the studies by De Dear and Brager [30], while ISO and EN standards are based on the SCATS project [18]. For naturally ventilated buildings, considering a greater potential of adaptation for users, the guidelines do not give a single $t_{op}$ value, but a range for each comfort category, as reported in Table 4. For clarity, outputs are reported for each $t_{op}$ limit value of the ranges given by the Standard (Tables 12-16), being the more extreme set-points of the ranges.

The results of the statistical model for each scenario are reported in Fig. 7 and Table 10 for winter, Figs. 8–11 and Tables 11–14 for summer, with in addition for this latter case results referring also to increments in the Vair values.

As it is possible to observe, the same dynamics as for MV buildings occur, being Greece the country that highlights the most significant differences in terms of users' TF compared to the other countries. Greek users experience in general more neutral to cool sensations, with acceptability rates decreasing as lower limits of $t_{op}$ decrease from I to IV categories. On the contrary, for what concerns UK, it is possible to observe some differences from the other countries. In fact, UK's occupants seem to experience sensations more on the warm side, with an acceptability rate that decreases with an increase in the upper limit values of $t_{op}$ from I to IV categories. Regarding France, Portugal and Sweden, they appear to have a similar winter response, with acceptability rates that starts to decrease as the lower limit $t_{op}$ values drop in the III and IV IEQ categories. In the following paragraph, results are presented for the summer period.

As highlighted for the winter period, Greece and UK show the most different behaviour compared to the countries considered in this study. Users in Greece have a higher acceptability rate for higher limit values of $t_{op}$ and very low for the lower limits, on the contrary UK's ones show a very low acceptability rate for higher temperatures. This trend is even more stressed with an increase in the $v_{air}$ values, as shown in Tables 14-15. The acceptability rates for Greek users drop for the lower limits of $t_{op}$, but slightly improve for UK users at the higher limits. In general, for the other three countries, acceptability rates tend to increase for higher limits of $t_{op}$ with an increase in the air velocity up to 0.6 and 1.2 m $s^{-1}$. As in the MV buildings, an increase in the air velocity values brings an additional comfort to users, enabling them to better tolerate higher values of indoor temperature.

### 4.4. Prediction of operative temperature values that optimize the thermal feeling and thermal preference of the users in different countries

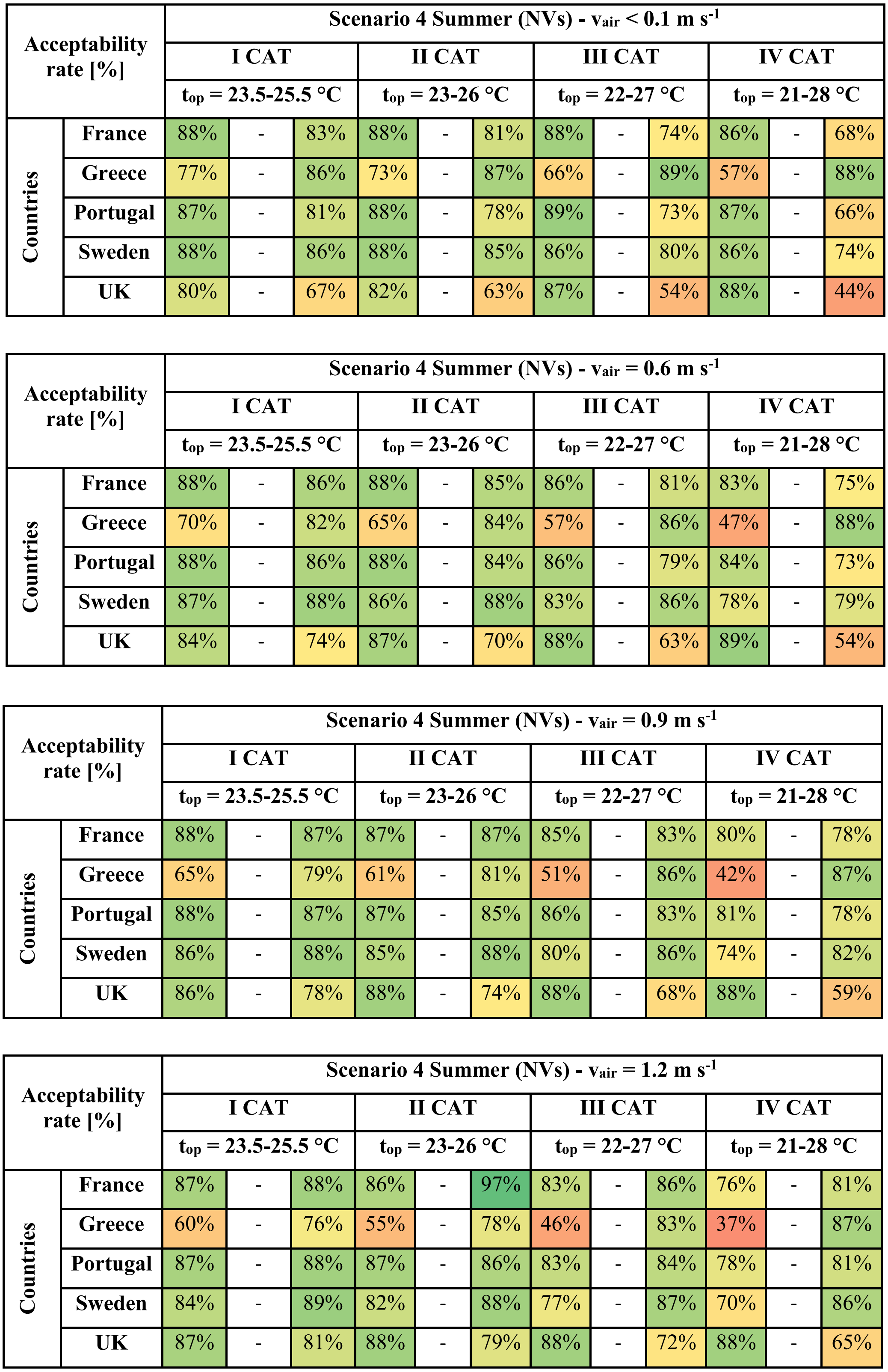
At this point of the work, it was possible to predict the operative temperature values that "optimize" the Thermal Feeling (neutral) and Thermal Preference (no change) of the users, referring also in this phase to each scenario in Table 4. Although for Thermal Preference the 'No Change' value is clearly the optimum from user perspective, from literature we know that this is not the same for Thermal Feeling, with users often preferring to feel something else than neutral [5].

Observing Table 15 and in line with analysis conducted by Humphreys and Hancock [5], it is evident in the first place that there is a difference between the operative temperature values that optimize the TF and the TP. This suggests that comfort not always matches with a condition of neutrality as stated in its commonly known definition, on the contrary every user can prefer different sensations according to their subjective expectations and climatic background. However, for both the variables, $t_{op}$ appears to achieve significantly high values in the winter period, over the standard recommended set-points: this can be explained with the negative trend that has being affecting buildings' occupants in the last decades, becoming "fussy" to the thermal environment as previously noticed in the works of Luo et al. [11,13], demanding increasingly higher temperatures, feeling endowment to comfort, to high IEQ conditions and convenience. Looking at the values it seems like that the temperatures are more representative of the condition that minimize the adaptation effort. This of course does not imply that users are comfortable only at such extreme conditions, but that if they have the chance to minimize their adaptation efforts simply changing the indoor environment as please, they would most likely aim for these temperatures.

As already noted in the above analysis, differences subsist among the five addressed countries. It is interesting, for the summer period, to notice how increments in $v_{air}$ lead to higher operative temperature values both for TF and TP. These results confirm, as previously noted, that air movement, if correctly designed to avoid local discomfort issues, can give a pivotal contribution to occupants' comfort at high indoor temperatures.

Temperatures for Greece are very different compared to the other

**Table 11–14**
Acceptability rates for each country for each IEQ Category, i.e., the % of users voting in the range Slightly cool – Neutral – Slightly warm. In green, the rates ≥ 80%, as prescribed by ANSI/ASHRAE Standard 55.



| Acceptability rate [%] | | Scenario 4 Summer (NVs) - $v_{air} < 0.1$ m s$^{-1}$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I CAT | | | II CAT | | | III CAT | | | IV CAT | | |
| | | $t_{op}$ = 23.5-25.5 °C | | | $t_{op}$ = 23-26 °C | | | $t_{op}$ = 22-27 °C | | | $t_{op}$ = 21-28 °C | | |
| Countries | France | 88% | - | 83% | 88% | - | 81% | 88% | - | 74% | 86% | - | 68% |
| | Greece | 77% | - | 86% | 73% | - | 87% | 66% | - | 89% | 57% | - | 88% |
| | Portugal | 87% | - | 81% | 88% | - | 78% | 89% | - | 73% | 87% | - | 66% |
| | Sweden | 88% | - | 86% | 88% | - | 85% | 86% | - | 80% | 86% | - | 74% |
| | UK | 80% | - | 67% | 82% | - | 63% | 87% | - | 54% | 88% | - | 44% |

| Acceptability rate [%] | | Scenario 4 Summer (NVs) - $v_{air} = 0.6$ m s$^{-1}$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I CAT | | | II CAT | | | III CAT | | | IV CAT | | |
| | | $t_{op}$ = 23.5-25.5 °C | | | $t_{op}$ = 23-26 °C | | | $t_{op}$ = 22-27 °C | | | $t_{op}$ = 21-28 °C | | |
| Countries | France | 88% | - | 86% | 88% | - | 85% | 86% | - | 81% | 83% | - | 75% |
| | Greece | 70% | - | 82% | 65% | - | 84% | 57% | - | 86% | 47% | - | 88% |
| | Portugal | 88% | - | 86% | 88% | - | 84% | 86% | - | 79% | 84% | - | 73% |
| | Sweden | 87% | - | 88% | 86% | - | 88% | 83% | - | 86% | 78% | - | 79% |
| | UK | 84% | - | 74% | 87% | - | 70% | 88% | - | 63% | 89% | - | 54% |

| Acceptability rate [%] | | Scenario 4 Summer (NVs) - $v_{air} = 0.9$ m s$^{-1}$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I CAT | | | II CAT | | | III CAT | | | IV CAT | | |
| | | $t_{op}$ = 23.5-25.5 °C | | | $t_{op}$ = 23-26 °C | | | $t_{op}$ = 22-27 °C | | | $t_{op}$ = 21-28 °C | | |
| Countries | France | 88% | - | 87% | 87% | - | 87% | 85% | - | 83% | 80% | - | 78% |
| | Greece | 65% | - | 79% | 61% | - | 81% | 51% | - | 86% | 42% | - | 87% |
| | Portugal | 88% | - | 87% | 87% | - | 85% | 86% | - | 83% | 81% | - | 78% |
| | Sweden | 86% | - | 88% | 85% | - | 88% | 80% | - | 86% | 74% | - | 82% |
| | UK | 86% | - | 78% | 88% | - | 74% | 88% | - | 68% | 88% | - | 59% |

| Acceptability rate [%] | | Scenario 4 Summer (NVs) - $v_{air} = 1.2$ m s$^{-1}$ | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I CAT | | | II CAT | | | III CAT | | | IV CAT | | |
| | | $t_{op}$ = 23.5-25.5 °C | | | $t_{op}$ = 23-26 °C | | | $t_{op}$ = 22-27 °C | | | $t_{op}$ = 21-28 °C | | |
| Countries | France | 87% | - | 88% | 86% | - | 97% | 83% | - | 86% | 76% | - | 81% |
| | Greece | 60% | - | 76% | 55% | - | 78% | 46% | - | 83% | 37% | - | 87% |
| | Portugal | 87% | - | 88% | 87% | - | 86% | 83% | - | 84% | 78% | - | 81% |
| | Sweden | 84% | - | 89% | 82% | - | 88% | 77% | - | 87% | 70% | - | 86% |
| | UK | 87% | - | 81% | 88% | - | 79% | 88% | - | 72% | 88% | - | 65% |

**Table 15**

Predicted summer operative temperatures that optimize the users' Thermal Feeling (TF) in the different countries. N stands for "Neutral", NC stands for "No Change".

| | | Operative temperature values [°C] for Thermal Feeling (TF) and Thermal Preference (TP) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | France | | Greece | | Portugal | | Sweden | | UK | |
| | | N | NC | N | NC | N | NC | N | NC | N | NC |
| MVw | | 22.3 | 22.5 | 28.2 | 25.9 | 22.5 | 22.5 | 24.1 | 23.8 | 20.5 | 21.4 |
| MVs* | $<0.1$ m $s^{-1}$ | 24.6 | 24.1 | 27.1 | 24.7 | 24.9 | 24.2 | 23.5 | 22.6 | 23.8 | 22.9 |
| | 0.6 m $s^{-1}$ | 26.4 | 25.8 | 28.9 | 26.4 | 26.7 | 25.8 | 25.3 | 24.3 | 25.6 | 24.5 |
| | 0.9 m $s^{-1}$ | 27.4 | 26.7 | 29.9 | 27.3 | 27.7 | 26.7 | 26.3 | 25.2 | 26.6 | 25.4 |
| | 1.2 m $s^{-1}$ | 28.4 | 27.6 | 30.9 | 28.2 | 28.7 | 27.7 | 27.3 | 26.1 | 27.6 | 26.3 |
| NVw | | 22.5 | 23.3 | 28.4 | 26.7 | 22.7 | 23.3 | 24.3 | 24.6 | 20.7 | 22.2 |
| NVs* | $<0.1$ m $s^{-1}$ | 25.1 | 24.6 | 27.6 | 25.2 | 25.4 | 24.7 | 24.0 | 23.1 | 24.3 | 23.4 |
| | 0.6 m $s^{-1}$ | 26.9 | 26.3 | 29.4 | 26.9 | 27.3 | 26.3 | 25.9 | 24.8 | 26.1 | 25.0 |
| | 0.9 m $s^{-1}$ | 27.9 | 27.2 | 30.4 | 27.8 | 28.3 | 27.2 | 26.9 | 25.7 | 27.1 | 25.9 |
| | 1.2 m $s^{-1}$ | 28.9 | 28.1 | 31.4 | 28.7 | 29.3 | 28.2 | 27.9 | 26.6 | 28.1 | 26.8 |

* with increasing $v_{air}$ values ranging from $< 0.1$ m $s^{-1}$ to 1.2 m $s^{-1}$

countries and always toward higher values. The differences are very strong especially if compared with UK, a country that has an opposite trend compared to Greece. These results are in line with the findings presented in the previous tables.

## 5. Conclusions

This work was conducted by the authors starting from the assumption that users with a different climatic background have different thermal feelings and preferences, which are influenced by a wide spectrum of aspects, i.e., mainly climatic, cultural, practice-related and social. The conducted analysis highlighted how thermal feeling of users can differ from one country to another, and usually it is far from being merely a sensation of neutrality.

The analysis highlighted that:

- There are statistically significant differences in terms of TF between users in different countries.
- In summer TF answers in Greece significantly differs from other countries, due to a lower tendency of users to vote towards the "Warm" side of the scale, while Sweden users have a higher tendency to vote in the "Warm" range of the scale.
- In winter, TF answers in Greece, Sweden and United Kingdom show a significant difference from France and Portugal. The first two countries show a negative estimated effect while UK has an estimated positive effect.
- In summer, TP votes in Sweden and UK differ from France, Greece, and Portugal, with a higher tendency to lower values of thermal preference (negative estimated effect).
- The impact of air speed is statistically significant for summer TF and TP.
- CLO has a statistically significant impact on TP in summer conditions.
- In line with the previous results, the model strongly highlighted the influence of the covariate "country" on the estimated percentage of acceptability votes for different standardized indoor conditions, both in NV and MV buildings.
- Air movement has an important role to enhance the tolerance of users towards higher values of indoor temperature for all the countries.
- The predict values of operative temperature that could optimize users' TF and TP in different countries are dissimilar, and too extreme from the point of view of an energy efficient control of the indoor environment.

Considering that the presented outcomes refer to the analysis of a specific database, the results are only to be ascribed to the available observations. In order to validate this work, it will be necessary to perform the same investigations to other similar databases, e.g., the ASHRAE thermal comfort database II [31], in order to evaluate if these preliminary results can lead to wider generalizations.

Developing further research in this direction would help to overcome the limited overall definition of comfort, which strives for static environments equal for all subjects all over the world. In this way, it would be possible to finally embrace diversity-driving factors and to acknowledge differences coming from users' long-term experiences and expectations. However, as highlighted in the work by Pistore and Pasut [6], these drivers can be of multiple natures: in this study, the different country represent just a label, but it implies a wide heterogeneity of variables, from climatic, to cultural, social, physiological, ethnical, etc.

This direction would eventually lead to a new paradigm in the design and operation of buildings, accounting for indoor conditions more dynamic, flexible, transient, and less energy-consuming, in line with the heterogeneity in users' interactions. In this respect, the use of energy efficient personalized comfort systems may go in the right direction of saving energy while enabling a new level of personalization of the indoor environment.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data is already publicly available

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## Appendix A Monthly climatology of mean temperatures in the period 1991-2020

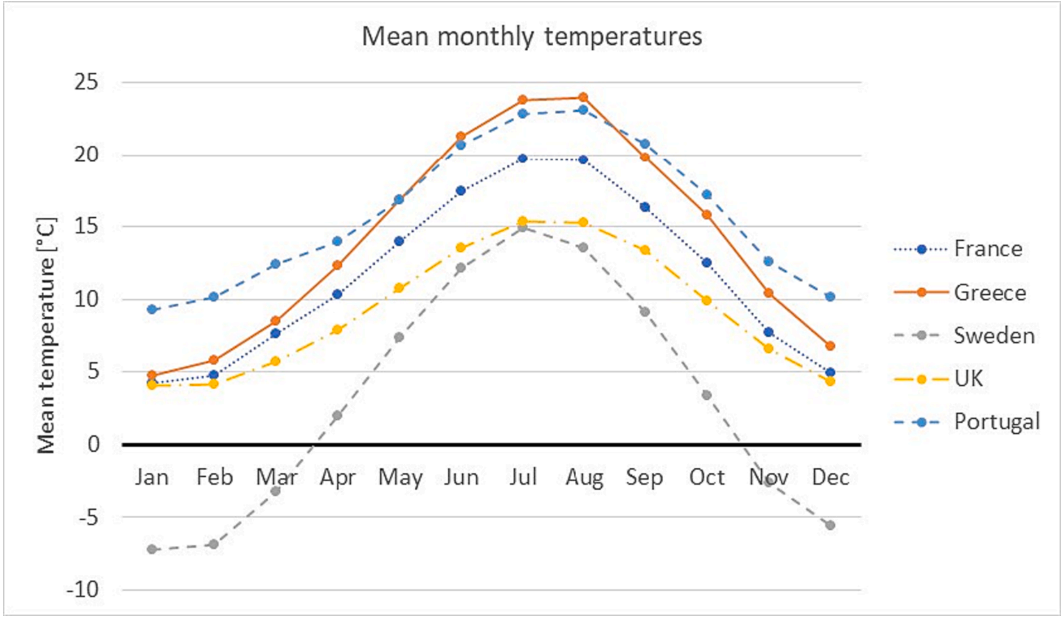

**Fig. 1A.** Mean monthly temperatures over the period 1991–2020 in the five investigated countries.

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