Statistical analysis of the ranking capability of long-term thermal discomfort indices and their adoption in optimization processes to support building design

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1. Introduction

The scientific literature and the standards ISO 7730 [1] and EN 15251 [2] offer a few methods for the long-term evaluation of the general thermal comfort conditions and for predicting the likelihood of the summer overheating occurrences in a building. Such methods — generally indices that cumulate over time and space, in a variety of ways, a chosen hourly and local discomfort metric — are also used for comparing the effect on the indoor environment of alternative design strategies. Several authors have used long-term thermal discomfort metrics to assess and compare the thermal comfort performance of different design options without discussing the influence of the used metric on the outcomes, and whether the adoption of a different metric might have provided a different result. Thus, the first objective of this paper consists in comparing and contrasting the ranking capability of the long-term thermal discomfort indices identified in literature in order to ascertain if the differences in their values are due to the different design options or to an inherently different manner to estimate long-term discomfort. Moreover, EN 15251 guides designers towards a two-step optimization procedure, which is based on the sequential use of two long-term discomfort indices. The first is based on the European adaptive model [3] and should be used for the dimensioning of passive means in summer conditions. The second is based on the Fanger comfort model [4] and has to be used if the adaptive limits proposed in EN 15251 cannot be guaranteed by adopting only

Acronyms: ASHRAE, American Society of Heating Refrigerating and Air Conditioning Engineers; CEN, European Committee for Standardization; CIBSE, Chartered Institution of Building Services Engineers; DhC, Degree hour criterion; EN, European Standards; EU, European Union; ISO, International Organization for Standardization; IWEC, International Weather for Energy Calculations; LPD, Long-term percentage of dissatisfied; NaOR, Nicol et al.'s overheating risk; PMV, Predicted mean vote; POR, Percentage outside range; PPD, predicted percentage of dissatisfied; PPDwC, PPD-weighted criterion; RHOR, Robinson and Haldi's overheating risk; SCATs, European Project Smart Controls and Thermal Comfort; Sum_PPD, Accumulated PPD.

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passive means, and, hence, the installation of a mechanical cooling system is unavoidable for providing thermal comfort [2]. However, Pagliano and Zangheri [5] show that employing the indices proposed by EN 15251 in such two-step optimization procedure brings to discontinuities when switching from the index based on the adaptive model to the one based on the Fanger model, since the indices identify different optimal building variants. Thus, the second objective of this paper is to identify, at least, a suitable pair of long-term discomfort indices that provide a similar ranking (even with different values) of building variants using an adaptive model and the Fanger comfort model.

The analyses are numerically carried out by using a dynamic energy simulation engine, EnergyPlus [6], guided by a parameterization engine, JePlus [7]. The case study, on which the analyses are carried out, is a large office building. Four design variables regarding the building envelope and passive strategies, such as (i) envelope quality (expressed through the steady-state transmittance of envelope components and air permeability), (ii) solar factor of glazed units, (iii) thermal mass and (iv) type of natural ventilation strategy, are identified; two options are proposed for the envelope resistance to heat flows and air infiltration and three options for the remaining design parameters. By combining the above design options, 54 building variants have been derived. Focusing on the summer period, the 16 long-term discomfort indices reported in Ref. [8] are employed for assessing the comfort performance of the 54 different building variants.

2. Background

2.1. Current use of the long-term discomfort indices in literature

A long-term thermal discomfort index is a metric that summarizes in one value the thermal comfort performance inside a building, evaluated over a long period. A number of authors use methods and indices for assessing thermal comfort for comparing the performance of different design strategies or for improving the overall design of a new building.

Pane [9] measures the frequency of exceedance of the threshold temperatures of 25 °C and 27 °C for studying the relationship between thermal mass and summer overheating. Schnieders [10] uses the frequency of the overheating events for comparing several options of glazing units and for assessing summertime climate in a passive house; to support designers against summer overheating, the frequency of exceedance of the temperatures of 25 °C and 26 °C has been included in the software 'Passive house planning package' (PHPP), which is used for the design and validation of the German Passivhauses [11]. Grignon-Massé, Marchio [12] use one of the long-term discomfort indices introduced by ISO 7730 and called 'Percentage outside range' (POR) to assess the cooling performance of several building-envelope-retrofitting techniques and ventilation strategies in offices and commercial buildings. Also Rohdin, Molin [13] use POR, and represent it using the foot-print proposed in EN 15251, for assessing thermal comfort conditions in nine passive houses in Sweden as a consequence of the change of the set-point temperature. Hwang and Shu [14] use the PPD weighted criterion derived by ISO 7730 to quantify discomfort due to overheating between May 1 and September 30. Cappelletti, Prada [15] also adopted the PPD weighted criterion to assess long-term thermal discomfort conditions due to different glazing units in an open-space office under controlled indoor thermal conditions. Yao [16] assesses the effect of movable solar shading calculated in two scenarios with the building in free-floating mode by comparing the distribution of PMV votes. Borgeson and Brager [17] propose two long-term discomfort indices called $\text{Exceedance}_{\text{PPD}}$ and $\text{Exceedance}_{\text{Adaptive}}$ and use them to assess, through simulations, summer thermal discomfort caused in a reference free-floating building simulated in the 16 different climatic zones of California. Di Perna, Stazi [18] use the version of POR based on the European adaptive comfort model and introduced by EN 15251 to assess the summer reduction of thermal discomfort offered by an increase of thermal mass.

In the last years, long-term discomfort metrics have been used more and more often in mathematical optimization of buildings where thermal comfort is employed as an objective function of the optimization problem, or as a constraint or penalty function. Wang and Jin [19] use a sum weighted method to solve a multi-objective optimization problem and one of the objective functions is thermal discomfort defined as the square of the hourly simulated 'Predicted mean vote' (PMV), which was introduced in Ref. [4]. Kolokotsa, Stavrakakis [20] and Mossolly, Ghali [21] use the square of the difference between a threshold PMV set by the user and the hourly simulated PMV. Angelotti, Pagliano [22] use PMV to optimize the design of ground exchangers and night ventilation strategies. Nassif, Kajl [23], and Kummert and André [24] minimize the hourly simulated index called 'Predicted percentage of dissatisfied' (PPD), which was introduced in Refs. [4], for optimizing a HVAC control system strategy. Magnier and Haghighat [25] build an objective function multiplying the average PMV over the whole year and over all occupied zones by a function directly proportional to the number of hours when the absolute value of PMV is higher than 0.5. Corbin, Henze [26] use as an objective function the deviation from the actual PMV with respect to the PMV thresholds of ±0.5, weighted by the floor area of every zone of the building. Emmerich, Hopfe [27] assess long-term thermal discomfort conditions in building counting the frequency of hourly exceedance of a threshold temperature fixed at 28 °C, and optimize a building by minimizing such long-term discomfort metric. Loonen, Trčka [28] use the same strategy but choose a temperature threshold fixed at 25 °C. Hoes, Hensen [29] minimize summer overheating and winter overcooling hours and, in order to ensure a minimal thermal comfort level, they set a constraint on the maximum number of discomfort hours fixed at 200 h. Stephan, Bastide [30] used POR and the 'Degree-hour criterion' (DhC) expressed in the EN 15251 version to optimize openings for night natural ventilation in order to activate the thermal mass and, hence, reduce diurnal thermal discomfort. An optimization procedure that adopts the 'Long-term Percentage of Dissatisfied' (LPD) to support the design of a net zero energy building located in a warm climate is proposed in Refs. [31,32]. Finally, besides energy and cost, a long-term metric based on thermal comfort has been used as the objective function in an optimization process [33,34]. Due to the large number of indices based on different assumptions found in the literature, Carlucci and Pagliano [8] collected and reviewed 16 long-term discomfort indices and grouped them into four families according to common features. This paper analyzes these 16 long-term discomfort indices and draws conclusions from their use for evaluating the long-term thermal comfort condition in a building model.

2.2. Comfort models and their applicability ranges

2.2.1. The Fanger model

The Fanger model was developed starting from studies carried out in controlled climate chambers [4]. The idea at the base of this comfort model is that thermal sensation felt by a person can be correlated to the heat balance of the human body under steady-state condition. According to this assumption, if total thermal power leaving the human body compensates the summation of power generated by and entering into it, a person is in a neutral state which corresponds to a theoretical comfort condition and is indicated with a ‘Predicted mean vote’ (PMV) of zero, in the ASHRAE seven-point scale of thermal sensation. According to Fanger, the heat balance of the human body depends on four physical variables of the thermal environment, i.e., dry-bulb air temperature, mean radiant temperature, air speed, and relative humidity, and on two variables related to the person, i.e., his/her metabolic activity and the thermal resistance of clothing (plus the chair when seated). The Fanger comfort model is valid for steady-state conditions, and if the following six main parameters remain within the intervals [1]:

- Air temperature: $t_a \in [10.0, 30.0]$ °C;
- Mean radiant temperature: $t_{mr} \in [10.0, 40.0]$ °C;
- Air speed: $\upsilon_a \in [0.0, 1.0]$ m s^{-1};
- Water vapour partial pressure: $p_a \in [0, 2700]$ Pa;
- Metabolic activity: $M \in [0.8, 4.0]$ met;
- Clothing insulation: $I_{\text{cloth}} \in [0.0, 2.0]$ clo.

Also, the applicability of the Fanger model is limited to values of PMV falling within the range $[-2, +2]$.

According to these limitations, the long-term discomfort indices based on Fanger model represent a reliable rating (depicted in solid gray in the following figures) only for those building variants whose indoor environmental conditions agree with the aforementioned intervals. On the contrary, the values of the long-term discomfort indices of those building variants whose indoor environmental conditions are outside aforementioned ranges have been calculated and are depicted in solid white, only to provide a graphical indication of the behavior of the indices, but they do not have to be considered as a reliable assessment of the thermal comfort performance according to the Fanger model.

2.2.2. The adaptive models

The Fanger model was developed with studies carried out in controlled climate chambers and assumes steady-state conditions. According to some authors, and Fanger itself [35], it overestimates summer discomfort in free-running buildings, because it does not take, or only partly takes, into account human thermal adaptation and other non-thermal issues such as *personal factors* (age, sex, culture, economic state etc.), *psychological factors* (thermal preference, thermal expectation, personal attitude etc.) and *interaction with the environment* (visual and acoustic perception, air quality level etc.) [3,36,37]. The theoretical base of adaptive comfort models is the concept of adaptation [36], which occurs in three ways: physiological, psychological and behavioral.

The adaptive models were derived from statistical analyses of formalized interviews of occupants (surveys) and physical data monitored in real buildings during regular operation conditions. In general, they provide a correlation between the theoretical indoor comfort temperature and time evolution of the outdoor temperature, in the form of a linear regression equation. The several adaptive models proposed during the last decades differ for the values of (i) the slope and (ii) the *y*-intercept of the equation, (iii) for the type of average used to represent the evolution of the outdoor air temperature, $f(T_{\text{out}})$, and (iv) for the extension of their applicability range.

Among a large number of models proposed in literature, two of them have gained an international consensus and were included in two standards: one is the American adaptive model and the latter is the European adaptive model. The American adaptive model was developed by de Dear and Brager [36] and was introduced for the first time in American standardization in 2004, through a revision of the standard ANSI/ASHRAE 55 [38]. Its application is limited to ‘naturally ventilated buildings’, i.e., “those spaces where the thermal conditions of the space are regulated primarily by the opening and closing of windows by the occupants” [38]. The European adaptive model was developed by Nicol and Humphreys [3] and was introduced in the European standardization in 2007, within the standard EN 15251 [2]. EN 15251 limits the adoption of the European adaptive model to those ‘buildings without mechanical cooling systems’. Both the models can be employed when the functions used to represent the evolution of the outdoor air temperature fall inside specific applicability ranges (Table 1); outside such ranges, they are not applicable.

3. The adopted methodology

The indices for the long-term evaluation of the general thermal comfort conditions in buildings are useful tools since they summarize the long-term thermal performance of a given building in a single value. As they assess thermal discomfort according to different assumptions and using diverse calculation approaches, they provide different results. In order to systematically analyze the differences among the 16 long-term discomfort indices, these indices have been compared and contrasted. The adopted methodology consisted of seven sequential phases.

3.1. Selection of the reference building and its numerical modeling

The selection of the reference building has fallen on an office building because (i) all comfort models were developed in office-like conditions, and this choice helps avoiding some critical issues of the application of the comfort models, such as for example the issue of occupied night hours, typical of the residential buildings; (ii) the reference assumptions about metabolic activity and clothing insulation in offices are suggested in standards, and this limits the arbitrariness of an analyst; then, (iii) offices have high internal loads that increase the likelihood of summer overheating.

Another issue that deserves to be discussed is the effect of thermal zoning on the distribution of the zone long-term discomfort indices. For this reason, the reference model is composed of a high number of thermal zones, i.e., 34. It is a large five-story office building characterized by an occupied volume of 32 706 m^3 and an external surface of 8 501 m^2, thus its shape ratio (S/V) is 0.26 m^{-1} (Fig. 1). The window-to-wall ratio is 40%.

The standard floor, which is repeated for each story, was zoned in five thermal zones. All five stories were simulated in order to take into account the differences in thermal comfort conditions

Table 1
Terms of the comfort equation according to the American and European adaptive models.

Model name	Standard name	Gradient	$f(T_{\text{out}})$	*y*-Intercept	Range of applicability
American adaptive model	ANSI/ASHRAE 55	0.31	Monthly mean outdoor air temperature	17.8	$f(T_{\text{out}}) \in [10.0, 33.5]$ °C
European adaptive model	EN 15251	0.33	Exponentially weighted running mean outdoor air temperature	18.8	$f(T_{\text{out}}) \in [10.0, 30.0]$ °C

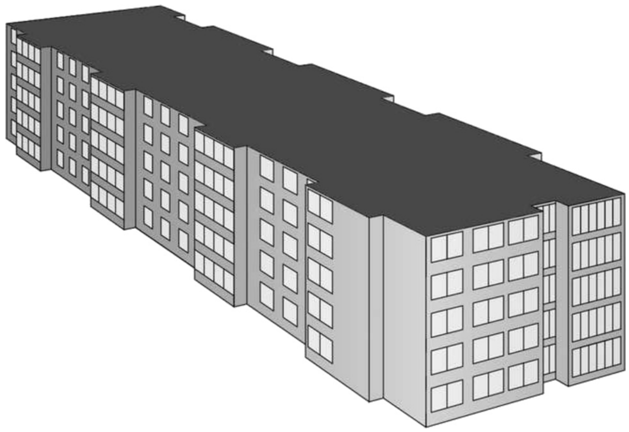

Fig. 1. Tridimensional visualization of the building model.

among the several typologies of zones. Internal loads follow the typical daily schedules shown in Fig. 2.

In energy simulation, windows automatically open, during night hours, if the hourly outside air temperature is lower than the hourly indoor air temperature with a difference in temperature of no more than 10 °C; The percentage of opening is a design variable and its options are reported in Table 2.

The weather file used in simulation is the 'International Weather for Energy Calculations' (IWEC) file of Rome. The calculation period is the typical Italian summer period from May 15 to September 30.

The dynamic energy simulation of the building was performed using the software EnergyPlus [6], version 6.0.0.23. Each released version of EnergyPlus undergoes two major types of validation tests [39]: analytical tests, according to ASHRAE Research Projects 865 and 1052, and comparative tests, according to ANSI/ASHRAE 140 [40] and IEA SHC Task34/Annex43 BESTest method. Within the capability of EnergyPlus, the building models were set up with a priority to reproduce quite in detail the geometrical features of the building and the physical phenomena that determine the thermal behavior of the building, although this was at the expense of rather large computational times. The update frequency for calculating sun paths was set to 7 days, rather than the default 20 days. The heat conduction through the opaque envelope was calculated via the finite difference method with a 3-minute time step, rather than using the default transfer function method with a 15-minute time step, in order to improve calculation accuracy in the presence of components with high thermal inertia [41]. The natural convection heat exchange near external and internal surfaces was calculated via the adaptive convection algorithm [42], to better meet the local conditions of each surface of the model. The initialization period of simulation was set at 25 days, instead of using the default value of 7 days, to reduce the uncertainties connected to the thermal initialization of the numerical model. The voluntary ventilation and involuntary air infiltration were calculated with the *AirflowNetwork* module, instead of using the much simpler scheduled approach, to better calculate the contribution of natural ventilation.

3.2. Construction of the building variants

The design variables selected for the optimization problem are those that mainly affect the summer behavior of a building according to [43]: (i) envelope quality (expressed through the steady-state transmittance of envelope components and air permeability), (ii) solar factor of glazing unit of the windows, (iii) exposed internal thermal mass and (iv) operable window area for night natural ventilation. Then, various options were assumed for each design variable as reported in Table 2. The focus was set on passive means in order to apply the first step of the design procedure proposed by

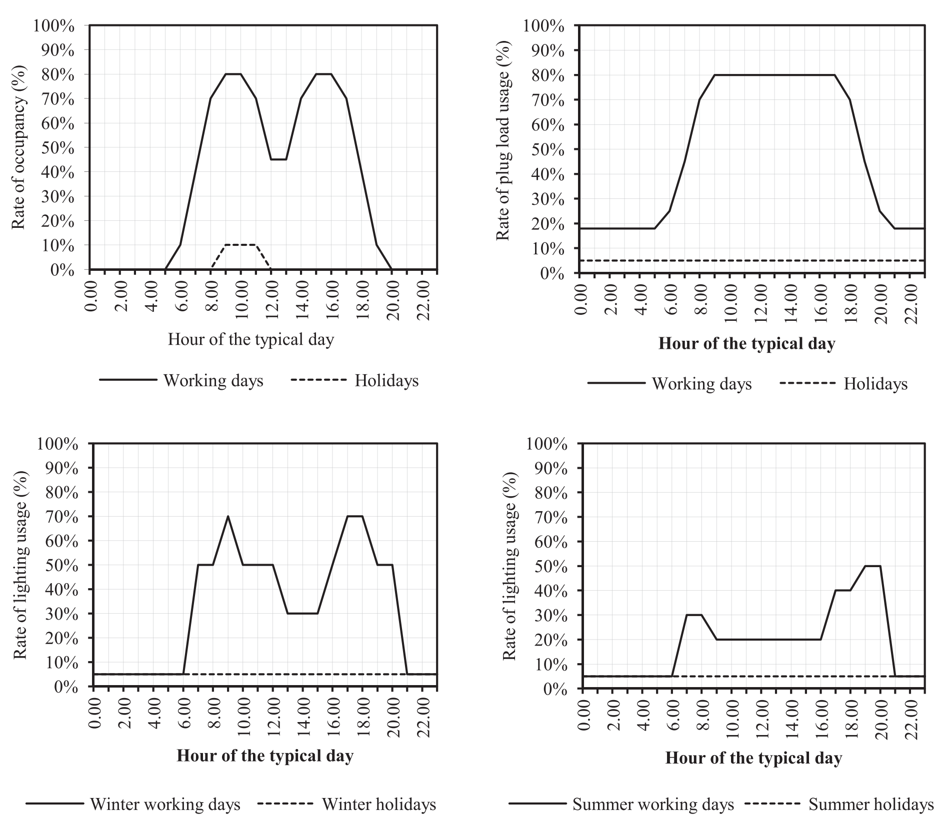

Fig. 2. Schedules of the occupancy rate and of the percentage of installed power in use at specified hours assumed in the simulations.

Table 2
Summary of the options proposed for each design variable and symbols assigned to each option.

Design variable	Option				
Steady-state transmittance of envelope components and air permeability of the envelope	o	Legal	Roof (Rome)	0.36	W m^{-2} K^{-1}
			External wall (Rome)	0.32	W m^{-2} K^{-1}
			Floor (Rome)	0.36	W m^{-2} K^{-1}
			Window (Rome)	2.40	W m^{-2} K^{-1}
			Air permeability[a]	5.0	m^3 h^{-1} m^{-2}
	+	Advanced	Roof	0.20	W m^{-2} K^{-1}
			External wall	0.20	W m^{-2} K^{-1}
			Floor	0.20	W m^{-2} K^{-1}
			Window	1.20	W m^{-2} K^{-1}
			Air permeability[a]	0.5	m^3 h^{-1} m^{-2}
Solar factor of glazed units	−	Existing typical	Façade N	–	–
			Façade NE–NW	0.70	–
			Façade E-SE-S-SW-W	0.70	–
	o	Medium	Façade N	–	–
			Façade NE–NW	0.40	–
			Façade E-SE-S-SW-W	0.40	–
	+	Advanced	Façade N	–	–
			Façade NE–NW	0.27	–
			Façade E-SE-S-SW-W	0.15	–
Exposed thermal mass	−	Low	External wall[b]	4.0	Wh m^{-2} K^{-1}
			Ceiling[b]	11.0	Wh m^{-2} K^{-1}
			Floors[b]	4.1	Wh m^{-2} K^{-1}
			Internal walls[b]	2.3	Wh m^{-2} K^{-1}
			Building[c]	20.0	Wh m^{-2} K^{-1}
	o	Medium	External walls[b]	15.4	Wh m^{-2} K^{-1}
			Ceiling[b]	18.6	Wh m^{-2} K^{-1}
			Floor[b]	12.7	Wh m^{-2} K^{-1}
			Internal wall[b]	8.9	Wh m^{-2} K^{-1}
			Building[c]	50.0	Wh m^{-2} K^{-1}
	+	High	External wall[b]	15.4	Wh m^{-2} K^{-1}
			Ceiling[b]	22.1	Wh m^{-2} K^{-1}
			Floor[b]	22.4	Wh m^{-2} K^{-1}
			Internal wall[b]	18.8	Wh m^{-2} K^{-1}
			Building[c]	80.0	Wh m^{-2} K^{-1}
Natural ventilation strategy	−	No	Percentage of total operable window area	0	%
	o	Medium	Percentage of total operable window area	25	%
	+	High	Percentage of total operable window area	50	%

[a] Air permeability is calculated at a pressure difference of 4 Pa according to SIA 180 [44] and is referred to the gross area of the building envelope.
[b] Thermal capacity of a building component is calculated according to EN ISO 13786 [45]. It is expressed per the net area of the building component.
[c] Thermal capacity for a building or a zone of a building is calculated according to the SIA definition [46] based on EN ISO 13786. It is expressed per the zone net floor area.

EN 15251, which aims at optimizing only the envelope and passive systems by using a long-term discomfort index based on the adaptive model. The second step requires the introduction of a mechanical cooling system and can be used for optimizing also active systems with respect to a long-term discomfort index based on the Fanger model. Then, 54 building variants of a reference-building model were constructed by combining all options of the four design variables (Table 3).

3.3. Simulation of the building variants and storage of the data

All 54 building variants have been simulated with the dynamic building performance software, EnergyPlus, and the hourly values of indoor air temperature, mean radiant temperature, relative humidity, air speed and PMV for each zone of building models have been stored in a database.

3.4. Statistical analysis of the indoor operative temperatures

In our analysis, occupants are assumed to be (i) in near sedentary metabolic activity (1.2 met), (ii) not exposed to direct sunlight and (iii) not exposed to an air speed greater than 0.20 m s^{-1}. Given these assumptions, operative temperature can be approximated with an acceptable accuracy by the arithmetic mean of air temperature and mean radiant temperature [38].

To provide a first comparison between the building variants, a statistical analysis of the indoor temperatures has been performed. One simulation has been carried out for every building variant, and it has delivered the hourly indoor operative temperature values for each zone of that building model. Then, the hourly indoor operative temperatures have been averaged on the sole occupied hours to have a single value for each zone of the building. To summarize, in the following we indicate with the term 'time-averaged indoor operative temperature' the operative temperature of a thermal zone, averaged over the occupied hours in the period May 15 to September 30.

Although the number of zones of the building model is quite high, the distribution of the time-averaged indoor operative temperature values does not follow the normal distribution in every building variant. Therefore, the distribution of the time-averaged indoor operative temperatures over the various thermal zones of each building variant has been represented with a box-and-whisker-plot graph reporting the median, the first and third quartiles, the tails of the distributions and the outliers values. The median is indicated with a solid horizontal segment, the distances from the median and the first and third quartiles are indicated with gray boxes, the tails of the distribution are indicated with two whiskers and show the highest and lowest data points (maximum or minimum time-averaged operative temperatures recorded in the building zones) or otherwise 1.5 times the box range [47]. The

Table 3
Building variants obtained by combining the options of the design variables.

Name of the building variant	Steady-state transmittance	Air permeability	Thermal mass	Solar factor	Night natural ventilation
Variant 01	o	o	−	+	−
Variant 02	o	o	−	+	o
Variant 03	o	o	−	+	+
Variant 04	o	o	−	o	−
Variant 05	o	o	−	o	o
Variant 06	o	o	−	o	+
Variant 07	o	o	−	−	−
Variant 08	o	o	−	−	o
Variant 09	o	o	−	−	+
Variant 10	o	o	o	+	−
Variant 11	o	o	o	+	o
Variant 12	o	o	o	+	+
Variant 13	o	o	o	o	−
Variant 14	o	o	o	o	o
Variant 15	o	o	o	o	+
Variant 16	o	o	o	−	−
Variant 17	o	o	o	−	o
Variant 18	o	o	o	−	+
Variant 19	o	o	+	+	−
Variant 20	o	o	+	+	o
Variant 21	o	o	+	+	+
Variant 22	o	o	+	o	−
Variant 23	o	o	+	o	o
Variant 24	o	o	+	o	+
Variant 25	o	o	+	−	−
Variant 26	o	o	+	−	o
Variant 27	o	o	+	−	+
Variant 28	+	+	−	+	−
Variant 29	+	+	−	+	o
Variant 30	+	+	−	+	+
Variant 31	+	+	−	o	−
Variant 32	+	+	−	o	o
Variant 33	+	+	−	o	+
Variant 34	+	+	−	−	−
Variant 35	+	+	−	−	o
Variant 36	+	+	−	−	+
Variant 37	+	+	o	+	−
Variant 38	+	+	o	+	o
Variant 39	+	+	o	+	+
Variant 40	+	+	o	o	−
Variant 41	+	+	o	o	o
Variant 42	+	+	o	o	+
Variant 43	+	+	o	−	−
Variant 44	+	+	o	−	o
Variant 45	+	+	o	−	+
Variant 46	+	+	+	+	−
Variant 47	+	+	+	+	o
Variant 48	+	+	+	+	+
Variant 49	+	+	+	o	−
Variant 50	+	+	+	o	o
Variant 51	+	+	+	o	+
Variant 52	+	+	+	−	−
Variant 53	+	+	+	−	o
Variant 54	+	+	+	−	+

outliers are the maximum or minimum values of the indoor operative temperature, in some zones of the building, respectively lower than the 1st percentile and higher than the 99th percentile.

3.5. Verification of the applicability of the comfort models

The simulated indoor conditions of each building variant have been compared with the applicability ranges of the three comfort models: the American and European adaptive models and the Fanger model.

The applicability ranges of the adaptive models depend on the two functions used to represent the evolution of the outdoor air temperature. Outdoor air temperature is the same for every simulation and does not depend on the options chosen for the design variables. Thus, the applicability of the adaptive models has been verified once for each of the two adaptive models. According to the IWEC file of Rome, during the period from May 15 to September 30, both the functions used to represent the evolution of the outdoor air temperature fall inside the two applicability ranges, and, hence, all long-term discomfort indices based on both the adaptive comfort models can be used to assess all building variants.

According to ISO 7730, the Fanger model should be used when the aforementioned six main parameters remain within the applicability ranges indicated in ISO 7730 (see Sect. 2.2.1). Since indoor air temperature, mean radiant temperature and air speed change as a consequence of the chosen options of the design

Table 4
List of the analyzed long-term discomfort indices and outcomes of the univariate and bivariate analysis.

Long-term discomfort index	Mean	Median	Coefficient of variation	Variance	Spearman's rank coefficient
$DhC_{Fanger,ISO\ 7730}$	3485 °Ch	1864 °Ch	1.05	13 346 773 °C²h²	0.995
$DhC_{Fanger,EN\ 15251}$	4559 °Ch	1884 °Ch	1.28	33 874 235 °C²h²	0.984
$DhC_{Adaptive}$	3032 °Ch	708 °Ch	1.71	26 859 886 °C²h²	0.925
$PPDwC_{ISO\ 7730}$	4635 h	2804 h	0.82	14 365 453 h²	0.988
$PPDwC_{EN\ 15251}$	4635 h	2804 h	0.82	14 365 453 h²	0.988
Sum_PPD	482 h	305 h	0.79	146 552 h²	0.993
$POR_{Fanger,PMV}$	0.71	0.69	0.30	0.05	0.980
$POR_{Fanger,T_{op}}$	0.70	0.67	0.32	0.05	0.979
$POR_{Adaptive}$	0.40	0.21	0.88	0.13	0.870
$Exceedance_{PPD}$	0.55	0.45	0.58	0.10	0.983
$Exceedance_{Adaptive}$	0.47	0.35	0.79	0.14	0.985
$CIBSE_J$	0.81	0.84	0.22	0.03	0.970
$CIBSE_A$	0.44	0.25	0.83	0.13	0.986
RHOR	0.35	0.28	0.57	0.04	0.232
<PPD>	0.41	0.25	0.76	0.10	0.985
NaOR	0.31	0.16	1.01	0.10	0.987

variables, the applicability of the Fanger model has to be verified for every building variant. Thus, if all parameters are within the applicability ranges, the values of the long-term discomfort indices for a given variant are representative of the general comfort conditions and are reported in the following figures with solid gray signs. Instead, if at least one of the six main parameters of a certain variant is outside its applicability range, the adoption of the Fanger model is outside the scope of ISO 7730; the values of the long-term discomfort indices for that variant are not representative of the general comfort conditions and are reported in the following figures with solid white signs. It is remarked that the objective of this work is not to discuss the applicability of a given comfort model, rather to investigate the ranking capability of long-term discomfort indices.

3.6. Calculation of the long-term discomfort indices and their analysis

The 16 long-term discomfort indices described and reviewed in Ref. [8] are:

1. CIBSE Guide J criterion, $CIBSE_J$ [48].
2. Accumulated PPD, Sum_PPD [1].
3. Average PPD, <PPD> [1].
4. Percentage of occupied hours when actual PMV is outside the Fanger comfort range, $POR_{Fanger,PMV}$ [1,2].
5. Percentage of occupied hours when the indoor operative temperature[1] is outside the Fanger comfort range, $POR_{Fanger,T_{op}}$ [1,2].
6. Degree-hour criterion based on the Fanger comfort model as proposed in ISO 7730, $DhC_{Fanger,\ ISO\ 7730}$ [1,2].
7. Degree-hour criterion based on the Fanger comfort model as proposed in EN 15251, $DhC_{Fanger,\ EN\ 15251}$ [1,2].
8. Degree-hour criterion based on the EN adaptive comfort model, $DhC_{Adaptive}$ [1,2].
9. PPD-weighted criterion as stated in ISO 7730, $PPDwC_{ISO\ 7730}$ [1,2].
10. PPD-weighted criterion as stated in EN 15251, $PPDwC_{EN\ 15251}$ [1,2].
11. CIBSE Guide A criterion, $CIBSE_A$ [49].
12. Percentage of occupied hours when the indoor operative temperature is outside the EN adaptive comfort range, $POR_{Adaptive}$ [2].
13. Robinson and Haldi's overheating risk, RHOR [50].
14. Nicol et al.'s overheating risk, NaOR [51].
15. $Exceedance_{PPD}$ [17].
16. $Exceedance_{Adaptive}$ [17].

Such indices have been calculated for the 54 building variants. It should be noted that the calculation rules of some indices do not report a guidance about how to compute the whole-building index in a multi-zone building from the single zone values; in such cases the individual zone values have been averaged over the net volume of each zone.

Although the mathematical models behind the long-term discomfort indices are well known, they cannot be directly compared since they are calculated in different ways and under different assumptions. Thus, assuming that the long-term discomfort indices are random variables with respect the time-averaged indoor operative temperature, some tools of the descriptive statistics provide the main features of their distributions. The univariate analysis is used for describing the distribution of the values of a single long-term discomfort index by quantifying its central tendency (through the mean and the median), its dispersion (through the coefficient of variation) and by measuring its location (through its variance). The bivariate analysis quantitatively measures the correlation between the single index and the corresponding time-averaged indoor operative temperature. This requires to test the hypothesis of normal distribution, and, since none of the indices passes the Shapiro–Wilk normality test [52], Spearman's rank coefficient is used to characterize correlation. Spearman's rank coefficient also provides estimation of how well a monotonic function represents a relationship between two ranked variables. Table 4 reports a summary of the descriptive statistical analysis.

Finally, only those indices representable on the percentage scale are fitted with an ordered logistic regression, and the ordered logistic regression models are compared in subsamples in order to quantify the differences or similarities among the analyzed long-term discomfort indices in ranking the same building variants.

[1] The limit values of PMV have been translated into operative temperatures adopting the assumptions contained in ISO 7730 for summer conditions: metabolic rate of 1.2 met, clothing resistance of 0.5 clo, air velocity of 0.1 m s^{-1}, relative humidity of 50%, mean radiant temperature equal to air temperature equal to operative temperature. The fact that some variables are forced to assume predefined fixed values should be kept in mind when evaluating the index.

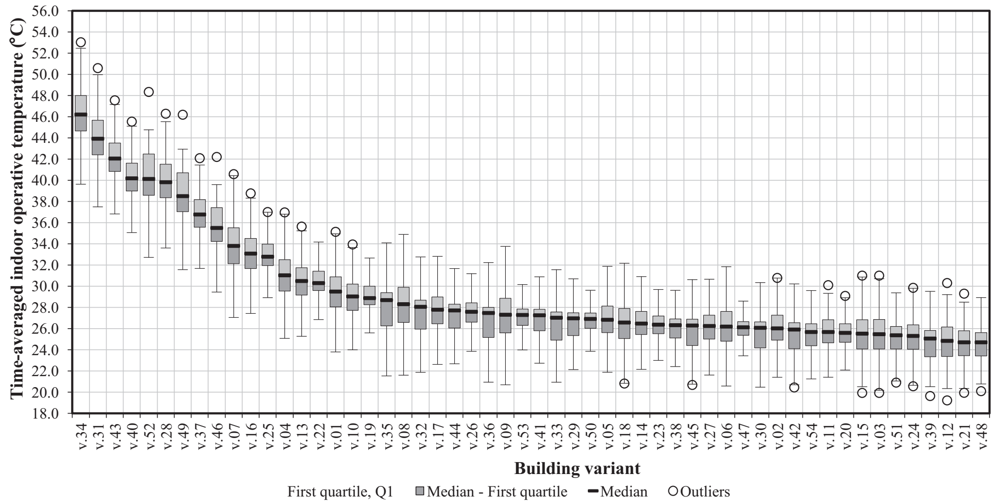

Fig. 3. Box-and-whisker-plot representation of the time-averaged indoor operative temperature distribution over the thermal zones for each building variant.

3.7. Pairing long-term discomfort indices to assess conditioned and free-floating buildings

One of the objectives of this work is to identify a pair of long-term discomfort indices made by an index suitable to be used in conditioned buildings (better if based on the Fanger model) and an index suitable in free-floating buildings (better if based on one of the adaptive models), which can be reliably adopted in a two-step optimization procedure. To this aim, the two indices should have a monotone and regular trend. The monotone behavior is required to ensure a paired ranking of thermal discomfort according the two indices, and, hence, Spearman's rank coefficient is used to estimate of how well a monotonic function represents the relationship between such two indices.

4. Discussion of the results

A detailed description of the 16 long-term discomfort indices analyzed in this paper and a comprehensive list of their strengths and weaknesses are reported in Ref. [8]. In this paper, they are calculated using as input the indoor environmental conditions simulated for each building variant (hence, the same input for all 16 indices), and their ranking capability is discussed. Obviously, the values of the indices presented in this paper are specific for the described case study, since they depend on the reference building that has been chosen, on the assumptions made about the occupant-related input variables, on the climate for which it has been simulated and the chosen calculation period, but the fact that the indices provide quite different rankings of the variants and drive the design process towards different 'optimal' variants is unlikely to depend on the specific case study. At the minimum, we have identified at least one case where the various indices would deliver different conclusions to a designer about the design of the analyzed case study.

The selected 16 long-term discomfort indices have been compared in subsets to identify their similarities and differences in ranking the building variants. Moreover, information is delivered about the implications of the choice of a given index on the design process (or on the assessment) of a building. The most general categorization of the long-term discomfort indices depends on whether they are representable on a percentage scale or not.

4.1. Statistical description of the indoor operative temperatures inside the building variants

The distributions over the thermal zones of each building variant of the time-averaged indoor operative temperatures of all building variants are compared in Fig. 3, and the building variants are ordered with respect to the value of the median, from the highest value to the lowest one.

The building variants on the left side of Fig. 3 are characterized by very high values of the indoor operative temperatures averaged on the sole occupied hours. According to this analysis, higher values of the solar factor of glazing units cause the rise of indoor temperature if the other design variables are kept constant, however solar factor is not the only responsible for the indoor conditions. Specifically, the building variants with the median of time-averaged indoor operative temperature:

- higher than 29 °C are all characterized by the absence of night ventilation, which is the only strategy to dissipate internal energy of the building in this analysis. During the summer period in climates with hot summer dissipation strategies are as important as strategies limiting the energy entering into the building;
- higher than 35 °C are also all characterized by the absence of night ventilation plus a high insulated envelope with a low air permeability. Without a dissipative possibility, the only way to decrease internal energy, when indoor temperature are higher than outdoor ones, is the heat exchange by conduction through the envelope and involuntary air infiltration; for this reason, an envelope with a high resistance to heat and air flows is pejorative if not coupled with effective dissipation strategies in summer dominated climates;
- higher than 40 °C are also all characterized by the absence of night ventilation plus a high insulated envelope with a low air permeability plus medium and low exposed thermal mass. Exposed thermal mass acts on the dynamic evolution of, at first, mean radiant and, then, air temperatures cutting their peaks. Low values of thermal mass are not able to reduce the temperature rise during hottest hours.

4.2. Descriptive statistical analysis of the long-term discomfort indices

The result of the univariate and bivariate analyses are reported in Table 4.

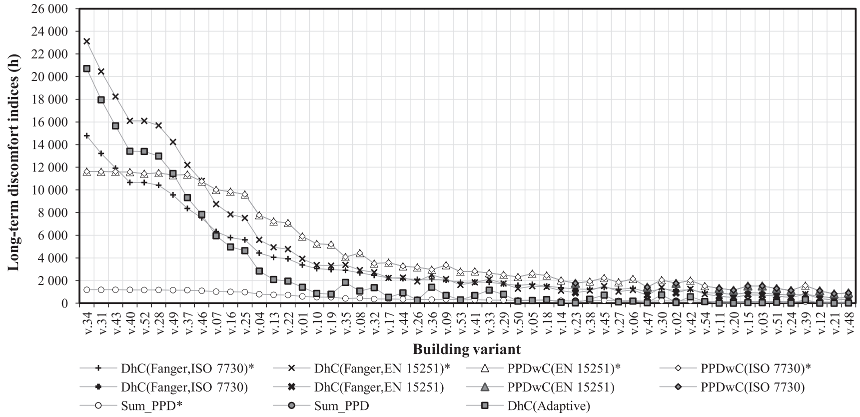

Fig. 4. Comparison of the cumulative indices (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

(Arithmetical) mean represents the central value of a data sample and median represents the numerical value separating the higher half of a data sample from the lower half. With the exception of the POR_{Fanger}, all other indices are characterized by substantially different values of the mean and median; this means that their distributions are not symmetrical. The central values of the indices built on the Fanger comfort model (or more generically, designed for mechanically cooled buildings) are higher than those built on an adaptive comfort model or designed for naturally ventilated buildings, for every family of indices.

The coefficient of variation represents a normalized measure of dispersion of a distribution in case of comparison between datasets with different units of measure (as in our case), because it is independent of the unit of the data; it can be computed only for data expressed on a ratio scale, as these that can only assume non-negative values. All long-term discomfort indices are ordinal data, since they admit a null value and do not admit negative values. Distributions with a coefficient of variation lower than 1 are considered low-variance, while those with the coefficient of variation higher than 1 are considered high-variance. The coefficient of variance shows that the long-term indices built on an adaptive comfort model are characterized by a higher dispersion, for every family of indices.

Variance is one of the estimators to measure the spread of a data sample. Applied to the long-term discomfort indices, it shows, similarly to the coefficient of variance, that spreads of the indices built on an adaptive comfort model or designed for naturally ventilated buildings are higher than those built on the Fanger comfort model or designed for mechanically-cooled buildings, with the exception of NaOR that has a value of variance equal to <PPD>.

Spearmen's correlation coefficient shows that most of the analyzed long-term discomfort indices prove to be highly correlated with the median of time-averaged indoor operative temperature, and the most correlated are the cumulative indices; instead, RHOR proves to be weakly correlated with the indoor conditions within the building variants, and the POR indices deliver outcomes not strictly close to the median of time-averaged indoor operative temperatures. The two versions of the PPDwC show to be equal in these tests, and the two indices that explicitly measure the likelihood of dissatisfied, NaOR and <PPD>, are also very close to each other.

In summary, the long-term discomfort indices built on the Fanger comfort model or addressed to mechanically cooled buildings are higher in value and less dispersed than those built on an adaptive comfort model or, more generically, addressed to naturally ventilated buildings. The two indices that measure the likelihood of dissatisfaction, NaOR and <PPD>, although are based on different comfort models and are respectively addressed to free-floating and mechanically conditioned buildings, show similar values of the variance and of correlation with the median of time-averaged indoor operative temperature, even if their central values are different; then in summary, NaOR and <PPD> deliver quite coordinated ratings of the building variants, slightly shifted in the values.

Table 5
Outcomes of the ordered logistic regression analysis applied to the percentage indices.

Long-term discomfort index	*a*	*b*	Root mean square deviation, *RMSD*	*x*-Value of the point of inflection
$POR_{Fanger,PMV}$	−13.826	0.537	0.040	25.8
$POR_{Fanger,T_{op}}$	−14.226	0.549	0.042	25.9
$POR_{Adaptive}$	−19.390	0.666	0.057	29.1
$Exceedance_{PPD}$	−19.872	0.725	0.048	27.4
$Exceedance_{Adaptive}$	−25.398	0.908	0.048	28.0
$CIBSE_{A}$	−22.243	0.782	0.041	28.5
$CIBSE_{J}$	−19.550	0.780	0.046	25.1
<PPD>	−12.995	0.440	0.019	29.6
NaOR	−12.156	0.384	0.014	31.6
RHOR	−4.645	0.134	0.107	34.6

4.3. Comparison of the cumulative indices

The long-term discomfort indices belonging to this category cannot be represented on a percentage scale and are $DhC_{Fanger,\ ISO\ 7730}$, $DhC_{Fanger,\ EN\ 15251}$, $DhC_{Adaptive}$, $PPDwC_{ISO\ 7730}$, $PPDwC_{EN\ 15251}$, Sum_PPD. These are weighted degree-hour indices, and accumulate all time intervals (generally one hour), when a discomfort condition occurs, by multiplying it for a given weighting factor, which could be the simple difference between hourly operative temperature and a boundary temperature of a specified comfort category (e.g., DhC), or the hourly PPD (e.g., Sum_PPD) or a more complex metric (e.g., PPDwC). All these indices are based on a comfort model; DhC and PPDwC are also category-dependent and asymmetric indices.[2] Instead, Sum_PPD does not depend on

[2] Asymmetric indices weigh in a different way hours of overheating and of overcooling; for the complete definitions and more details on the features of the indices see Ref. [53]. The issue whether and when to include summer overcooling in the indices (i.e., the choice between symmetric and asymmetric indices) is subject of debate in the literature and in the standardization committees.

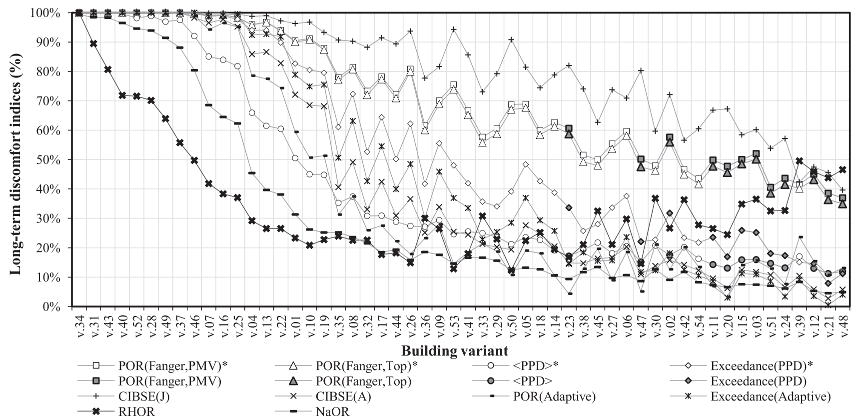

Fig. 5. Comparison of the indices, which can be represented on the percentage scale (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

comfort categories and is symmetric. Their behaviors are compared in Fig. 4.

Since DhCs indices measure the accumulation of the temperature offset from a comfort threshold per each hour, they are higher in those building variants with higher indoor operative temperatures; for this reason, DhCs have trends similar in shape to the trend of the time-averaged indoor operative temperature (Fig. 3).

PPDwCs (both the ISO and EN versions) accumulate the product of a weighing factor for the time (one hour) per each discomfort hour; this weighting factor corresponds to the ratio between the actual PPD and the boundary PPD of a specified category, hence, the hourly weighting factor tends to a constant value for PPD = 100% and for this reason it shows a tendency to saturate to a finite value (corresponding to PPD = 100% in each hour of the calculation period).

Sum_PPD accumulates the hourly value of PPD for each discomfort hour, hence, it saturates to a finite value that corresponds to the product of PPD = 100% per the total number of hours of the calculation period. Sum_PPD shows similar trends to PPDwC due to their similar analytical formulation, but their values differ for an order of magnitude.

The correlation analysis shows that all these indices are closely correlated to the medians of the time-averaged indoor operative temperature (Spearman's rank coefficient, *r*, varies from 0.925 to 0.995).

These indices have the limitation that their scale does not have a higher limit, and they could be impractical for comparing buildings since their values strongly depend on the duration of the calculation period.

$\text{Exceedance}_{\text{PPD}}$ and $\text{Exceedance}_{\text{Adaptive}}$ [17] are also weighted degree-hour indices, since they weigh every hour, when actual PPD is higher than 20%, with a weighting factor that is the actual or forecasted occupation rate, but the summation over all calculation period is divided by the summation of all hourly occupation rates, resulting in a percentage index.

In summary, cumulative indices are able to deliver a measure of the severity of thermal discomfort, but are not normalized with respect to the duration of the calculation period, which depends on the arbitrary choice of the analyst.

4.4. Comparison of the Percentage, Risk and Averaging indices

All these long-term discomfort indices can be expressed on a percentage scale, and for this reason the exceedance indices have been also included in this analysis. They are a large and complex group, composed of indices based or not on comfort models, indices dependent or not by comfort categories, symmetric and asymmetric indices. Also, some of them are provided with discomfort thresholds chosen somewhat arbitrarily rather than based on a comfort model.

The whole list of the indices here analyzed is reported in Table 5 and their comparison is represented in Fig. 5.

Table 5 also reports the ordered logistic regression equations for these indices and the corresponding value of the Root mean square error (RSME) with respect to the original data. The canonical form of the ordered logistic equation is $P(x) = e^{a+bx}/(1 + e^{a+bx})$. In our case the variable *x* is chosen as the median of time-averaged indoor operative temperature.

They deliver results, which are extremely different in the value and in the trend: the difference between the values for a given building variant can differ up to 85% and some indices have a descending trend from the left to the right, but others invert the trend increasing for those variants with lower values of the median of time-averaged indoor operative temperatures (Fig. 5). To have more precise and comprehensive information about their behavior, the aforementioned long-term discomfort indices have been compared in subsets.

4.4.1. Percentage-outside-range indices

These indices measure thermal discomfort as the frequency of the deviations of the PMV, or of the indoor operative temperature, outside a given comfort range. For the analyzed case, the reference comfort category is the Category II of EN 15251, which has to be used for new buildings and renovations. According to it, acceptable PMV values are within the range [−0.5, +0.5] when using the Fanger model, and acceptable indoor operative temperatures must have deviations not greater than 3 K above and below the European adaptive comfort temperature.

Regarding $\text{POR}_{\text{Fanger,PMV}}$, the hourly actual PMV has been extracted from the simulation results having assumed a metabolic activity set to 1.2 met, clothing resistance set to 0.5 clo and external work set to zero met. During an occupied hour, if actual PMV is outside the range corresponding to the Category II, one hour of discomfort is recorded. Then, all discomfort hours within the calculation period are accumulated and are normalized for the total number of hours of the calculation period.

Regarding $\text{POR}_{\text{Fanger,T}_{\text{op}}}$, thermal neutrality (PMV = 0) is translated into operative temperature (24.7 °C) by assuming an air temperature equal to the mean radiant temperature (and hence equal to operative temperature), an indoor air relative humidity of 50%, an air velocity of 0.1 m s^{-1}, a metabolic activity of 1.2 met, a clothing insulation of 0.5 clo and an external work of zero met. The

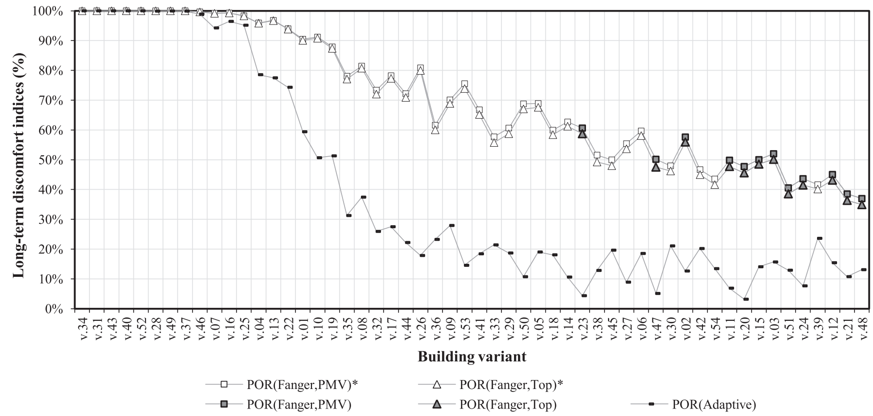

Fig. 6. Comparison of the trends of the Percentage-outside-range indices when category boundaries are expressed via PMV or operative temperature (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

Category II comfort range is identified by an offset of ±1.7 °C from the thermal neutrality temperature, according to ISO 7730. As a result, the upper and lower boundary operative temperatures of the comfort range result respectively in 26.4 °C and 23.0 °C. During the occupied period, one hour of discomfort is recorded each time the hourly indoor operative temperature falls outside the aforementioned comfort range. Then, all the discomfort hours within the calculation period are accumulated and are normalized for the total number of hours of the calculation period. Compared with the previous index, also the value of the relative humidity has to be fixed *a priori*; therefore, $POR_{Fanger,T_{op}}$, results to be less precise than $POR_{Fanger,PMV}$.

Regarding $POR_{Adaptive}$, one hour of discomfort is recorded when the hourly indoor operative temperature falls outside the aforementioned European adaptive comfort range corresponding to the Category II. The temperature range is defined by an offset of ±3 K from the adaptive theoretical comfort temperature.

Such three indices are represented in Fig. 6 as functions of the median of time-averaged indoor operative temperature of every building variant.

$POR_{Fanger,PMV}$ and $POR_{Fanger,T_{op}}$ show values that are very close, as one may expect, since they differ only because the former has been calculated by using the actual indoor relative humidity, while the latter has been calculated by imposing the relative humidity equal to the fixed value of 50%. This outcome confirms that humidity has only a little influence on the long-term thermal comfort assessment in moderate environments, and this agrees with the Fanger comfort model [54].

While $POR_{Fanger,PMV}$ and $POR_{Fanger,T_{op}}$, show (with some fluctuations) a progressive reduction of the discomfort percentage up to Variant 48, $POR_{Adaptive}$ reaches (with some fluctuations) the minimum discomfort value for Variant 20 and the index has a slightly increasing trend for those building variants with the lowest average indoor operative temperatures. Since, during hot periods, the boundary temperatures of the adaptive comfort range are higher than the boundary temperatures of the Fanger comfort range, the increase of discomfort might be due to the increase of the hours when the indoor operative temperature is lower than the adaptive comfort range (overcooling hours), but falls inside the Fanger range (comfort hours). We remind here that night hours are excluded from the calculation period in the present study.

Also an ordered logistic regression (Fig. 7) proves that $POR_{Fanger,PMV}$ and $POR_{Fanger,Top}$, are very similar: the *x*-values of their inflection points ($-a/b$) are respectively 25.8 °C and 25.9 °C and the gradients of the linear segment of the regression models (b) are 0.537 and 0.549 respectively. $POR_{Adaptive}$ is characterized by a significantly higher *x*-value of the inflection point (29.1 °C) and by a higher gradient ($b = 0.67$).

4.4.2. Symmetric indices and the overcooling phenomenon

To analyze if the detected overcooling phenomenon depends only on the definition of the categories, we compare the already mentioned $POR_{Fanger,PMV}$, $POR_{Adaptive}$ that are category-dependent indices and the <PPD> that is category-independent. With respect to the Category II, we disaggregate the frequencies of deviations above the upper comfort boundaries (overheating occurrences) and below the lower comfort boundaries (overcooling occurrences) in Fig. 8.

$POR_{Fanger,PMV}$ records some overcooling phenomena, but discomfort due to overheating is predominant for every variant.

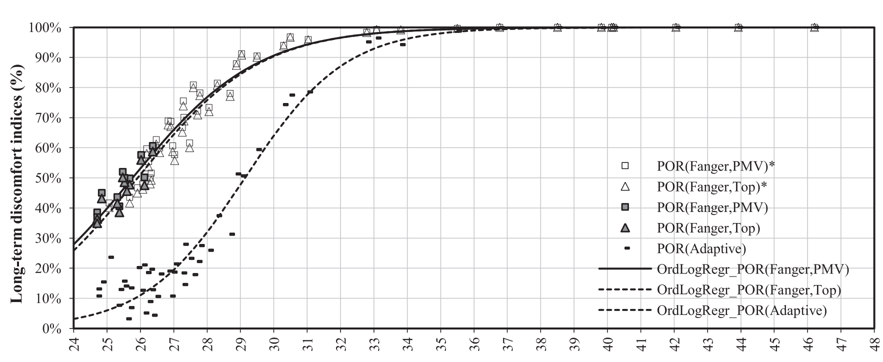

Fig. 7. Ordered logistic regression of the Percentage-outside-range indices.

$POR_{Adaptive}$ also records a number of overcooling phenomena and it results the sole cause of discomfort for the three building variants with the lowest average operative temperatures. <PPD> also records overcooling, and discomfort due to overcooling is comparable with overheating for those variants with the lowest median of time-averaged indoor operative temperatures. It should be noted that the building variants with the lowest average operative temperature – described as affected by overcooling by these indices – are characterized by high levels of natural night ventilation and high level of thermal mass (Table 2).

In summary, (i) symmetric indices detect overcooling that can take place, for example, in those variants characterized by a high level of thermal mass coupled with an efficient night natural ventilation, and this has a significant influence in the ranking of building variants; (ii) the difference between $POR_{Fanger,PMV}$, $POR_{Adaptive}$ is due to the definition of the two comfort ranges in term of theoretical comfort temperature and extension in degrees; (iii) the Percentage-outside-range indices just measure the frequency of hours outside a given comfort range; on the contrary, <PPD> also takes into account the severity of discomfort in each hour since it is related to the likely human thermal perception measured by PPD at each time step.

From this analysis we derive that, in order to interpret correctly the results obtained by using symmetric indices, one should explicitly report their disaggregation in overheating and overcooling. In addition, since $POR_{Fanger,PMV}$ is a simple counter of the hours outside the comfort range, while <PPD> provides a measure of the human thermal perception by accounting for the severity of discomfort in each hour, we believe that <PPD> should be preferred to $POR_{Fanger,PMV}$ when assessing thermal discomfort according to the Fanger comfort model.

4.4.3. Exceedance indices

$Exceedance_{PPD}$ and $Exceedance_{Adaptive}$ are asymmetric indices, i.e., in summer, they take into account only discomfort due to overheating. For both indices, discomfort is considered to occur when hourly indoor conditions exceed a discomfort threshold fixed at 20%. It corresponds to a PPD value of to 20% (PMV = 0.85) for

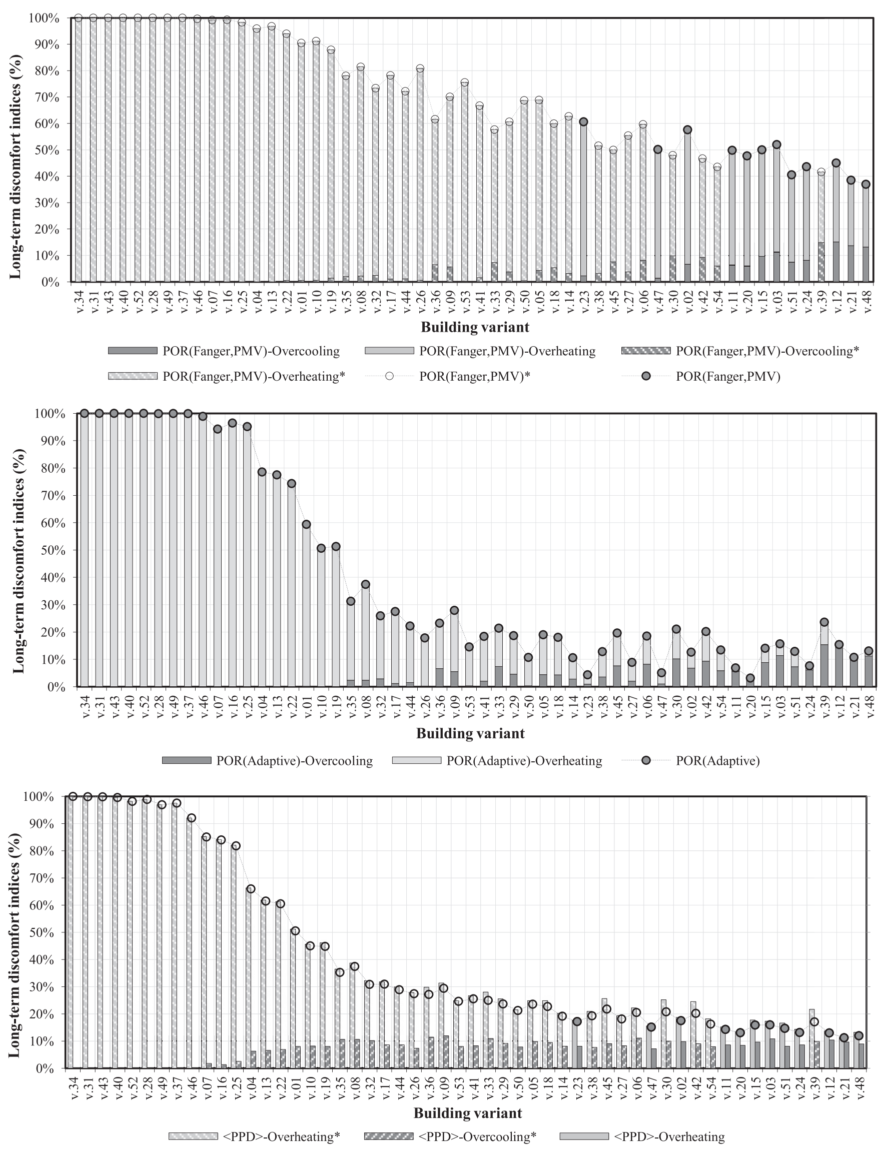

Fig. 8. Comparison between the global values of three symmetric indices and their components due to overheating and overcooling (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

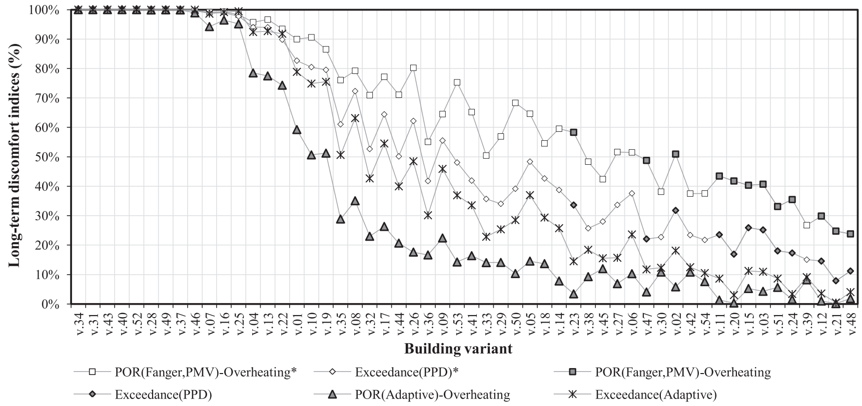

Fig. 9. Comparison among the portions of $POR_{Fanger,PMV}$ and $POR_{Adaptive}$ due to sole overheating, and $Exceedance_{PPD}$ and $Exceedance_{Adaptive}$ (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

$Exceedance_{PPD}$ and to a temperature rise of 3.5 K with respect to the optimal ASHRAE adaptive temperature [38] for $Exceedance_{Adaptive}$.

In both $Exceedance_{PPD}$ and $Exceedance_{Adaptive}$, the weighting factor is the ratio between the number of occupants for a given hour and the total number of people computed over the calculation period. If hourly occupation rate is almost the same in each zone of the building, $Exceedance_{PPD}$ and $Exceedance_{Adaptive}$ converge to the time frequency of exceedance outside the aforementioned comfort boundaries. In our case, since the simulated building is quite completely composed by offices similar by size, occupation rate and occupation schedule, $Exceedance_{PPD}$ is close to evaluate the frequency of exceedance the threshold for PMV = 0.85 and $Exceedance_{Adaptive}$ is close to evaluate the frequency of exceedance the ASHRAE adaptive comfort temperature rise of 3.5 K. The main differences between $Exceedance_{PPD}$ and $Exceedance_{Adaptive}$ and Percentage-outside-range indices are that the former are asymmetric and are just used to assess summer overheating, while the latter are symmetric and can be used also for winter assessments. Their comparison follows in Fig. 9.

Considering Category II and accounting only for overheating, $POR_{Fanger,PMV}$ considers the frequency of exceeding the threshold for PMV = +0.50, which is a stricter condition than the $Exceedance_{PPD}$ threshold set at PMV = +0.85; this explain why the values of $POR_{Fanger,PMV}$ are higher than $Exceedance_{PPD}$ and the apparent shift of the two trends.

$POR_{Adaptive}$ considers the frequency of exceedance of ±3.0 K from the EN adaptive comfort temperature, which is at first sight a stricter condition than the one used in $Exceedance_{Adaptive}$ where the exceedance threshold is set to +3.5 K; however, for most climates the EN theoretical adaptive comfort temperature is higher than the ASHRAE adaptive comfort temperature. When the difference between the two comfort temperatures is higher than 0.5 K, the ASHRAE adaptive threshold is lower than the EN adaptive threshold and $Exceedance_{Adaptive}$ is hence higher than $POR_{Adaptive}$.

In summary, an interesting feature of $Exceedance_{PPD}$ and $Exceedance_{Adaptive}$ is that they take into account occupancy and this implies that (i) they require a detailed description of the occupation schedules inside each zone of the building in order to be applied correctly and (ii) if zoning is simplified they tend to coincide with measuring the percentage of hours outside the specified comfort ranges, similarly to the Percentage-outside-range indices.

$Exceedance_{PMV}$ differs from $POR_{Fanger,PMV}$ due to a different definition of the boundary values of the acceptability class and of the comfort category respectively; $Exceedance_{Adaptive}$ differs from $POR_{Adaptive}$ due to (i) the different definition of the boundary values of the acceptability class and the comfort category respectively, and (ii) the different optimal adaptive comfort temperatures, which shall be calculated according to ANSI/ASHRAE 55 and EN 15251 respectively.

4.4.4. CIBSE criteria

The two CIBSE criteria consider the time frequency by which the dry-resultant temperature [49] exceeds a specified reference temperature in summer: for $CIBSE_J$ this reference temperature is 25 °C

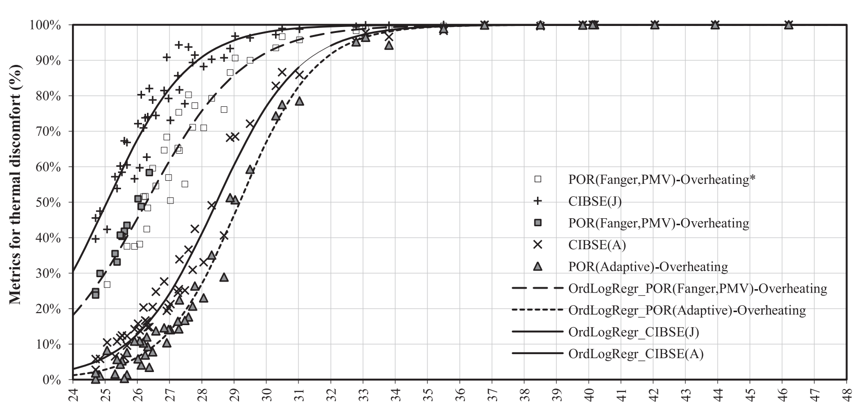

Fig. 10. Comparison between a selection of the Percentage-outside-range indices (only assessing overheating) and the CIBSE criteria (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

[48], whilst for $CIBSE_A$ it is 26 °C for bedrooms and 28 °C for all other rooms [55]; $CIBSE_A$ is suggested for naturally ventilated buildings. According to their definitions, both CIBSE criteria are asymmetric.

Although both CIBSE criteria are proposed for application in United Kingdom, they are applied to the climate under investigation in this paper, since the CIBSE reports are proposed for use in a worldwide network. Both these indices are compared in Fig. 10 with the sole portions of $POR_{Fanger,PMV}$ and $POR_{Adaptive}$ representing overheating.

Both CIBSE criteria only measure the frequency of overheating and do not take into account its severity. The sole shift of the reference temperature from 25 °C to 28 °C (there are no bedrooms in the analyzed model) causes a strong change in the values of the CIBSE indices, and causes the fact that $CIBSE_J$ is relatively close to $POR_{Fanger,PMV}$ that is addressed to mechanically cooled buildings and $CIBSE_A$ is relatively close to $POR_{Adaptive}$ that is instead addressed to non mechanically cooled buildings (the *x*-values of the inflection point of the ordered logistic regressions are 25.1 °C and 26.3 °C respectively for $CIBSE_J$ and $POR_{Fanger,PMV}$(overheating), while 28.5 °C and 29.2 °C respectively for $CIBSE_A$ and $POR_{Adaptive}$). These two behaviors are due to:

- The upper PMV limit for Category II translated into operative temperature is equal to 26.4 °C (according to the assumptions presented in Sect. 3.6); therefore, the $CIBSE_J$ criterion (25 °C) is generally stricter than the upper boundary of Category II according to the Fanger model expressed in operative temperature.
- The $POR_{Adaptive}$ boundary depends on the exponential weighted running-mean outdoor air temperature [2] and, hence, depends on climate. During the analyzed calculation period, it is higher than 28 °C and this explains why discomfort assessed by $CIBSE_A$ is higher than $POR_{Adaptive}$(overheating). Fig. 11 presents a comparison of boundary temperatures for the climate of Rome (IT) during the analyzed calculation period.

In summary, CIBSE criteria are a measurement of the sole summer overheating frequency and do not account for the type of intervention (new construction, renovation), for the health status of occupants (healthy or fragile) and for the overcooling phenomenon. However, some authors, supported by the analyses of large databases of measurements and surveys, have found evidence that summer comfort temperature varies with the outdoor dry-bulb air temperature in naturally ventilated buildings or in buildings without a mechanical cooling system [3,56]. Thus, indices based on a fixed reference temperature seem to be a somewhat crude approximation for naturally ventilated or not mechanically cooled buildings and are also a simplification for assessing mechanically cooled building since the Fanger summer comfort temperature, though not dependent on external climate explicitly, may vary considerably depending on choices made by building occupants about clothing insulation, air velocity etc., which in turn may be correlated to external climate. Using the words of Fanger and Toftum [35]: “The PMV model has been referred to as a static model, indicating that it should prescribe one constant temperature. But this is not true. The PMV model may actually predict any air temperature between 10 and 35 °C as neutral, depending on the other five variables in the model”.

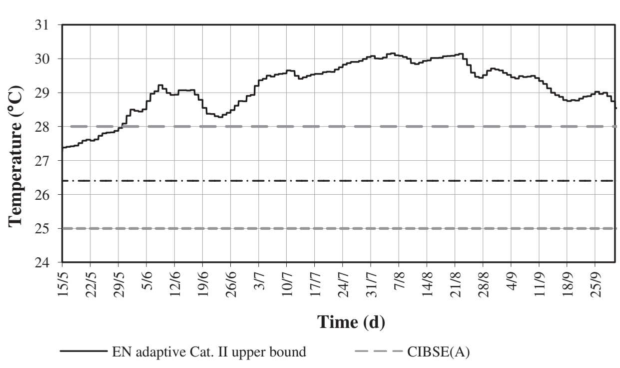

Fig. 11. Comparison of the boundary temperatures of the Percentage-outside-range and the CIBSE indices (EN adaptive curve calculated for the climate of Rome, IT).

4.4.5. *Robinson's and Haldi's overheating risk*

RHOR was developed for predicting the hourly likelihood of summer overheating using an electrical capacitor analogy to describe the thermal state of a human body. It delivers a short-term indication of the percentage of dissatisfaction and, in order to have a long-term index comparable with the other indices, it has been averaged exclusively on the occupied hours of the calculation period. This index requires to set the values of two time constants: one is used to model the charging of human body due to heat *stimuli* – it is indicated with ‘α’ and was set to 4.75×10^{-4} – and the second is used to model the discharging of human body – it is indicated with ‘β’ and it was set to 4.75×10^{-3} as suggested in Ref. [50]. The overall comparison of the percentage indices represented in Fig. 3 shows that RHOR, when compared with all other indices, provides comparatively lower discomfort values for those variants with higher indoor operative temperatures and tends to comparatively higher discomfort values in those variants with lower indoor operative temperatures. As suggested also by the authors of this index, this result might be caused by the necessity to tune both the time constants for charging and for discharging in relation with the specific building features and the local climate. This remark, if confirmed, would imply that RHOR is not easy to use and it is difficult to generalize.

The statistical analysis indicates that it is weakly correlated to the time-averaged indoor operative temperature and that its values graphed with respect to the time-averaged indoor operative temperature do not have a monotone tendency.

In summary, this index seems to be hard to be generalized and, to date, it is far from delivering design information comparable with the other indices. Neither it proved to be correlated with the indoor operative temperature.

4.4.6. *Indices which explicitly measure the likelihood of dissatisfied*

The relationship between thermal discomfort indices and indoor temperatures depends on thermal sensation of occupants and it does not follow a linear relationship. In Fanger's words, ‘human thermal discomfort’ can be translated with ‘predicted percentage of dissatisfied’ (PPD), whilst ‘thermal sensation’ with ‘predicted mean vote’ (PMV). Nicol and Humphreys [57] showed by analyzing the SCATs database that ‘offset from comfort temperature’ is related to the ‘percentage preference’ (the complementary of human thermal discomfort) through a logistic function.

<PPD> and NaOR deliver a short-term indication of the predictable percentage of dissatisfaction according to given indoor conditions, thus, they have been averaged on the sole occupied hours of the calculation period to have two long-term discomfort indices comparable with the other indices (Fig. 12).

Even if these indices are based on different comfort models addressed to conditioned and free-floating buildings, their trends are very similar, although their values are different, and select the same optimal variants (in this example Variant 21), at least in this case study. Moreover, they are sensible enough to assess different

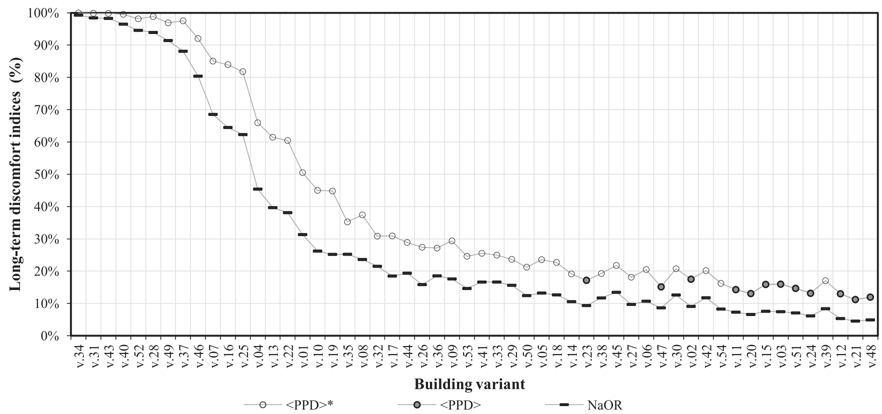

Fig. 12. Comparison of the indices directly derived from thermal sensation votes (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

building variants and their values fluctuate less than the other indices when ordered accordingly to the median of the time-averaged indoor operative temperature; therefore they result to be more robust than the other indices with respect to the median of the time-averaged indoor operative temperature.

The ordered logistic regression analysis applied to the data of <PPD> and NaOR delivered two models that fit their values with a high accuracy ($RMSD_{\mathrm{NaOR}} = 0.014$ and $RMSD_{<\mathrm{PPD}>} = 0.019$) (Fig. 13).

Since the *x*-value of the inflection point ($-a/b$) of the ordered logistic regression of NaOR is 31.6 °C and of <PPD> is 29.6 °C and the gradients of the linear section of the two ordered logistic models are quite similar ($b_{\mathrm{NaOR}} = 0.384$ and $b_{<\mathrm{PPD}>} = 0.440$), the two models seem to be hence translated of about 2 °C.

Summarizing, the strengths of <PPD> and NaOR are: (i) they are based on two underlying accepted comfort models and, therefore, they account for severity of thermal discomfort, (ii) they provide similar design information and identify the same optimal variant, (iii) they assess building performance in similar ways (similar gradients of the two models) and the ranking appears to be just translated, (iv) they result to be more robust than the other indices because, compared to them, they show a more regular trend when ordered in term of decreasing median of the time-averaged indoor operative temperature and (v) both of them can be calculated simply from hourly outputs of the most common dynamic building performance software tools. On the other side, assuming to use <PPD> for mechanically cooled and NaOR for non mechanically cooled buildings, some issues need to be pointed out: (i) by definition <PPD> is symmetrical and NaOR is asymmetrical, thus they respond differently in those situations when summer overcooling may be predominant and their complementarity breaks down; (ii) if they are simply averaged on the occupied hours of the calculation period, they do not account for the occupancy profiles in the several zones of a multi-zone building.

4.5. Analysis of paired indices

The uniform pairs of indices that can be formed by coupling one index suitable in conditioned buildings and one in free-floating buildings among those analyzed are:

- Pair n. 1: $\mathrm{DhC}_{\mathrm{Adaptive}}$ and $\mathrm{DhC}_{\mathrm{Fanger,\ EN\ 15251}}$;
- Pair n. 2: $\mathrm{POR}_{\mathrm{Adaptive}}$ and $\mathrm{POR}_{\mathrm{Fanger,PMV}}$;
- Pair n. 3: $\mathrm{Exceedance}_{\mathrm{Adaptive}}$ and $\mathrm{Exceedance}_{\mathrm{PPD}}$;
- Pair n. 4: $\mathrm{CIBSE}_{\mathrm{A}}$ and $\mathrm{CIBSE}_{\mathrm{A}}$;
- Pair n. 5: NaOR and <PPD>.

Nonlinear regression models have been carried out for every pair of indices using the generalized reduced gradient (GRG) method, which is robust and reliable in nonlinear regressions [58]. Since the indices designed for the building in free-floating mode are characterized by a higher variance, they are used as independent variable and the indices designed for the conditioned buildings are the dependent variable. To better fit the data, the nonlinear regression model that minimizes the coefficient of determination (R^2) is chosen for every pair of indices: specifically a natural logarithmic equation is used for Pair n. 4, while a polynomial of second

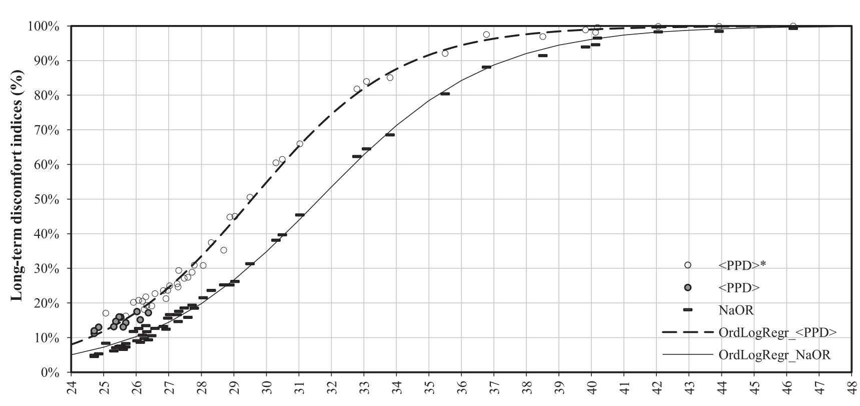

Fig. 13. Comparison of the ordered logistic models of NaOR and <PPD> (*Values calculated even if indoor conditions are outside the applicability ranges of the Fanger comfort model).

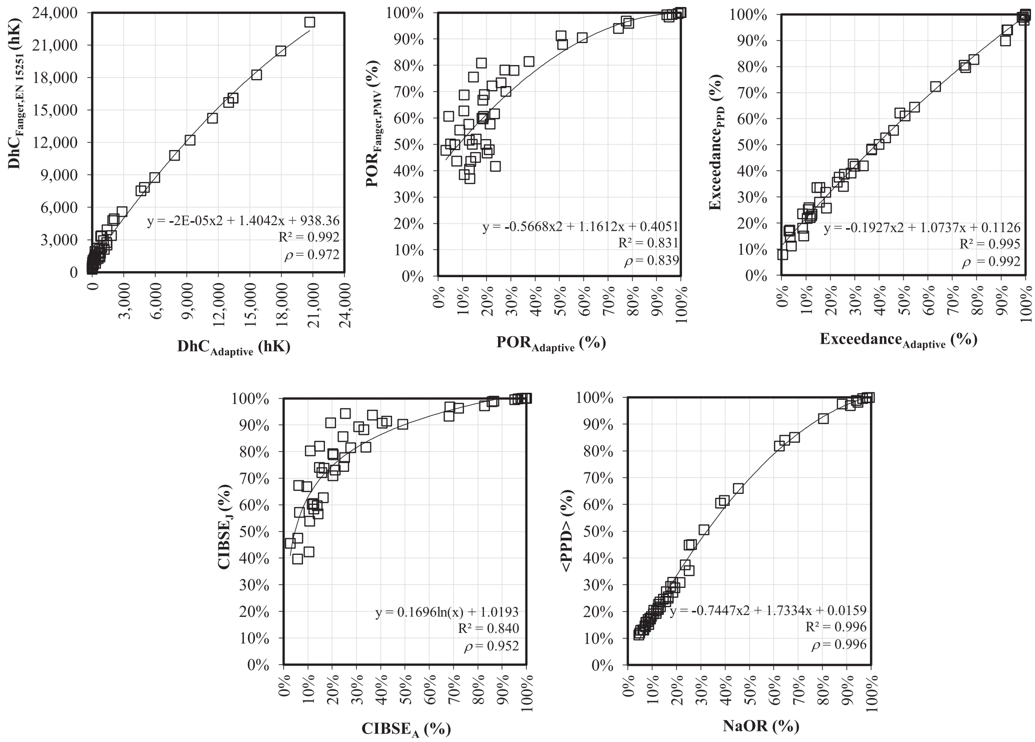

Fig. 14. Regression models of the pairs of indices based on the Fanger and adaptive comfort models, 95% confidence intervals, coefficient of determination (R^2) and Spearman's rank coefficient (ρ).

order best fits the remaining four pairs. The outcomes of the regression analyses and Spearman's rank coefficients are reported in Fig. 14 for the five pairs.

The relationship between the two indices of Pair n. 5 proves to be better described using a monotonic function since its Spearman's rank coefficient of 0.996 was the highest and to be better fit by a regression model with the highest value of the coefficient of determination of 0.996.

5. Conclusions

In this paper we present a study that compares and contrasts through a statistical analysis how various indexes used for assessing long-term thermal comfort performances of a building respond to the same group of datasets comprising time series of local values of operative temperature, air velocity etc. The 54 datasets were generated via dynamic simulation of 54 building variants of a 34-zone office building located in Rome during the summer season. We present the results of the application of the study on 16 long-term thermal discomfort indices. The indices delivered significantly different values for a given dataset/building variant and significantly different ranking orders.

The first objective of this research work consists in comparing and contrasting the ranking capability of such long-term discomfort indices in order to understand their differences and identify their similarities. The second objective is to identify, at least, a suitable pair of long-term discomfort indices that provide a similar ranking order of building variants adopting respectively one of the adaptive models and the Fanger comfort model in order to set up in a viable way the optimization procedure suggested by the European standard EN 15251.

A number of remarks and suggestions have been drawn from this analysis and here we summarize those most relevant for practical use and for further theoretical developments:

- Percentage, Risk and Averaging indices deliver results that are extremely different in the value and in the ranking order: the difference between the values for a given building variant can differ up to 85% and while some indices have a certain trend, others invert the trend increasing for those variants with lower values of the median of the time-averaged indoor operative temperatures. They would hence deliver different guidance conclusions to a designer for the optimization of a building;
- The long-term discomfort indices built on the Fanger comfort model (or more generally addressed to mechanically cooled buildings) are higher in value and have narrower ranges than those built on an adaptive comfort model (or more generally addressed to naturally ventilated buildings);
- Symmetric indices may be useful to represent in a comprehensive way the overall discomfort performance of a building, since they account both for overheating and overcooling phenomena. However, their disaggregation in overheating and overcooling should be explicitly reported in order to allow for a complete and correct interpretation. Further studies based on comfort surveys should address the question whether summer overheating and overcooling are in fact perceived with the same 'discomfort weight' by building occupants, also in connection to personal control possibilities (e.g., clothing adjustment, air velocity adjustment etc.);
- Indices based on a fixed reference temperature are an assessment of the sole summer overheating frequency and do not account for the type of intervention (new construction, renovation or fragile occupants) and for the overcooling phenomenon; they seem to be a somewhat crude approximation for assessing naturally ventilated or not mechanically cooled buildings where, on the contrary, summer comfort temperature has been documented to depend mainly on external climate; This group of indices are also an approximation when assessing mechanically cooled buildings since the Fanger summer comfort

temperature, though not dependent on external climate explicitly, may vary considerably depending on choices made by building occupants about clothing insulation, air velocity etc., which in turn may be correlated to external climate;

- Cumulative indices deliver a measure of the severity of thermal discomfort, but are not normalized with respect to the duration of the calculation period, which depends on the arbitrary choice of the analyst; so they result to be impractical for ranking buildings in different climates or in not standardized conditions.
- ISO 7730 and EN 15251 propose either the PMV or operative temperature as options for the calculation of the Percentage-outside-range indices, based on the Fanger comfort model. $POR_{Fanger,PMV}$ and $POR_{Fanger,T_{op}}$ show very little differences even if the former uses the simulated hourly relative humidity, while the latter assumes a constant value for the relative humidity when translating PMV into operative temperatures. This outcome is correlated to the fact that humidity has only a little influence on the long-term thermal comfort assessment in moderate environments, (see e.g., ISO 7730);
- Since $POR_{Fanger,PMV}$ is a simple counter of the hours outside the comfort range, while <PPD> provides a measure of human thermal perception by accounting for severity of discomfort in each hour, we suggest that <PPD> should be preferred when assessing thermal discomfort according to the Fanger comfort model;
- The two indices that measure the likelihood of dissatisfied, NaOR and <PPD>, although being based on different comfort models and respectively addressed to free-floating and mechanically cooled buildings, deliver quite coordinated rating orders of the building variants, slightly shifted in the absolute values;
- Moreover, NaOR and <PPD> prove, at least in this case study, to be the most suitable pair of discomfort indices for having correlated complementary thermal comfort assessments based on the Fanger and the EU adaptive comfort models. Their use in the two-step comfort-optimization procedure suggested by EN 15251 should avoid the discontinuities due to the use of the other indices proposed by EN 15251, discontinuities which happen when switching from an adaptive-based index to a Fanger-based one.
- On the other hand, <PPD> and NaOR, in their current formulations, account differently for those situations when overcooling may be predominant, thus their complementarity breaks down in those cases.
- $Exceedance_{PPD}$ and $Exceedance_{Adaptive}$, by taking into account the number of occupants for each zone and time interval, give a more detailed description of overall discomfort in a multi-zone building if compared to indices that use the floor area of the zone as a weight. However, the Exceedance indices require a detailed zoning of the building and a detailed description of the occupation schedules inside each zone in order to be used effectively. In case the hourly occupation rate is almost constant in each zone of the building or if zoning is extremely simplified, $Exceedance_{PPD}$ and $Exceedance_{Adaptive}$ converge to measure the frequency of exceedance of the specified comfort threshold, similarly to the Percentage-outside-range indices.
- RHOR index seems to be hard to generalize and, to date, it is far from delivering design information comparable with the other indices. Neither it proved to be correlated with the indoor operative temperature.

Finally, in most of the low- or zero-energy buildings the power available from passive or active systems is limited, thus internal conditions might show slightly larger fluctuations due to occupant behavior than in buildings equipped with large, possibly oversized active systems, and the passive systems might require longer times for adjusting the indoor climate [59]. The objective of optimizing the envelope, plants and controls of a building towards long-term comfort, rather than for a few 'design days', might hence become more and more relevant. The availability of a sound long-term thermal discomfort index becomes necessary for this task. Further work is hence needed to bring together the most desirable features showed by various indices for developing a new long-term thermal discomfort index and to test it in a series of significant cases. The detailed quantitative comparison of the 16 long-term discomfort indices presented in this paper might be one of the bases for this development.

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