Fifty Years of PMV Model: Reliability, Implementation and Design of Software for Its Calculation

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Abstract: In most countries, PMV is the reference index for the assessment of thermal comfort conditions in mechanically conditioned environments. It is also the basis to settle input values of the operative temperature for heating and cooling load calculations, sizing of equipment, and energy calculations according to EN 16798-1 and 16798-2 Standards. Over the years, great effort has been spent to study the reliability of PMV, whereas few investigations were addressed to its calculation. To study this issue, the most significant apps devoted to its calculation have been compared with a reference software compliant with EN ISO 7730 and the well-known ASHRAE Thermal Comfort Tool. It has been revealed that only few apps consider all six variables responsible for the thermal comfort. Relative air velocity is not considered by ASHRAE Thermal Comfort Tool and, finally, the correction of basic insulation values due to body movements introduced by EN ISO 7730 and EN ISO 9920 Standards has only been considered in one case. This implies that most software and apps for the calculation of PMV index should be used with special care, especially by unexperienced users. This applies to both research and application fields.

Keywords: PMV; comfort indices; thermal comfort; software; app; building simulation

1. Introduction

1.1. Background

The building stock in the world uses approximately 40% of the total energy and it is responsible for one third of the global greenhouse gases emissions [1,2]. As a consequence, achieving sustainable energy usage in buildings has received significant attention in the past years [2,3]. The requirements of high levels of Indoor Environmental Quality (IEQ) in terms of thermal, visual and acoustic comfort and indoor air quality may increase the energy demand. This means that especially thermal comfort conditions for occupants must be accurately calculated in designs of new buildings or refurbishments of existing buildings to evaluate the energy performance and safeguard the well-being of occupants [4–7].

In buildings with mechanical cooling, the basis for establishing thermal comfort criteria is the use of the PMV-PPD and local thermal discomfort indices [8–10]. PMV is also the basis for energy calculations, as underlined by European Standards EN 16798-1 [11] EN 16798-2 [12]. EN 16798-1 specifies indoor environmental input parameters for design and assessment of energy performance of

buildings addressing IEQ, whereas EN 16798-2 explains how to use EN 16798-1 by specifying additional information as: (i) input parameters for building system design and energy performance calculations; (ii) methods for long term evaluation of the indoor environment; (iii) criteria for measurements which can be used if required to measure compliance by inspection; (iv) parameters to be used by monitoring and displaying the indoor environment in existing buildings. With reference to thermal comfort, EN 16798-1 suggests specific design ranges of operative temperature consistent with the desired level of environmental quality (see Table 1).

Table 1. Temperature ranges for hourly calculation of cooling and heating energy for some indoor environment (Category II) according to EN 16798-1 and EN 16798-2 Standards [11,12]. Resultant insulation values $I_{cl,r}$ to be used [6] are 0.5 clo (cooling) and 1.0 clo (heating).

Type of Building Space	Operative Temperature Range for Heating (°C)	Operative Temperature Range for Cooling (°C)
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, and classrooms). Sedentary activity: M = 1.2 met	20.0–24.0	23.0–26.0
Department store Standing-walking activity: M = 1.6 met	16.0–22.0	21.0–25.0

Finally, PMV is used for the attribution of the class of risk in the prevention of stress or discomfort in thermal working conditions according to ISO 15265 Standard [13,14], and in the field of the thermal bioclimate [15,16] where more specific metrics should be applied [17,18].

1.2. Open Issues about the Evaluation of PMV/PPD Indices

In the past, several studies have been undertaken to highlight the limitations of PMV in predicting thermal comfort conditions in naturally ventilated buildings (and in hot and humid climates) where adaptation phenomena have to be considered. Despite this interest that has led to the formulation of modified PMV indices (e.g., ePMV [19] and aPMV [20,21]), two issues remain unresolved in the scientific debate: the effect of measurement uncertainties and its calculation.

To calculate PMV and PPD indices, the evaluation/measurement of six variables are required: the air temperature, the mean radiant temperature, the relative humidity, the air velocity, the metabolic rate and finally the clothing insulation [8]. These quantities can be measured or evaluated according to the Standards in the field of the Ergonomics of the Thermal Environment [22–25].

Although technical Standards specify methods, protocol of measurement and accuracy levels [23], due to the sensitivity of PMV to each involved quantity, the uncertainty on its final value can reach 2–3 decimals points on the PMV scale (for each single input variable) as shown in Figure 1. This phenomenon might affect the category of the environmental quality as prescribed by ISO 7730 and EN 16798-1 (See Table 2). This implies that the most accurate measurement methods for the assessment of the variables should be used [26–28].
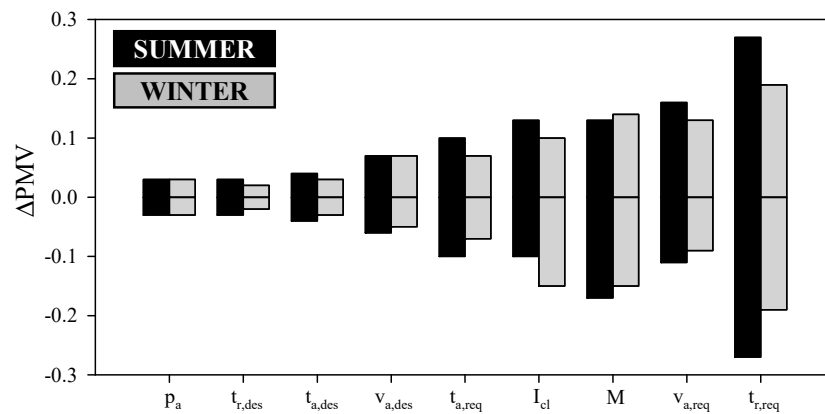
Figure 1. PMV sensitivity (ΔPMV) to the accuracy of each quantity required for the thermal environment assessment according to ISO 7730 Standard [9] under thermal neutrality conditions (PMV = 0). M = 1.2 met [20]. "req" and "des" subscripts are referred to the required and desired accuracy levels prescribed by ISO Standard 7726 [23].

Table 2. The classification proposed by ISO 7730 [9] and EN 16798-1 [11] Standards.

Category		Thermal State of the Body as a Whole	
ISO 7730	**EN 16798-1**	**Percentage of Dissatisfied (PPD), %**	**Predicted Mean Vote (PMV)**
A	I	<6	$-0.20 < PMV < 0.20$
B	II	<10	$-0.50 < PMV < 0.50$
C	III	<15	$-0.70 < PMV < 0.70$
-	IV	<25	$-1.0 < PMV < 1.0$

For calculating the PMV, ISO 7730 Standard reports two different procedures:

- Using tables in the ANNEX E of the Standard;
- Using the computer program in BASIC in the Annex A.

To obtain reliable results both procedures (see Figure 2) require some specific conditions often not clearly reported by standards or ignored even by skilled users [29].
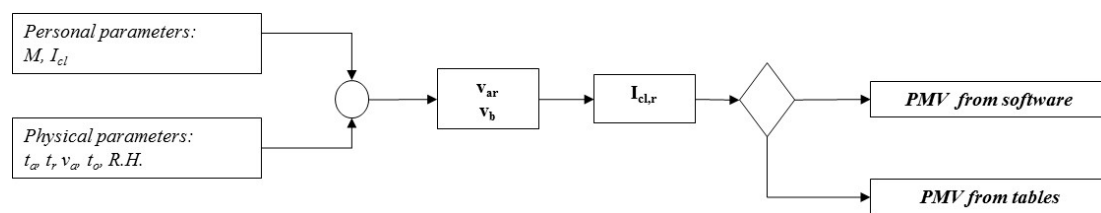

Figure 2. Flow chart for the calculation of PMV as required by ISO 7730 Standard [9].

ISO 7730 explicitly states that PMV values given in tables in Annex E only apply to a relative humidity of 50%. However, slight deviations from this reference value do not affect significantly the PMV, due to the relatively small influence of humidity in Fanger's thermal comfort model [30]. In addition, since the input value of tables is the operative temperature [9], the accuracy of PMV values is acceptable provided that the difference between air temperature t_a and mean radiant temperature t_r is less than 5 °C [6,9,31]. Although slight differences between mean radiant temperature and air temperature might result in negligible differences of PMV values, some problems occur in terms of environmental category assignment. As seen from Table 3, while keeping constant the operative temperature value, PMV index can vary as air temperature and mean radiant temperature vary. Consequently, the attribution of the environmental category becomes uncertain [9].

Table 3. Effect of the operative temperature on the PMV evaluation. M = 1.2 met, v_a = 0.10 m/s, *R.H.* = 40% in winter (60% in summer), $I_{cl,r}$ = 1.0 clo in winter (0.5 clo in summer).

t_a (°C)	t_r (°C)	t_o (°C)	PMV (-)	Category
		Summer		
24	28		0.1	I
25	27		0.1	I
26	26	26	0.2	II
27	25		0.3	II
28	24		0.4	II
25	29		0.4	II
26	28		0.5	II
27	27	27	0.6	III
28	26		0.6	III
29	25		0.8	IV
		Winter		
18	22		−0.8	IV
19	21		−0.7	III
20	20	20	−0.6	III
21	19		−0.6	III
22	18		−0.5	II
19	23		−0.5	II
20	22		−0.4	II
21	21	21	−0.4	II
22	20		−0.3	II
23	19		−0.3	II

Another very important issue concerns the calculation of the PMV by software. Firstly, ISO 7730 requires the correction of the basic values of the clothing insulation related to the effect of body movements with the algorithms described in ISO 9920 Standard [9,22,32,33]. This is not the case of ASHRAE Standard 55 [10], because the correction is optional and restricted only for moving occupants with the following equation:

$$I_{cl,r} = I_{cl}\left(0.6 + \frac{0.4}{M}\right) \tag{1}$$

with the metabolic rate M expressed in met.

In addition, to evaluate the heat transfer coefficient by convection, ISO and ASHRAE algorithms require the relative air velocity v_{ar} given by:

$$v_{ar} = v_a + v_b \tag{2}$$

where v_b is given by:

$$v_b = 0.0052(M - 58.2) \tag{3}$$

In short, the BASIC program in ISO 7730 requires additional information not clearly reported in the text with unforeseeable consequences in the implementation of software devoted to the calculation of the PMV as recently discussed by our team in a short communication devoted to Fanger's equation [29]. In particular, the wrong calculation of PMV via software [29] results in uncertainties even greater than one point on the ASHRAE thermal sensation scale that is unacceptable if compared to the "physiological" uncertainty due to the measurement precision of input variables.

This applies not only to researchers and scientific studies but also to less skilled users performing the calculation of PMV during an inspection or auditing for conformity checking.

1.3. Aim of the Paper

50 years after Fanger's studies, the PMV index remains the most used tool for the objective assessment of indoor thermal comfort. The index is used both for evaluation in existing buildings and in building simulations for the prediction of thermal comfort levels [34]. The lack of clear information in technical Standards and wrong interpretations of the standards [29,35–37] result in increased inaccuracy in its calculation. This also applies to microclimatic dataloggers provided with built-in software.

Until a few years ago ISO and ASHRAE software ran only on Windows platform. Today, the continuous innovation of smartphones and tablets with high performances and unique portability characteristics has favored the release of web applications (web apps) and specific applications for mobile devices (apps) for thermal comfort and heat stress assessment.

Based on the above, in this investigation the reliability and the compliance with International Standards of commonly used software, web apps and apps available in the stores will be verified. This will help both professionals and researchers in the correct use of such tools, which are designed under specific conditions that are often not clearly specified. Finally, the main findings from the present study will be useful for standardization aimed at verification/certification of software.

2. Methods

In this study we investigated the most popular apps available on the web and apps available on the market (Apple Store and Google Play), as summarized in Table 4.

Table 4. Summary of web apps and apps used for the present investigation.

Label.	OS	Details	Manufacturer	First Release	Last Update	Last Access
A	Web app	CBE Thermal Comfort Tool [38]	Center for the Built Environment, University of California, Berkeley (USA)	2014 [39]	2017	11.2019
B	Web app	Java APPLET for ISO 7730 [40]	Lund University, Sweden	2008	2008	11.2019
C	iOS	IEQ calculator for apartment	Fishball Studio, Department of Building Services Engineering, Polytechnic University, Hong Kong	2015	n.a.	05.2019
D	iOS	PMV	Zantedeschi System Integrator	n.a.	2010	05.2019
E	iOS	PMV Simulator	Ozaki Seiichi	n.a.	2013	05.2019
F	Android	PMV calculator	Fishball Studio	2011	2011	05.2019
G	Android	IEQ calculator for classrooms [41,42]	Fishball Studio, Department of Building Services Engineering, Polytechnic University, Hong Kong	2012	n.a.	05.2019

As reference for comparisons, we have used: (i) the values reported in the tables of the Annex E of ISO 7730 Standard; (ii) a software consistent with the code reported in Annex D of EN ISO 7730 Standard (TEE, Thermal Environment Evaluation) [29,43,44]; (iii) the well-known ASHRAE Thermal Comfort Tool [45] validated by ASHRAE and provided with a user-friendly interface for calculating thermal comfort parameters and making thermal comfort predictions.

The microclimatic conditions for comparisons have been based on standards EN 16798-1 and 2 [11,12] that recommend typical values of operative temperature for energy calculation for four categories of Indoor Environmental Quality (see Table 1). The air velocity value used for the investigation was 0.10 m s^{-1} because it is the minimum value accepted by the ASHRAE Thermal Comfort Tool (despite in several environments lower values can be observed), whereas reference relative humidity values were 40% (60%) for heating (cooling) according to EN 16798-1 [11].

The comparison phase consists of the following steps:

1. PMV calculation
2. Comparison among obtained results
3. Analysis of inconsistent results
4. Attribution of possible causes of inconsistencies

In Table 5 are reported more specific information strictly related to input and output variables considered by each software.

Table 5. Input and output data for software and apps used for comparisons. (×) Included; (-) not included. [1] Input value for clothing is the resultant clothing insulation $I_{cl,r}$. [2] Input value is the air speed. [3] Input value is a "generic" clothing level or value. [4] Input value is the relative air velocity, v_{ar}. [5] Only specific values for the metabolic rate can be used (e.g., 1.2, 1.8 and 2.0 met). [6] Data sliders move with a random step. [7] Input value is a generic temperature (probably the air temperature). [8] Only one decimal value is accepted. [9] PMV value is rounded to one decimal place. [10] Only integer values are accepted. [11] This app returns only the value of PPD index according to and the sign of the thermal sensation. [12] Does not work on Android 4.4 and later based devices (data sliders do not appear).

Software or App	Input Data						Output Data		
	t_a	t_r	RH	v_a	M	I_{cl}	PMV	PPD	Thermal Sensation on the ASHRAE Scale
TEE	×	×	×	×	×	×[1]	×	×	×
ASHRAE Thermal Comfort Tool 2.0	×	×	×	×[2]	×	×[3]	×	×	×
A	×	×	×	×[2]	×	×[3]	×	×	×
B	×	×	×	×[4]	×	×	×	×	-
C	×	-	×	-	×[5]	-	-	-	×
D[6]	×[7]	-	×	×	×[8]	×[3,8]	×[9]	×	-
E	×[10]	×[10]	×[10]	×[4]	×[8]	×[3,8]	-	×[11]	-
F[12]	×	×	×	×	×	×	×	×	-
G	×	×	×	×	×	-	-	-	×

It is important to emphasise that only apps A, B, E and F take into account all the variables required for the calculation of the PMV. Apps C and D do not consider the mean radiant temperature (or, probably, they assume $t_a = t_r$). This implies that they are not accurate in non-uniform environments (e.g., near windows or terminal units of HVAC systems) where the difference between air and mean radiant temperature may be significant [6]. The app C does not consider the air velocity and, similarly to the app G does not consider clothing insulation among input variables. In short, apps C, D and G are poorly designed due to the lack of one or more variable necessary to solve the heat balance equation on which PMV is based [7,9,29].

3. Results and Discussion

3.1. Uniform Environments ($t_r = t_a$)

In Table 6 are summarized the values of the PMV index calculated by means of all investigated apps for the operative temperature values in Table 1 and under homogeneous conditions ($t_a = t_r = t_o$). This hypothesis allows to investigate even apps C and D which consider only one temperature input value. No values have been reported for the app F because it crashes.

According to output data of each app, PMV values reported in Table 6 are those directly obtained only for A, B and D. In case of the app E, which returns only the PPD and the sign of the thermal sensation, the PMV has been calculated from the standard equation [7,9]:

$$PPD = 100 - 95 \cdot \exp\left(-0.3353 PMV^4 - 0.2179 PMV^2\right) \tag{4}$$

As the apps C and G return as output values only the description of the thermal state consistent with the ASHRAE 7-point thermal sensation scale [46,47], in these cases the *PMV* values were attributed by converting them into a thermal sensation vote (e.g., +1 for slightly warm, 0 for neutral and so on) [47].

Table 6. PMV values and comfort categories obtained with the investigated software and comparison with values from ISO 7730 tables. Relative velocity has been calculated according to Equation (2). [1] PMV value has been calculated by means of Equation (4). [2] It is not allowed changing the metabolic rate value.

Input Data					PMV								
$t_a = t_r$ (°C)	RH (%)	v_a (m/s)	M (met)	$I_{cl,r}$ (clo)	ISO 7730	TEE	ASH RAE	A	B	C	D	E [1]	G
23.0	60	0.10	1.2	0.5	−0.69	−0.66	−0.45	−0.45	−0.69	−1	−0.7	−0.78	+3
26.0					0.24	0.31	0.46	0.46	0.28	+1	0.2	0.22	
21.0			1.6		−0.65	−0.58	−0.18	−0.18	−0.61	(2)	−0.6	−0.62	
25.0					0.36	0.44	0.72	0.72	0.43		0.4	0.44	
20.0	40	0.10	1.2	1.0	−0.47	−0.53	−0.39	−0.39	−0.55	−1	−0.6	−0.58	0
24.0					0.45	0.38	0.47	0.47	0.36	+1	0.3	0.31	+3
16.0			1.6		−0.63	−0.65	−0.38	−0.37	−0.67	(2)	−0.7	−0.69	0
22.0					0.42	0.39	0.58	0.58	0.38		0.4	0.38	+3
Input Data					Thermal Environment Category								
23.0	60	0.10	1.2	0.5	III	III	II	II	III	-	IV	IV	-
26.0					II	II	II	II	II	-	B	B	
21.0			1.6		III	III	I	I	III	(2)	III	III	
25.0					II	II	IV	IV	II		II	II	
20.0	40	0.10	1.2	1.0	II	III	II	II	III	-	III	III	I
24.0					II	II	II	II	II	-	II	II	-
16.0			1.6		III	III	II	II	III	(2)	IV	III	I
22.0					II	II	III	III	II		II	II	-

From a quick analysis of data in Table 6 it seems that only the TEE, app B, and, partially, app E return values compliant with the ISO 7730 tables, especially if the comparison is based on the agreement of the environmental category. The difference between the values obtained by the TEE and the tables is often negligible and consistent with the different values of relative humidity used for our comparison.

The ASHRAE Thermal Comfort Tool and the web app A give values similar to those obtained by using a program consistent with ISO 7730 only at low metabolic rate (M = 1.2 met). At higher metabolic rate value (1.6 met), the PMV values are about 3–4 decimal points higher than those obtained by ISO 7730 tables. A reasonable explanation of this apparent inconsistency could be the input value used by the ASHRAE Comfort Tool for the air velocity. Particularly, the ASHRAE Comfort Tool requires as input value the air speed that, according to ASHRAE Standard 55 [10] is defined as "the rate of air movement at a point without regard to direction". However, according to Fanger's model [8,9], the input value for air velocity is the air velocity relative to the person which includes body movements as expressed by Equation (2). This implies that the overestimation of PMV values at higher metabolic rate could be related to the underestimation of the heat transfer by convection which occurs when air velocity does not take into account body movements.

To verify this hypothesis, we have analysed the difference between PMV values calculated with the ASHRAE Thermal Comfort Tool (PMV$_{ASHRAE}$) and by tables of the Annex E (PMV$_{7730}$). The analysis has been carried out as a function of the operative temperature both in summer ($I_{cl,r}$ = 0.50 clo) and in winter ($I_{cl,r}$ = 1.0 clo) by using as input value the air velocity v_a and the relative air velocity v_{ar} calculated by means of Equation (2). Obtained results are depicted in Figure 3.
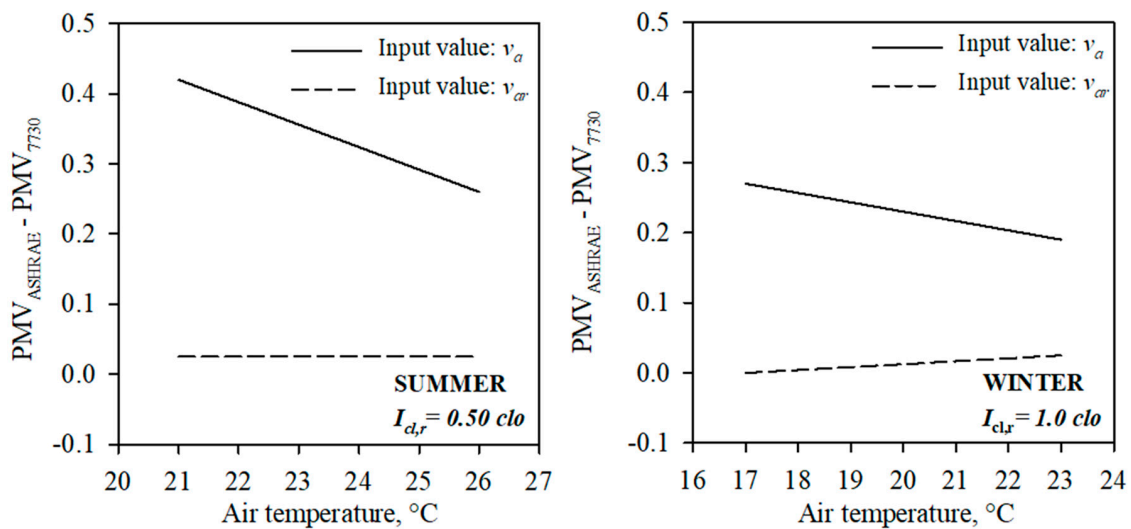
Figure 3. Difference between PMV values calculated by means of the ASHRAE Thermal Comfort Tool and tables reported in the Annex E of ISO 7730 Standard by using as input value air velocity (continuous lines) and relative velocity (dashed lines). M = 1.6 met; $t_a = t_r = t_o$; v_a = 0.10 m s^{-1}; RH = 50%.

All plots reported in Figure 3 clearly demonstrate that the ASHRAE Comfort Tool is consistent with tables of ISO 7730 Standard provided that the input value for air velocity is v_{ar}. However, in the case of the wrong use of the input value of the air velocity, the overestimation of the PMV value varies from 0.26 to 0.42 in summer and from 0.19 to 0.27 in winter that is of the same order of magnitude of the effect of uncertainty due to the measurements of each microclimatic parameter [26,27].

3.2. Non-Uniform Environments ($t_r \neq t_a$)

To verify the reliability of investigated software also under non-uniform conditions ($t_r \neq t_a$), we have calculated the PMV index under the same operative temperature conditions summarized in Table 6 by applying slight differences between mean radiant temperature and air temperature (1 °C and 2 °C).

Results are summarized in Table 7 and show that only app B gives values consistent with those reported in ISO 7730 Standard and those obtained by the TEE. To the contrary, ASHRAE Thermal Comfort Tool and web app A are in agreement with each other only when the effects of the body movements are negligible as observed above (e.g., at low metabolic rate and in winter, when the contribution of the air boundary layer to the total clothing insulation is less significant).

Table 7. PMV values and comfort categories obtained with the investigated software and comparison with values from ISO 7730 tables for the operative temperature values in Table 6 with (t_r–t_a) values of 1 °C and 2 °C. Apps C and D were not considered as they allow only one data input value for the temperature. [(1)] PMV value has been calculated by means of Equation (4).

Input Data							PMV						
t_o (°C)	t_a (°C)	t_r (°C)	RH (%)	v_a (m/s)	M (met)	$I_{cl,r}$ (clo)	ISO 7730	TEE	ASH RAE	A	B	E [(1)]	G
23.0	22.0	24.0					−0.69	−0.71	−0.49	−0.49	−0.74	−0.85	
	22.5	23.5	60	0.10	1.2	0.5	−0.69	−0.71	−0.46	−0.46	−0.71	−0.75	
26.0	25.0	27.0					0.24	0.26	0.44	0.44	0.24	0.22	
	25.5	26.5					0.24	0.28	0.45	0.45	0.26	0.22	+3
21.0	20.0	22.0					−0.65	−0.66	−0.23	−0.23	−0.68	−0.69	
	20.5	21.5	60	0.10	1.6	0.5	−0.65	−0.62	−0.20	−0.20	−0.64	−0.54	
25.0	24.0	26.0					0.35	0.37	0.70	0.70	0.36	0.31	
	24.5	25.5					0.35	0.41	0.71	0.71	0.39	0.54	
20.0	19.0	21.0					−0.47	−0.56	−0.40	−0.40	−0.58	−0.65	0
	19.5	20.5	40	0.10	1.2	1.0	−0.47	−0.54	−0.39	−0.39	−0.56	−0.49	0
24.0	23.0	25.0					0.45	0.34	0.46	0.46	0.33	0.31	+3
	23.5	24.5					0.45	0.36	0.46	0.46	0.34	0.44	+3
16.0	15.0	17.0					−0.63	−0.71	−0.41	−0.41	−0.41	−0.72	0
	15.5	16.5	40	0.10	1.6	1.0	−0.63	−0.68	−0.39	−0.39	−0.39	−0.62	0
22.0	21.0	23.0					0.42	0.34	0.57	0.57	0.57	0.31	+3
	21.5	22.5					0.42	0.37	0.57	0.57	0.57	0.44	+3
Input Data							Thermal Environment Category						
23.0	22.0	24.0					III	IV	II	II	IV	IV	
	22.5	23.5	60	0.10	1.2	0.5	III	IV	II	II	IV	IV	
26.0	25.0	27.0					II	II	II	II	II	B	
	25.5	26.5					II	II	II	II	II	B	-
21.0	20.0	22.0					III	III	II	II	III	III	
	20.5	21.5	60	0.10	1.6	0.5	III	III	II	II	III	III	
25.0	24.0	26.0					II	II	IV	IV	II	II	
	24.5	25.5					II	II	IV	IV	II	II	
20.0	19.0	21.0					II	III	III	III	III	III	I
	19.5	20.5	40	0.10	1.2	1.0	II	III	II	II	III	II	I
24.0	23.0	25.0					II	II	II	II	II	II	-
	23.5	24.5					II	II	II	II	II	II	-
16.0	15.0	17.0					III	IV	II	II	IV	III	I
	15.5	16.5	40	0.10	1.6	1.0	III	III	II	II	III	III	I
22.0	21.0	23.0					II	II	III	III	II	II	-
	21.5	22.5					II	II	III	III	II	II	-

3.3. Clothing Insulation Input Value

The last issue regarding the comparison is devoted to the verification of possible effects of the input value for the clothing insulation [22,32,33]. The PMV values under the microclimatic conditions in Table 6 have been calculated by using as input value the basic clothing insulation I_{cl} instead of the resultant clothing insulation $I_{cl,r}$ as specifically required by ISO 7730 [9]. Results (see Table 8) clearly prove that PMV varies only for the app B, which is the only explicitly based on the basic clothing insulation (see Table 5). This means that only the software designed by the Lund University (B) is compliant with procedures reported in ISO 7730 Standard. Unlike ISO, the ASHRAE Thermal Comfort tool—consistently with ASHRAE 55 [10]—does not take into account both the adjustment of the basic clothing insulation and the relative air velocity, and, consequently, it returns higher PMV values. However, this software can be used provided that the input value for clothing is the resultant clothing insulation and the air speed input value is the relative velocity.

Table 8. PMV values and comfort categories calculated with the investigated software and comparison with values from ISO 7730 tables. Relative velocity has been calculated according to Equation (2). [1] PMV value has been calculated by means of Equation (4). [2] It is not allowed changing the metabolic rate value.

Input Data					PMV								
$t_a = t_r$ (°C)	RH (%)	v_a (m/s)	M (met)	$I_{cl,r}$ (clo)	ISO 7730	TEE	ASH RAE	A	B	C	D	E [1]	G
23.0	60	0.10	1.2	0.5	−0.69	−0.66	−0.45	−0.45	−0.69	−1	−0.7	−0.78	+3
26.0					0.24	0.31	0.46	0.46	0.28	+1	0.2	0.22	
21.0			1.6		−0.65	−0.58	−0.18	−0.18	−0.61	(2)	−0.6	−0.62	
25.0					0.36	0.44	0.72	0.72	0.43		0.4	0.44	
20.0	40	0.10	1.2	1.0	−0.47	−0.53	−0.39	−0.39	−0.55	−1	−0.6	−0.58	0
24.0					0.45	0.38	0.47	0.47	0.36	+1	0.3	0.31	+3
16.0			1.6		−0.63	−0.65	−0.38	−0.37	−0.67	(2)	−0.7	−0.69	0
22.0					0.42	0.39	0.58	0.58	0.38		0.4	0.38	+3

3.4. Final Observations

In Table 9 precautions to be adopted when using all investigated software are briefly summarized.

Table 9. Summary of precautions to be adopted when using investigated software or apps.

Software or App	Precautions
ASHRAE Thermal Comfort Tool	• Air speed is the relative air speed • Clothing insulation input value is the basic clothing insulation value (ASHRAE 55) or the resultant clothing insulation (ISO 7730)
A	As above
B	No precautions
C	Not reliable
D	Reliable only in uniform environments ($t_a = t_r = t_o$)
E	Clothing insulation input value is the basic clothing insulation value (ASHRAE 55) or the resultant clothing or the resultant clothing insulation (ISO 7730)
F	Unable to be tested
G	Not reliable

Unfortunately, no further discussion can be provided for the other investigated software because their algorithms and listings are not accessible to users.

These results also rise some interesting questions that cannot be easily answered:

1. Is the assessment of thermal comfort conditions easy enough to be carried out merely with a software, without experience and ergonomic skills?
2. Are smartphones suitable replacements for commercial equipment and able to measure all the needed physical variables (particularly, the air velocity and the mean radiant temperature)?
3. With accurate commercial equipment, are the standards defined completely enough and clearly enough that non experts can assess thermal comfort accurately?

4. Conclusions

Software for the evaluation of thermal comfort conditions by means of PMV index, presently on the market, have to be used with special care. This is also for software designed by Academics and posted on Universities web pages in the absence of clear specifications for input values (e.g., the

relative air velocity and the resultant clothing insulation). In addition, most apps do not consider one or more variables affecting the thermal sensation. Regarding the mean radiant temperature this means that calculated values of PMV index are reliable only in homogeneous environments (or in the presence of very small differences between air temperature and mean radiant temperature). This is not acceptable, especially in environments with large windows or close to HVAC terminal units.

Software developers should be aware that all computer programs available in annexes of international Standards give correct results only when all specifications are considered. In particular, ISO 7730 Standard requires that basic clothing insulation values have to be preliminary adjusted for wind and body movements.

Professional and experts should be aware of the risks related to the use of unvalidated evaluation tools. This is even more important in case of cold and hot environments, where the goal of the thermal environment assessment is the safety of working conditions.

The analysis reported in this paper is not able to provide further details about the reasons why some of the investigated software fail, because their code is inaccessible to the users (closed code).

This investigation has demonstrated that the unreliability of software/apps is mainly related to a wrong interpretation of International Standards and not to inaccurate coding. This implies that International Standards should be written to avoid ambiguous or undefined input parameters (i.e., relative air velocity) resulting in inaccurate tools.

Finally, this study has emphasized that the assessment of the thermal environments requires specific skills and robust tools. Software and apps are only the final step of the objective measurement of the variables responsible for the thermal sensation. This is another crucial issue, because all measurement devices required for the objective survey are impossible to miniaturize in a smartphone. However, beyond the intrinsic limitations of the PMV model and of measurement uncertainties, it is unthinkable that the main cause of unreliable assessments might be caused by poor software implementations of the standard.

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Acronyms and Symbols

I_{cl}	Basic clothing insulation, m^2 K W^{-1} or clo
$I_{cl,r}$	Resultant clothing insulation adjusted for wind and body movements, m^2 K W^{-1} or clo
M	Metabolic rate, W m^{-2} or met
nZEB	Nearly Zero Energy Buildings
p_a	Water vapor partial pressure, Pa
RH	Relative humidity, %
PMV	Predicted Mean Vote, 1
PMV_{ASHRAE}	PMV value calculated by means of the ASHRAE Thermal Comfort Tool, 1
PMV_{7730}	PMV value calculated from tables in the Annex E of ISO 7730 Standard, 1
PPD	Predicted Percentage of Dissatisfied, %
t_a	Air temperature, °C
$t_{a,des}$	Air temperature measured within desired accuracy prescribed by ISO 7726, °C
$t_{a,req}$	Air temperature measured within required accuracy prescribed by ISO 7726, °C
t_o	Operative temperature, °C
t_r	Mean radiant temperature, °C
$t_{r,des}$	Mean radiant temperature measured within desired accuracy prescribed by ISO 7726, °C
$t_{r,req}$	Mean radiant temperature measured within required accuracy prescribed by ISO 7726, °C

v_a	Absolute air velocity, m s^{-1}
$v_{a,des}$	Absolute air velocity measured within desired accuracy prescribed by ISO 7726, m s^{-1}
v_{ar}	Relative air velocity, m s^{-1}
$v_{a,req}$	Absolute air velocity measured within required accuracy prescribed by ISO 7726, m s^{-1}
v_b	Velocity due to body movement, m s^{-1}

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