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TECHNICAL NOTE

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Proposal for the assessment of thermal indoor climate based on the thermal acceptability, in addition to the thermal (dis)satisfied.

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Abstract: For the sake of energy and cost savings, it is sometimes necessary to maintain the indoor climate in a room at conditions that deviate from optimal thermal comfort. More important than thermal sensation is how a change in conditions will affect the thermal acceptability of a space and whether the percentage of people who are (dis)satisfied with the environment will change with regard of the acceptability. The aim of this technical note and arithmetic study is to find out to what extent the thermal indoor climate can be assessed on the basis of thermal acceptability, in addition to the thermal (dis)satisfied, by making use of research that has already been carried out. In addition to the relationship between the percentage of (dis)satisfied and acceptability, attention is paid to how this result relates to current Dutch government building regulations. The paper concerns a proposal for the assessment of thermal indoor climate based on the thermal acceptability, in addition to the thermal (dis)satisfied.

Keywords: Mathematical modelling; Thermal comfort; Thermal acceptability; Environmental indoor quality; Adaptive thermal comfort

1. Introduction

The applicable dress code in the Netherlands usually does not allow shorts, t-shirts and sandals in the office environment. This is not the case in all countries, Japan for instance, during warm periods of the year. Due to the energy shortage, offices there are legally not allowed to be cooled below 26 to 27 degrees Celsius. Japanese office workers may go to work in chinos, polo shirts and even Hawaiian shirts. 'Cool biz' and 'Supercool biz' are the names of the campaigns launched by the Japanese government to promote this. Could this also be the case in Dutch offices in the future? And if so, what does this mean for the standards and guidelines? To what extent should

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we place more control in the hands of the user of the building? To answer these questions, it must first be known how thermal (dis)satisfaction relates to thermal acceptability and how this result relates to current regulations. For now, in this paper attention will be focused on the last two issues.

Therefore, for the sake of energy and cost savings, it is sometimes necessary to maintain the indoor climate in a room at conditions that deviate from optimal thermal comfort. How these deviations affect the users of that space is important for, for example, the designer, owner and operator of a building. The relationship between thermal sensation and environmental as well as personal parameters is, as a result of extensive experimental testing, reasonably well defined. A well-known thermal sensation scale, which is used here, is for example the seven-point ASHRAE scale. Mathematical equations have been developed to relate the thermal sensation experienced under test conditions of seated and active subjects to the thermal conditions. Furthermore, through various thermal physiological modelling techniques, the experimental results of thermal sensation can be extended and applied over a fairly wide range of conditions. More important than thermal sensation is how a change in conditions will affect the thermal acceptability of a space and whether the percentage of people who are (dis)satisfied with the environment will change with regard of the acceptability. Someone who feels slightly cool or warm may not be satisfied or comfortable, but the environment may still be thermally acceptable. That is why it is important to have algorithms to quantify, predict and assess this complex of perceptions of the users of a space.

The aim of this technical note and arithmetic study is to find out to what extent the thermal indoor climate can be assessed on the basis of thermal acceptability, in addition to the thermal (dis)satisfied, by making use of research that has already been carried out.

2. Primary Thermal Requirement For Dutch Government Offices

For Dutch government offices, the primary thermal requirement is that the thermal sensation must be maintained between -0.5 and 0.5 in at least 90% of the working time. PMV ± 0.5 (PPD = 10 %) may be exceeded under special circumstances for a maximum of 10 % of the working hours up to PMV ± 1 (PPD approx. 26 %)[1]. The aforementioned requirement is the basis of the so-called weighing factor method (Annex H, method C in NEN-EN-ISO-7730)[2]. and the adaptive thermal comfort method, as described in ISSO-publication 74[3].

3. Adaptive Thermal Comfort

Behavioral adaptation (e.g. adjusting clothing and air speed), physiological adaptation (i.e. more active skin blood circulation and sweat production) and psychological adaptation (namely: 'logical that it is warm inside if it is warm outside') play an important role in the assessment of the thermal indoor climate in a building where climate control is absent or limited. In the literature, this situation is referred to as adaptive thermal comfort, where it is customary to evaluate the indoor climate primary on the basis of thermal acceptability instead of the (dis)satisfied with the thermal indoor climate[3].

A condition when designing and commissioning a building, with thermal acceptability as the criterion, is that people in such a building can influence the indoor climate and the perception of it. Namely: being able to adjust the clothing, set the thermostat higher or lower, open or close windows and control the air speed where a fan is present in the workplace, depending on the indoor temperature. In addition, it is of course important that there is not too much glass in the facade, that there is good sun protection that can be operated yourself and that a building has sufficient heat accumulation if the situation is to be acceptable, when designing and taking into use[3]. For such a building, these are together not to be neglected starting points, for which frameworks must be set, preferably laid down in a standard and guideline; but at all times in a List of Requirements.

4. Guideline and Standards

A Dutch guideline, a Dutch / European standard and an American standard apply to this subject. All three will be briefly discussed below.

4.1 ISSO publication 74

The adaptive thermal comfort method, as presented in ISSO publication 74[3], gives minimum and maximum limits for the indoor temperature in Dutch office buildings, where the height of the permitted operative indoor temperature depends on the weighted average outside temperature. These limit values are based on extensive analysis of international field research; initially based on the ASHRAE RP-884 database, but in the second version on the data from the EU project Smart Controls and Thermal Comfort (SCATs). A distinction is made between two climate types, referred to as climate type ‘Alpha’ (α-building) and climate type ‘Bèta’ (β-building). Users of an Alpha-type building have options to individually influence the indoor climate and to open windows. Users of the Beta type do not have these options or to a lesser extent. In addition, a distinction is made between three defined quality classes. In the first version of the publication, the classification was based on the degree of acceptability of the indoor climate (namely: Class A: *at least 90% acceptability*, Class B: *at least 80% acceptability* and Class C: *at least 65% acceptability*). In the second version of the publication, the degree of acceptability is no longer explicitly stated, but the classification is described on the basis of the expectations of the users and whether it concerns new construction or existing construction. In the first version no exceedance hours were allowed. In the second version, an exceedance of 3-5% is tolerated[3,4].

4.2 NEN-EN-16798

The adaptive model in the European standard[5]. applies to buildings without mechanical cooling. The model is based on data from the EU project Smart Controls and Thermal Comfort (SCATs). The standard describes three pairs of different indoor temperature lines, as a function of the average weighted outdoor temperature and the expectations of the users, within which the current indoor temperature should in principle be maintained. An exceedance of 3-5% is tolerated[4]. The model is most similar to the model described in the second version of ISSO-74 (2014), but it is limited to buildings without mechanical cooling and the shape of the indoor temperature lines to be observed differ from each other. In the Netherlands, in practice, the evaluation of adaptive thermal comfort in office buildings in accordance with the ISSO-74 (2014) guideline appears to prevail over an evaluation in accordance with the NEN-EN-16798 standard.

4.3 ANSI/ASHRAE Standard 55

The adaptive model in the US standard[6] also only applies to buildings without mechanical cooling. The model is based on the ASHRAE RP-884 database. The standard also describes three pairs of different indoor temperature lines, as a function of a certain average outdoor temperature and the degree of thermal acceptability (i.e. minimum 90%, 80% and 65% acceptability), within which the actual indoor temperature must be maintained. The model is most similar to the first version of ISSO publication 74 (2004), but the shape of the indoor temperature lines to be observed deviated from that of the American standard. Although this American standard is not used in practice in the Netherlands, it seemed useful to mention it here, for the sake of completeness.

5. Thermal Acceptability as a Function of Thermal Sensation

Where ISSO-74, NEN-EN-16798 and ANSI/ASHRAE Standard 55 has established a relationship between thermal acceptability, indoor temperature and outdoor temperature, Berglund has established a relationship between the thermal acceptability and the thermal sensation[7] (**Figure 1**), namely:

$$Tacc = 98.753 + 2.378*TSV - 11.592*TSV^2 - 0.239*TSV^3 \ [\%] \quad (5.1)$$

Herein is:

- Tacc = thermal acceptability [%]
- TSV = thermal sensation, according to the ASHRAE 7-point scale [-].

Berglund’s research shows that the relationship between thermal acceptability and thermal sensation is more nuanced than the assumption that thermal acceptability occurs when the thermal sensation (PMV) is between -1.5 and 1.5 (ergo: $-1.5 < PMV < 1.5$), as defined for example in the report on the ASHRAE RP-884 database[8]. As mentioned, this is the file on which the adaptive comfort model, as presented in ANSI/ASHRAE Standard 55, and as presented in the first version of ISSO Publication 74, is based[3]. The thermal acceptability is not completely symmetrical with respect to the optimum, since the thermal acceptability decreases faster on the cool side of the optimum than on the warm side of the optimum. The reverse is the case with the satisfied curve, based on the research of Rohles[9]. It is also striking that the difference between the acceptability curve and the satisfied curve is smaller on the cold side of the optima than on the warm side.

The percentage of dissatisfied is defined in the way as Fanger describes in his thesis on page 130[10].

"The thermal dissatisfied are defined here as those who vote -2 or -3, 2 or 3. One could perhaps object that those voting -1 to 1 were not included also, but as evidenced by Gagge *et al*[11], real discomfort is first expressed by those voting higher than 2 or lower than -2. It has therefore been decided here to describe as dissatisfied, only those persons who feel comfort according to the above definition[10].

The thermal acceptability is defined as those who find the thermal situation acceptable regardless of thermal comfort.

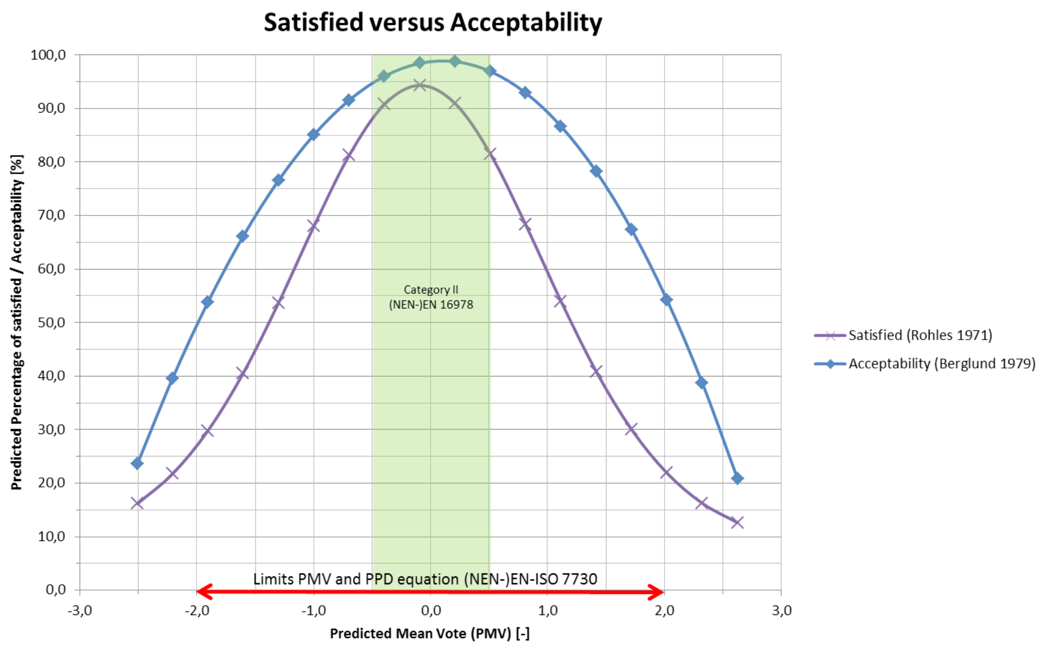

Figure 1. Satisfied versus Acceptability.

6. Proposal Classification

With the research of Berglund[7], general thermal comfort can be classified in the following way, based on thermal sensation - and implicit satisfied - as well as acceptability(see **table 1**).

Table 1. Classification based on thermal sensation and thermal acceptability.

Class	Thermal sensation [-] 1)	Thermal acceptability [%] 2)
I	-0.2 < PMV < 0.2	> 98
II	-0.5 < PMV < 0.5	> 95
III	-0.7 < PMV < 0.7	> 92
IV	-0.8 ⩽ PMV ⩽ 1.0	⩾ 90
V	-1.2 ⩽ PMV ⩽ 1.4	⩾ 80
VI	-1.6 ⩽ PMV ⩽ 1.8	⩾ 65

1) 100% of the working time on an annual basis
2) Excluding partial discomfort.

7. Indoor Thermal Climate Assessment

7.1 General

To get an impression of how the foregoing relates to the Dutch office situation, some temperature simulation calculations have been carried out for an office room (w*d*h: 3.6*5.4*2.7 m) oriented to the south and fitted with a second-skin façade.

7.2 Computer program

The dynamic heat balance of the room per hour is simulated with the aid of a computer program based on a mathematical model, drawn up according to the finite element method. The computer program offers the possibility to include the thermal activation of a built construction and the air exchange of the space, behind a second-skin façade, with outside air, based on a validated model. This computer program calculates, among other things, the indoor temperature, the PMV value and the weighing factor for each hour.

7.3 Climate data

Hourly climate data of the Dutch reference climate year, in accordance with NEN-5060 (2018, Annex E)[12], suitable for temperature exceedance calculations, have been used for the calculations. The reference climate year has a 1% chance that the actual outside temperature will be higher. For this year's assessment of the thermal indoor climate in the current situation, the entire year has been considered, taking summer time into account.

7.4 Assumptions

In order to be able to calculate the PMV value[2], the following is assumed:

• an average activity level: 70 [W/m^2] (light sedentary activity)

• a minimum average air speed : 0.10 [m/s]

• a clothing resistance: 0.7, 0.9 and 0.8 clo (respectively: June to Aug., Dec. to Feb. and other months)

• clothing adjustment to 0.5 clo if PMV ⩾ 0.8

• airspeed adjustment in clothing fitting, in accordance with[13]

• a calculation in accordance with[14], as there may be an indoor temperature greater than or equal to 27.8°C. This is the maximum temperature within the study of Nevins *et al*[15], on the basis of which the NEN-EN-ISO-7730 model for sedentary activities was derived.

Indoor air quality is based on category II, in accordance with NEN-EN-16798. It is assumed here:

• Perceived air quality of the outside air: 0.2 decipol

• Sensory pollution load of the building and the installations: 0.1 olf/m^2.

With an occupancy rate of 1 person per 10 m^2, a metabolism of 1.2 met and a ventilation effectiveness of 0.95, this results in a fresh air volume of at least 71 m^3/h per person.

The other principles are shown in **appendix 1**.

7.5 Variant calculations

A number of variant calculations have been carried out for a standard office room, on a mezzanine and on a south orientation of an office building. The other relevant principles are shown in Appendix 1. The variant calculations are:

1. a second-skin façade, thermal activation of floor and ceiling, constant floor temperature of 23°C during working hours and 15 hours after working hours, constant ceiling temperature of 23°C during working hours, Central Government Real Estate Agency guideline criterion, PMV calculated in accordance with NEN-EN-ISO 7730[2]

2. as 1, however PMV calculated in accordance with[14]

3. as 2, but no cooling of the inlet air and no ceiling cooling, a constant floor temperature of 21°C

4. as 3, but a constant floor temperature of 20°C

The calculations concern an alpha building.

7.6 Calculation results

The calculation results are shown in the **tables 2** and **3**. The shaded cells represent applicable guidelines and requirements (see the three criteria at the bottom of the table) that are met.

Table 2. Overview of calculation results for temperature and PMV exceedances.

Variant	Indoor temperature			Weighing time	Primary thermal requirement Dutch government offices		
	$Tinb_{max}$[°C]	Ti_{max}[°C]	Ti ⩾ 25.5°C [h/jaar]	{PMV ⩾ 0.5} [weighing hours]1)	-0.5 < PMV < 0.5 [%/year]2)	PMV ⩾ 0.5 [%/year]3)	PMV ⩾ 1.0 [%/year]
1	22.5	26.5	152	149	94.6	5.4	0.0
2	22.5	26.5	152	25	99.0	1.0	0.0
3	Tbu+1.5	32.3	387	337	91.4	8.5	0.9
4	Tbu+1.5	31.8	323	273	92.4	7.6	0.4

1) ⩽ 150 weighing hours, in accordance with the Central Government Real Estate Agency guideline[16]

2) ⩾ 90 %/year, in accordance with primary thermal requirement Dutch government offices[1]

3) ⩽ 5 %/year, in accordance with primary thermal requirement Dutch government offices[1].

Herein is:

• $Tinb_{max}$: maximum inlet temperature during working hours [°C]

• Ti_{max} : maximum indoor temperature in working time [°C]

• PMV: Predicted Mean Vote, in accordance with NEN-EN-ISO-7730[2]

• Weighing time: in accordance with the weighing factor method of the Central Government Real Estate Agency guideline[16].

Table 3. Overview calculation results class limit exceedance and thermal acceptability.

Variant	Class Limit Exceedance [%/year] 4)			Thermal Acceptability [%/year] 5)		
	Class B	Class C	Class D	⩾ 90%	⩾ 80%	⩾ 65%
1	1.8	0.0	0.0	100	-	-
2	1.8	0.0	0.0	100	-	-
3	10.3	5.5	2.3	99.0	99.9	100
4	8.7	4.0	1.7	99.4	100	-

4) In accordance with ISSO-74, α-building[3]

5) In accordance with research Berglund[7].

8. Conclusion

By linking thermal acceptability to thermal sensation and (dis)satisfied, a more nuanced picture of a permissible thermal indoor climate is created than is currently the case in practice. This makes it easier to assess a situation that deviates from an optimal thermal indoor climate. In the situation of climate change, this becomes more and more important.

Based on the calculation results, the following can be concluded for the present situation:

• The evaluation of the thermal indoor climate in the office space, on an annual basis, shows a significant difference if the PMV is calculated in accordance with NEN-EN-ISO-7730 or in accordance with the proposal, as done by Roelofsen *et al*.[14] (see variant 1 and 2 in **table 2**). For an explanation of why this is the case, see[14]. In short, it means that the NEN-EN-ISO 7730 model[2] overestimates the temperature sensation in non-air-conditioned buildings[17]. Roelofsen *et al*[14] show why this is the case and why the model, for sedentary activities, can be better based on Rohles' research[9] than Nevins *et al*'s research[15].

• For classes B, C and D, in accordance with ISSO-74 (α-building, 2014), over 90% of working time on an annual basis is -0.5 < PMV < 0.5

• The limits for classification B to D, according to ISSO-74 (α building, 2014), appear to correspond, in terms of acceptability, to respectively ⩾ 90% (class IV), ⩾ 80% (class V) and ⩾ 65% acceptability (class VI). For the record it should be noted that the aforementioned classification, based on the degree of acceptability, was also used in the first version of ISSO-74 (2004)

• With a minimum of class B, according to ISSO-74 (2014), the primary thermal requirement, as set for Dutch government offices, can be met

• The thermal indoor climate in Dutch government offices, in accordance with the primary thermal requirement, can be classified in class IV within the framework of this study, as shown in **table 1**.

By information, such as:

• seasonal clothing resistance (Van der Linden, Loomans, & Hensen, 2008) and

• the clothing and airspeed adjustment as a function of the thermal sensation and

• the air speed, as a function of the indoor temperature[13,17] and

• the thermal sensation at temperatures higher than 27.8°C[14,18]

to be processed in the thermophysiological model, the discrepancy, as described in the literature[19], between the calculation results with the thermophysiological NEN-EN-7730 model and an adaptive model, in the situation of a building of the Alpha type, can be significantly reduced[20]. This is also evident from this calculation study.

N.B.: It should be clear that an evaluation of the adaptive thermal comfort in the aforementioned way - i.e. based on thermal acceptability - is not limited to the consideration of a sedentary activity (Metabolism: 1.0-1.2 met) or an office building.

By assessing the thermal indoor climate, on an annual basis, on the basis of thermal sensation - and implicit satisfied - as well as thermal acceptability, the general thermal comfort can be determined and divided into classes (see **table 1**) in a more nuanced way than is currently the case. In addition, for the evaluation of the thermal indoor climate, use should be made of a thermophysiological model based on more test subjects and suitable for a wider field of application than the current model, as shown in NEN-EN-ISO-7730. The so-called NEN-EN-ISO-7730 model should be revised[14,18] and re-derived[21], if one still wants to continue to use it worldwide, as a standardized model, for evaluating the thermal indoor climate in enclosed spaces, with regard of moderate activities[22] and/or to warm situations, as a result of for instance climate change.

In the discussion at the end of DeDear and Auliciems' publication[23], one of the forerunners in adaptive comfort, Fanger says: "The suggestion of the authors to predict the neutral temperatures from the outdoor temperature regardless of clothing, activity, velocity and radiation would, in my opnion, be a step backwards and would ignore 50 years of research on heat transfer between man and his environment". In a paper of Fanger and Toftum[24] Fanger makes a proposal to include adaptive comfort in the PMV model. From both, it can be concluded that Fanger preferred to incorporate the adaptive comfort aspect into the thermophysiological model or the PMV-model.

The adaptive models in the standards and guidelines, mentioned before, are regression equations that relates the neutral indoor temperature to the monthly average outdoor temperature or a moving average outdoor temperature respectively. The only variable is thus the outdoor temperature, which at the highest may have an indirect impact on the human heat balance. An obvious weakness of the adaptive models is that they do not include human clothing or activity or the four classical thermal parameters that have a well-known impact on the human heat balance and therefore on the thermal sensation. Although the adaptive models predicts the thermal sensation fairly well for non-air-condioned buildings of the 1900s located in warm parts of the world, the question remains as to how well it would suit buildings of new types in the future where the occupants may wear different clothing and change their activity pattern[24].

It is clear that the aforementioned problems have been largely resolved with the proposal made above and matches ISSO 74 calculation results as well as Fanger's preference.

Conflict of Interest

The authors declare no conflict of interest.

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Appendix 1

Principles for the temperature exceedance calculations

- Mezzanine
- Glass percentage facade : 80 [%]
- U-value glazing : 0.94 [W/(m^2.K)]
- G- value glazing: 0.26 [-]
- G- value glazing + sun protection: 0.14 [-] (sun blind slats in the cavity)
- LT value glazing : 0.60 [-]
- Person occupancy : 1 person at 80 [W / 10 m^2]
- Installed lighting power : 10 [W/m^2]
- Heat emission equipment: 10 [W/m^2]
- Plenum space function : negative pressure
- Infiltration rate : 0.3 [m^3/(h.m^3)]
- Mechanical ventilation rate : 2.7 [m^3/(h.m^3)]
- Minimum inlet temperature : 16.0 [°C]
- Fan and duct heating : 1.5 [°C]
- Inlet temperature : outside temperature
- Working hours : 09:00 to 17:00
- Minimum indoor temperature : 22.0 [°C] during working hours

- Minimum indoor temperature : 15.0 [°C] after working hours
- Blinds operated during working hours : if Qtransmitted sun ⩾ 120 [W/m^2]
- No sun blind after working hours
- Additional ventilation through facade (during working hours) : if Ti > 24°C, Tu > 16°C, (Ti-Tu) > 1 K
- Additional ventilation through facade (after working hours): none
- Net opening glass outer side of the facade : 0.2 [m^2/m]
- Net opening glass inner side of the facade : 2.08 [m^2/m]
- Type of opening outer side of the facade : flaps (opening angle: 15 degrees)
- Type of opening inner side of the facade: tilt window (opening angle: 15 degrees)
- Surface gap under door: 0.005 [m^2]
- Night/weekend ventilation : none
- Inner walls : Metal Stud
- Floor construction (top – bottom) :
    - ○ project carpet
    - ○ 36 mm plasterboard (incl. water tubes)
    - ○ 50 mm screed
    - ○ 200mm concrete floor
    - ○ Plenum space
    - ○ 50mm mineral wool
    - ○ 18 mm plasterboard (incl. water tubes)