Modelling drivers of variance and adaptation for the prediction of thermal perception and energy use in zero energy buildings

IOP Conf. Series: Materials Science and Engineering **609** (2019) 042039 doi:10.1088/1757-899X/609/4/042039

Modelling drivers of variance and adaptation for the prediction of thermal perception and energy use in zero energy buildings

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Abstract. As thermal perception is a subjective "condition of mind", a high variance in observed thermal sensation votes does not come to a surprise. Literature reviews show a large number of individual and contextual influences. However, the quantification of the effect of individual drivers on thermal perception as well as thermal adaptation and their integration into thermal comfort models is still an open field of research. Still, analyses of the energy balance of zero-energy buildings (ZEB) are using assumptions related to the user's needs e.g. in terms of thermal comfort. First, this paper explores a novel combination of a biophysical model and an adaptive framework (called the ATHB*TNZ approach) and discusses the applicability of such approach to model individual differences in thermal perception. Second, results of an implementation of these individualized comfort prediction on the energy balance of a zero energy building are presented together with the resulting discomfort hours. Results show that the consideration of physiological differences and adaptive processes in the modelling approach can replicate observed variations in thermal perception. The energy balance of a ZEB is hardly affected by set point adjustments due to individual requirements, but discomfort hours strongly depend on individual characteristics of occupants.

1. Introduction

As thermal perception is a subjective "condition of mind" [1], a high variance in observed thermal sensation and thermal comfort votes does not come to a surprise. Literature reviews show numerous influences on thermal perception, which can be grouped into physiological, psychological, and context-related drivers [2–5]. However, the quantification of the effect of these drivers on thermal perception and their integration into thermal comfort models is still an open field of research [3, 6, 7]. In a recent review, Schweiker et al. [3] discuss ways forward towards a holistic mathematical model including variance due to physiological aspects and the level of adaptation. They present a combination of the thermos-neutral zone (TNZ) model by Kingma et al. [8] and the adaptive thermal heat balance (ATHB) framework by Schweiker and Wagner [9]. These two approaches offer the potential to look at individual differences and adaptive processes in thermal sensation and thermal satisfaction.

At the same time, analyses of the energy balance of (nearly) zero-energy building (n)ZEB are using assumptions related to the user's needs e.g. in terms of thermal comfort requirements. Traditionally, the heating demand has a major share in the energy use of buildings. In ZEB, the percentage of energy use related to heating is reduced while appliances and lighting play a much more dominant role. Still, a closer look into the variance in thermal perception and the effect of such variance on the energy balance and thermal perception in ZEB is meaningful in order to avoid dissatisfied clients, here users, once the building is operated. Such dissatisfaction can arise out of energy or comfort related predictions, not met in reality.

The main part of this paper explores the potential of the approach presented by Schweiker et al. [3] to model individual variance and adaptation. This model is then applied to building performance simulation in order to analyse the effect on the energy balance of an exemplary ZEB.

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2. Methods

This methods section first describes the modelling approach by Schweiker et al. [3] and followed by the description of the building performance evaluation.

*2.1. The ATHB*TNZ approach to thermal sensation and satisfaction*

The ATHB*TNZ approach combines the TNZ model by Kingma et al. [8] with the ATHB approach by Schweiker and Wagner [9].

The TNZ model is a steady state heat balance model, which combines two heat balances: the internal heat balance, i.e. within body, and the external heat balance, i.e. from body to environment. The basic intention of the TNZ model is to search for combinations of body core temperature, skin temperature and operative temperature that are supportive for both heat balances and are also physiologically feasible [8]. Input parameters for the TNZ model are internal heat production, body tissue insulation, clothing insulation, air speed, relative humidity, and operative temperature. Previous research suggests that the probability density function (pdf) of all combinations of operative temperature and skin temperature leading to a core temperature within the thermoneutral zone (pdf_{TNZ}), i.e. between e.g. 36.5°C and 37.5°C (see figure 1a), is related to thermal satisfaction [3]. In the context of this paper, the range of operative temperatures ($TNZ_{Top\ range}$) with a density above .05 is considered as satisfactory. In addition, previous research suggests that the operative temperature in the center of the TNZ ($T_{op\ centroid}$) is related to a neutral thermal sensation vote [10, 11]. Figure 1a summarizes the terms introduced above.

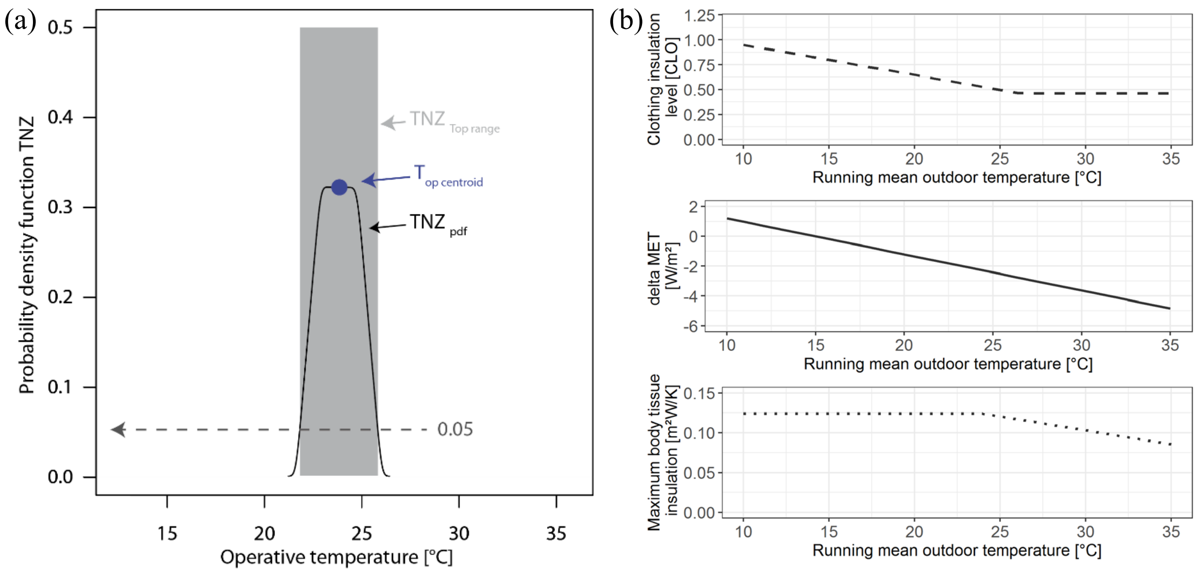

Figure 1. (a) Schema explaining key terms related to TNZ approach; (b) Resulting input values for TNZ model based on behavioural and physiological adaptation.

The ATHB approach [9, 12] established a framework to model individual processes of thermal adaptation (behavioral, physiological, psychological) and was applied to the heat balance model by Fanger [9], the SET model by Gagge [9, 12], and the TNZ model [3].

Schweiker et al. [3] presented two alternative methods to include the effect of adaptation into the TNZ model. Here, only their second approach as outlined in the following is applied. Within this approach, three input parameters of the TNZ model were made "adaptive", i.e. dependent on the running mean outdoor temperature (T_{rm}) (see also figure 1b):

1) To account for behavioral adaptation of clothing, the *clothing insulation level* is calculated according to the original values of the ATHB approach [9] by

$$CLO_{adapt}[CLO] = 1.252594 - 0.03 * T_{rm}\ with\ 0.46 < CLO_{adapt} < 1 \quad (1);$$

2) To account for behavioral adaptation of internal heat production, metabolic rate is reduced according to the equation by Hori [13] by

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$$\Delta MET_{adaptHori}[W/m^2] = 0.208 * (T_{rm} - 15) * 1.16 \quad (2)$$

(i.e. for example at T_{rm}=30°C, metabolic rate would be reduced by 3.6 Watts/m²);

3) To account for physiological adaptation the maximum body tissue insulation was interpolated between T_{rm}=24°C and T_{rm}=29°C to be 10% lower value for the latter, e.g. 0.124 m²W/K at T_{rm}=24°C and 0.11 m²W/K at T_{rm}=29°C.

Psychological adaptation is not dealt with in this paper. All calculations were performed with the statistical software R [14] and the library comf [15].

2.2. Building performance simulation

In order to analyze the effect of individual variance and adaptation on the building performance, an existing ZEB (see below) is modelled in DesignBuilder and the .idf-file exported.

The ZEB considered exemplarily is a two apartment building in Switzerland with a floor occupied by 7 persons and a net floor area of 302.4 m² and well documented in [16]. It uses a geothermal heat pump (COP 5.7) for heating and domestic hot water. Ventilation is supported through earth tubes, which warms the air in winter and slightly cools it in summer. No cooling other than through the earth tubes is available. With the high level of insulation (U_{mean} = 0.19 W/m²K including windows) and air tightness (N_{50} = 0.5 1/h), reasonable window-to-wall-ratio, and thermal as well as photovoltaic solar collectors, the buildings energy balance was calculated to be positive, with an energy use of 35 kWh/m²a including appliances and lighting and a solar power yield of 45 kWh/m²a. The model implemented in EnergyPlus was calibrated in order to reflect these overall figures as well as individual figures for the energy use of heating, domestic hot water, lighting, and appliances.

The .idf file exported from DesignBuilder is used to run simulations directly in EnergyPlusV9-0-1. Simulations were started within the R software environment [14] and simulation results were gathered and analyzed in this software environment as well.

Two simplified approaches were applied to look at the variance in thermal perception and adaptation within the context of a ZEB:

a) In order to analyse the effect of the variance in thermal perception on the energy balance, heating set points were adjusted according to the results from the ATHB*TNZ model; and
b) In order to analyse the effect of adaptation, the hours within the $TNZ_{Top\ range}$ were analysed with, without adaptation, and for different individual characteristics.

3. Results, discussion and limitations

*3.1. Individual difference in thermal perception and adaptation modelled through the ATHB*TNZ approach*

The effect of individual differences in thermal perception due to variations in age, sex, and body composition is shown in figure 2a. Indoor environmental and personal conditions underlying this figure are a relative humidity of 50%, an air velocity of 0.15 m/s, a clothing insulation level of 1 CLO (winter case) and a metabolic rate of 1.1 MET.

On the one hand, there is a large overlap in $TNZ_{Top\ range}$ between females (height = 160 cm), males (height = 175 cm) with normal (BMI = 22) and overweight (BMI = 28) body composition. On the other hand, there is a clear tendency towards cooler preferred conditions from normal weight female to overweight male. As pointed out by Schweiker et al. [3] , these observations coincide with findings from a large scale Brazilian field study [17]. In addition, the $T_{op\ centroid}$, which is related to a neutral sensation, increases with age, an effect also found by others [18]. Given standard set point temperatures for the heating season, a clothing insulation level of 1 CLO might be already too high for specific sub-populations such as male obese person.

It should be noted that the effect of age is modelled here solely by adjusting the basal metabolic rate according to Roza and Shizgal [19]. It can be expected that additional physiological changes alter thermal perception with age [20], which may need to be covered by future versions of this modelling approach.

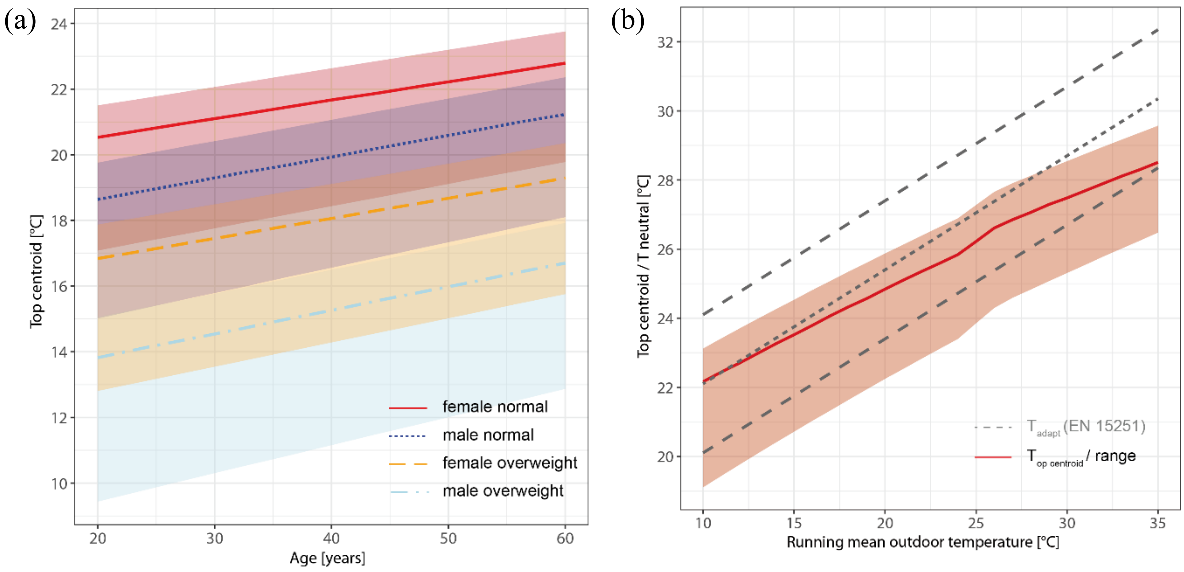

Figure 2. (a) Effect of age, sex, and body composition on $T_{op\ centroid}$ and $TNZ_{Top\ range}$ (b) Comparison between adaptive comfort temperature (EN 15251) and $T_{op\ centroid}$ and $TNZ_{Top\ range}$.

In Figure 2b, the adaptive comfort temperature, T_{adapt}, calculated based on EN 15251 is compared with $T_{op\ centroid}$ and $TNZ_{Top\ range}$ of the ATHB*TNZ approach. In both cases, there is a positive relationship between the T_{rm} and resulting indoor thermal conditions predicted as comfortable. With higher T_{rm}, the gap between T_{adapt} and $T_{op\ centroid}$ increases. Reasons might be that either the adaptive comfort model suggests a linear increase in comfort temperature, while there are limitations to human adaptation decreasing the effect of adaption at high T_{rm}'s as discussed [9]. Alternatively, the ATHB*TNZ approach likely does not capture all adaptive mechanisms implicitly included in the adaptive approach. As pointed out above, psychological adaptation is not modelled here. In addition, the data used for the derivation of the adaptive comfort model (EN 15251) likely includes higher air velocities at higher T_{rm}'s.

The advantage of the ATHB*TNZ approach is, that the effect of air velocity can be shown directly. In figure 3a, an elevated air velocity reduces the gap between T_{adapt} and $T_{op\ centroid}$ at higher T_{rm}.

Besides the ability to model the effect of air velocity within an adaptive context, the ATHB*TNZ approach permits first predictions with individual differences and adaptation as shown in figure 3b.

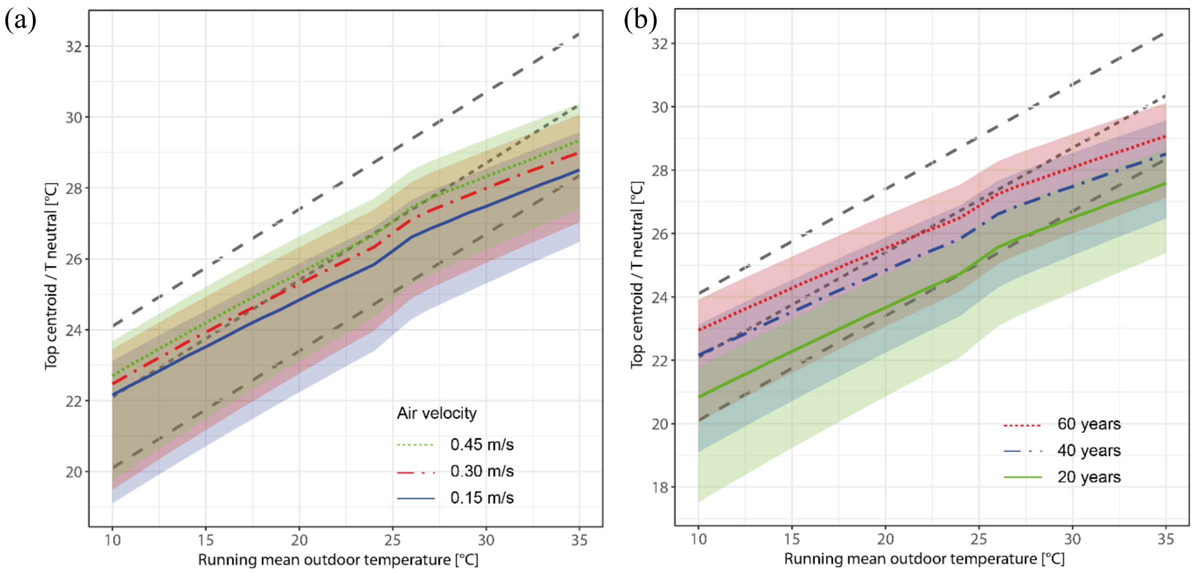

Figure 3. Effect of air velocity (a) and age (b) on $T_{op\ centroid}$ and $TNZ_{Top\ range}$.

Based on the current implementation, there is a non-linear effect of age shown by the comparison of $TNZ_{Top\ ranges}$. At low T_{rm}, the overall range of all age groups is 6.5 K (at T_{rm}=10°C from 17.5°C to 24°C). At high T_{rm}, the range is 5 K. This reduction in the overall range is due to the adaptive capacity of 20 year old persons is 6.7 K (defined here from Top centroid at T_{rm}=10°C (20.8°C) vs. T_{rm}=35°C (27.5°C), while it is 6 K for 60 year old persons. The adaptive capacity of elderly seems to be lower than that of younger persons. As mentioned above, these findings need to be considered with precaution and validated against data from field measurements. Furthermore, additional effects of adaptation, e.g. with respect to altered core temperatures at physiologically adapted conditions of the human body, diurnal changes as well as Q10 effects may need to alter above findings and need to be included in future versions.

3.2. Effect on energy balance and thermal satisfaction in ZEB

In order to analyse the effect of the variance in thermal perception on the energy balance of the given ZEB, two cases were simulated with set points for the heating system based on the ATHB*TNZ approach (see also Figure 2a). Case 1, a young normal weight male person, was using a set point of 19°C for occupied hours and 17°C for unoccupied or sleeping hours. Case 2, an elderly normal weight female person would have set points of 23°C and 18°C, respectively. Yearly simulations were run with all other settings remaining the same.

Table 1 presents the energy balance for the two cases. Due to the high quality of building envelope and the usage of a heat pump, there is only a marginal effect of these two behavioural patterns on the energy balance and the ration between generated and used electrical energy. Due to the existing highly positive balance, higher set points do not turn the energy balance negative. However, for buildings with a more tight balance, the sign of the balance could change depending on the comfort requirements.

Table 1. Effect of variations in comfort requirements on energy balance of ZEB.

End use [kWh/m²a]	*Case 1 (Young normal weight male)*	*Case 2 (Elderly normal weight female)*
Heat pump (electricity)	4.2	5.1
Lighting	18.5	18.5
Appliances	11.5	11.5
Electricity use total	34.2	35.1
PV total	45	45
Ratio (generated/ used)	1.32	1.28

Table 2. Hours of discomfort above satisfaction range depending on comfort model

Case		*Sex*	*Age [years]*	*Air velocity [m/s]*	*Hours of discomfort*
Fixed >25		-	-	-	727
Fixed >26		-	-	-	126
Fixed >27		-	-	-	0
Adaptive (EN 15251)		-	-	-	0
ATHB* TNZ	Standard	Female	45	0.15	643
	Elevated air velocity	Female	45	0.30	115
	High air velocity	Female	45	0.45	40
	Young	Female	20	0.15	5880
	Standard	Female	45	0.15	643
	Elderly	Female	60	0.15	13

The indoor operative temperature during summer time, when heating is off, is the same for both cases described above. Due to the absence of a cooling system, there is no effect on the energy balance in this simulation due to different thermal preferences in summer. However, in reality, occupants would behave differently in the building in terms of window opening and ventilation usage, or even decide to buy an active cooling system in case thermal satisfaction is very low.

Table 2 presents the number of hours in which the building is occupied and indoor operative temperature is higher than the thermal satisfaction requirements based on fixed cut-off values, the adaptive thermal comfort model, and the ATHB*TNZ model for different scenarios. There is a large variance between the scenarios ranging from 13 hours to nearly 6000 hours. Such effect shows, that it is crucial for a ZEB approach to consider the type of occupants and their thermal satisfaction requirements. In case the building was designed with false assumptions, occupants may need to adopt additional adaptive behaviour to increase the air velocity, reduce clothing insulation (though it is already at .46 CLO for warm indoor conditions) or they will decide to install further active cooling systems.

4. Conclusions

This paper presents an advance method to incorporate adaptive processes and individual physiological differences into classical comfort models, able to capture differences in clothing insulation level and air velocity. Results show the ability of the ATHB*TNZ approach to model these diversities. However, the modelling also shows limitations related to questions how far can physiological adaption go, how diverse are levels of adaptation and adaptive capabilities between and within different groups such as male, female, young, elderly, normal weight and overweight persons.

Implementing these individual differences in building performance simulation shows that the energy balance of a ZEB is affected to a low extent, while discomfort hours above thermal satisfaction ranges vary strongly depending on the chosen group. This emphasises the need to have a closer look at individual processes of adaptation to warm conditions and their predictability during the design phase.

Acknowledgements

This analysis was conducted within the WIN-Kolleg "Thermal comfort and pain" funded by the Heidelberg Academy of Sciences and Humanities. The modelling and discussion in this paper benefitted from the work and discussions with Boris Kingma, Gesche Hübner, Hannah Pallubinsky and Rick Kramer during the preparation of an earlier literature review [3].

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