

Review

# Models and Indicators to Assess Thermal Sensation Under Steady-State and Transient Conditions

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**Abstract:** The assessment of thermal sensation is the first stage of many studies aimed at addressing thermal comfort and at establishing the related criteria used in indoor and outdoor environments. The study of thermal sensation requires suitable modelling of the human body, taking into account the factors that affect the physiological and psychological reactions that occur under different environmental conditions. These aspects are becoming more and more relevant in the present context in which thermal sensation and thermal comfort are represented as objectives or constraints in a wider range of problems referring to the living environment. This paper first considers the models of the human body used in steady-state and transient conditions. Starting from the conceptual formulations of the heat balance equations, this paper follows the evolution occurred during the years to refine the models. This evolution is also marked by the availability of increasingly higher computational capability that enabled the researchers developing transient models with a growing level of detail and accuracy, and by the validation of the models through experimental studies that exploit advanced technologies. The paper then provides an overview of the indicators used to characterise the local and overall thermal sensation, indicating the relations with local and overall thermal comfort.

**Keywords:** living environment; local thermal sensation; overall thermal sensation; thermal comfort; steady-state conditions; transient models; standards

## 1. Introduction

Thermal sensation (*TS*) and thermal comfort (*TC*) are vital concepts for the life of the occupants in living environments. These two concepts are defined in the ASHRAE Standard 55-2017 [1] concerning indoor environments. *TS* is a physical property of the body, defined as “a conscious feeling commonly graded into the categories cold, cool, slightly cool, neutral, slightly warm, warm and hot”. *TC* is defined as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. The thermal environment represents “the characteristics of the environment that affect a person’s heat loss”.

*TS* is the result of the body “psycho-physical reaction” to the thermal stimuli related to indoor conditions. *TS* depends on the human body temperature, which in turn is a function of the effects of the comfort factors. These comfort factors are indoor environmental factors (mean air temperature around the body, relative air velocity around the body, humidity, and mean radiant temperature to the body [2]) and personal factors of the occupants (metabolic rate or internal heat production in the body, which vary with the activity level, and clothing thermophysical properties such as clothing insulation and vapour clothing resistance). Furthermore, *TS* expresses the perception of the occupants, while *TC* assesses this perception taking into account physiological and psychological factors [3].

In physiology, the concept of thermal neutrality is defined by the Thermal Neutral Zone (*TNZ*) as the ambient temperature range in which the human body can maintain the body core temperature with no regulatory change in the metabolic heat production or sweating [4]. In these conditions,

the temperature regulation is only obtained from the control of the sensible heat loss. From the biological point of view, the human thermoregulation system aims to maintain the temperature homeostasis (i.e., to keep a stable internal environment within the body) when the external environment is changed.

The main physiological indicators of the human responses to thermal environments are the skin temperature, which changes due to the ambient and body activity; the internal body or core temperature, which is the mean temperature of the thermal core of the body; the sweat rate, that represents the quantity of fluids lost by the body through sweat during exercise; the skin wettedness, which is the portion of the total skin surface area of the body covered with sweat, and the arterial and venous flow rates [5]. The lack of physiological experimental data is a major issue for the validation of the thermoregulation models.

The psychological factors include naturalness (an environment where the people tolerate wide changes of the physical environment), expectations and short/long-term experience (which directly affect individuals' perceptions), time of exposure, perceived control, and environmental stimulation [6]. In addition, the psychological response of the individuals depends on social, economic and cultural aspects [7]. Furthermore, sensations of pleasure or pain, and the behaviour of the individuals (e.g., to change clothing or change the setting of a thermostat) are based on psychological responses that cannot be easily predicted on the basis of physical or physiological aspects.

The most used models to assess *TS* of the human body with respect to the environment have been developed starting from the Fanger empirical model [3] for steady-state conditions, and from the Gagge model [8] for transient conditions. Fanger's work introduced a different and engineering-based approach with respect to the physiological approach that was used in the American School (see some historical notes in [9]). In the Fanger model, the thermoregulatory system of the human body creates a heat balance in a wide range of the environmental variables in indoor environments. The Fanger empirical model was used in the Standard ISO 7730 first issued in 1984 [10], and in its successive editions. Further studies considered that the occupants tend to make adaptations to reach better thermal comfort, following different approaches such as behavioural adjustment, physiological adaptation, and psychological expectations [11]. Thereby, adaptive models were developed for indoor spaces that can be controlled by the occupants, in which the outdoor climate can affect the indoor conditions. The adaptive model of de Dear and Brager [11] for indoor spaces with no heating, ventilation and air conditioning (HVAC) systems was included for the first time in the Standard ASHRAE 55:2004 [12]. In Europe, an adaptive model was included in the European Standard EN 15251:2007 [13], and further regulatory documents worldwide have incorporated an adaptive thermal comfort model [14].

To obtain an accurate assessment of *TS*, the best way generally considered is to ask the individuals directly. The metrics referring to *TS* and *TC* concepts are presented in the Standards [15] and [16]. Table 1 summarises various scales.

*TS* is represented by using the ASHRAE 7-point scale [15], the 9-point scale used in other prediction models, and the 11-point scale used in the Fanger model [3]. The Gagge model uses the 11-point Thermal Discomfort (*TD*) index to predict *TS* [17]. Although the use of these scales does not explain why the subjects indicate their sensation on a given point of the scale, the direct responses obtained provide practical information to be elaborated together with the physiological information and the physical characteristics of the environment [2].

The most used concept to address the opinion of the subjects concerning *TS* is the Thermal Sensation Vote (*TSV*). The subjects express their vote to rate their *TS* when they are exposed to given thermal conditions, by using a scale from cold to hot, with a predefined number of points. *TSV* can refer to the whole body, to quantify the global sensation, as well as to local body parts, indicating a local sensation. In the latter case, it is possible to compare the *TSV* results with the results of the physiological measurements carried out in the corresponding parts of the body [18]. Takada et al. [19] propose a nonlinear multiple regression analysis to predict *TSV* in function of the mean skin temperature and its

differences in time. In general, it is very hard to correlate the physiological variables with information concerning global and local sensation.

**Table 1.** Scales used to represent the *TC*, *TS* and *TD* indicators.

Indicator	<i>TC</i>	<i>TS</i>	<i>TS</i>	<i>TS</i>	<i>TD</i>
Scale	ISO 4-point *	ASHRAE 7-point	9-point	11-point	11-point
+5	--	--	--	intolerably hot	intolerably warm discomfort
+4	--	--	very hot	very hot	limited warm discomfort
+3	--	hot	hot	hot	very uncomfortable warm
+2	comfortable	warm	warm	warm	uncomfortable and unpleasant warm
+1	slightly comfortable	slightly warm	slightly warm	slightly warm	slightly uncomfortable but acceptable warm
0	--	neutral	neutral	neutral	neutral
-1	slightly uncomfortable	slightly cool	slightly cool	slightly cool	slightly uncomfortable but acceptable cold
-2	uncomfortable	cool	cool	cool	uncomfortable and unpleasant cold
-3	--	cold	cold	cold	very uncomfortable cold
-4	--	--	very cold	very cold	limited cold discomfort
-5	--	--	--	intolerably cold	intolerably cold discomfort

\* The 4-point scale uses relative expressions only. The position in the table is indicative of the absence of a neutral level.

Recent reviews deal with *TS* models. Walgama et al. [20] present computational and empirical models to predict thermal response and *TS* in the transient non-uniform environment for the automotive sector. Seven *TS* prediction models are experimentally compared in [21], indicating how the accuracy of the input parameters and the characteristics of the model affect the prediction accuracy. Schlader et al. [22] investigate the control of the human thermoregulatory behaviour during rest and exercise. The control of thermal perceptions, the perceived exertion and the importance of the skin temperature as thermal input to maintain temperature regulation are analysed. To evaluate *TS*, Alahmer et al. [23] focus on human thermal physiological models, psychological models, thermal manikin models, and combined models. Cheng et al. [24] address specific models based on physiological and environmental parameters.

Khodakarami and Nasrollahi [25] deal with the levels of productivity of the staff workers in hospitals. This analysis is useful considering that the thermal conditions have a significant influence on the health, safety and welfare of the occupants who work in these environments. Katić et al. [26] consider the thermophysiological models that describe the physiological responses, taking into account the heat transfer in the human body under different environmental conditions. In addition, they describe the issues about modelling isolated body segments for evaluating the sensitivity of different body zones and body extremities for various thermal environments. Mishra et al. [27] include a section dealing with *TS* in non-uniform ambient, with details on local sensations and comfort. Schweiker et al. [28] provide an overview of the scales used in studies in which *TS* scale, thermal preference scale, *TC* scale, thermal acceptance scale, and other scales are exploited. Psikuta et al. [29] deal with the usage of thermal manikins to assess the opportunities and constraints of thermo-physiological human simulators, including automotive field, artificial microclimates for human occupancy, clothing research, and urban environment. A review of local and overall *TS* models is presented in [30].

Table 2 summarises the recent review papers presented above. The relevant topics addressed are categorised into thermoregulatory control, applications to different contexts, human thermal physiological and psychological models, and numerical comparison with different software tools.

The table shows that generally these reviews cover dedicated aspects of models and indices for *TS* prediction in specific environments.

**Table 2.** Categorisation of recent literature reviews.

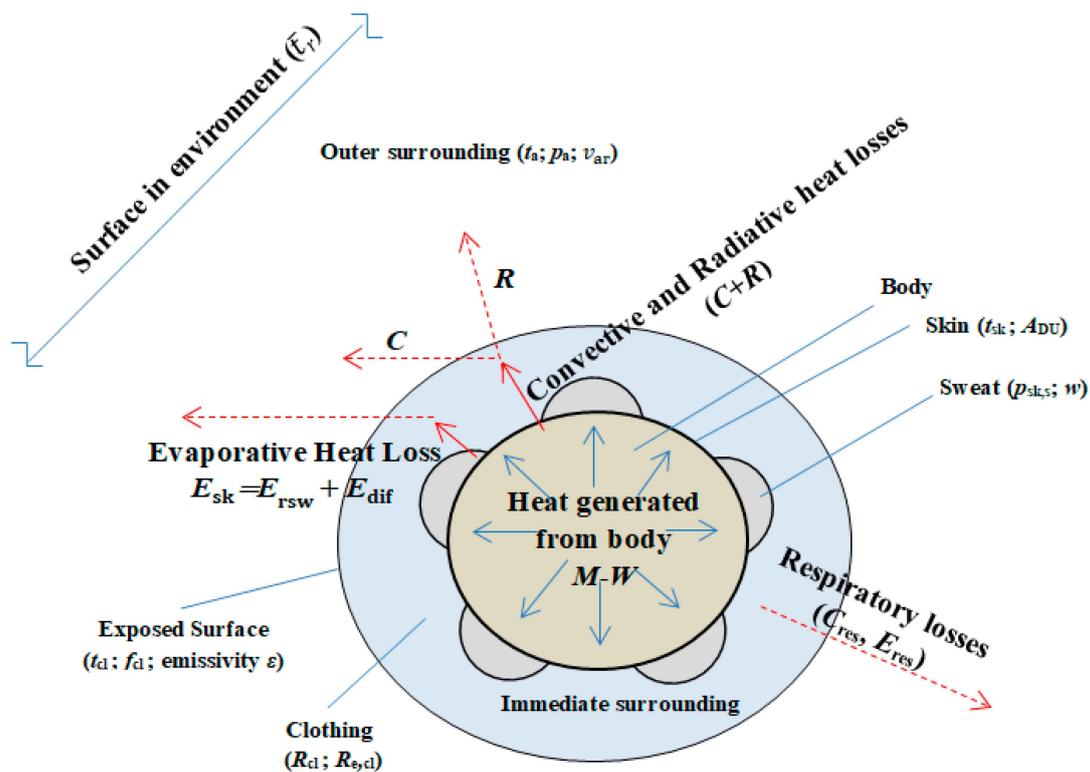
Review Paper Reference	Thermoregulatory Control	Applications	Thermal Manikins Model	Human Thermal Physiological Model	Human Thermal Psychological Model	Numerical Comparison with Different Tools
Walgama et al. [20]	-	vehicles	yes	yes	yes	-
Schlader et al. [22]	yes	during rest & exercise	-	-	-	-
Alahmer et al. [23]	-	vehicles	yes	yes	yes	-
Cheng et al. [24]	-	-	yes	yes	yes	CFD
Khodakarami and Nasrollahi [25]	-	hospitals	-	-	-	-
Katić et al. [26]	-	vehicles	-	yes	-	THESEUS-FE
Mishra et al. [27]	-	building	-	-	-	-
Schweiker et al. [28]	-	<i>TS</i> scales	-	-	-	-
Psikuta et al. [29]	yes	outdoor and building	controlled by models of human thermo-regulation	yes	-	CFD
Fang et al. [30]	-	calculation of <i>LTS</i> (head; upper and lower parts of the body) and <i>OTS</i>	-	-	-	-

This paper presents a review of the models of the human body used in steady-state and transient conditions for *TS* assessment. The conceptual formulation of the heat balance equations of the human body is recalled, with the corresponding models and indices for *TS* prediction in steady-state conditions. The attention is then focused on the models developed in transient conditions, following the evolution occurred during the years to define and refine these models. This evolution is also marked by the availability of increasingly higher computational capability that enables the researchers developing transient models with a growing level of detail and accuracy. Specific issues are pointed out, concerning the ways to model physiological aspects, the importance of the clothing model, the conditions of validity of the existing models, the model validation referring to the need to progressively correct the models on the basis of experimental data, and the differences emerging from different approaches, also on the standardisation side. Many of the models and indices are valid only in specific thermal conditions (e.g., moderate environments, cold or hot environments; indoor or outdoor conditions). The limitations of the models, also due to the lack of physiological and psychological aspects, and the possible incorporation of psychological aspects are discussed.

The last part presents an overview of the indicators used to characterise the local thermal sensation (*LTS*) and the overall thermal sensation (*OTS*), to show the link between these indicators and the models used in *TC* studies.



$q_{res}$	total rate of heat loss through respiration;
$C + R$	sensible heat loss from skin;
$C$	convective heat flow, “the heat exchange by convection between the boundary surface (clothing or skin) and environment”;
$R$	radiative heat flow, “the heat exchange by radiation between the boundary surface (clothing or skin) and environment”;
$E_{sk}$	the evaporative heat flow at the skin, “the rate at which heat energy is transferred by evaporation from or condensation on the skin”;
$C_{res}$	respiratory convective heat flow, “the heat exchanges by convection in the respiratory tract”;
$E_{res}$	respiratory evaporative heat flow, “the heat exchanges by evaporation in the respiratory tract”;
$S$	body heat storage rate, “the rate of increase (+) or decrease (−) in the heat content of the body caused by an imbalance between heat production and heat loss”;
$S_{sk}$	rate of heat storage in the skin compartment;
$S_{cr}$	rate of heat storage in the core compartment.



**Figure 1.** Heat exchanges from human body to environment (adapted from ASHRAE 2017 [35]).

The body is considered as two thermal compartments: the skin and the core [8,36,37]. In this case, the body heat storage rate is the sum between the rate of heat storage in skin compartment  $S_{sk}$  and rate of heat storage in core compartment  $S_{cr}$  [35]:

$$S = S_{sk} + S_{cr} = (1 - \alpha_{sk}) \cdot m \cdot c_{p,b} \cdot A_{DU}^{-1} \cdot \frac{dt_{cr}}{d\tau} + \alpha_{sk} \cdot m \cdot c_{p,b} \cdot A_{DU}^{-1} \cdot \frac{dt_{sk}}{d\tau} \quad (2)$$

where:

- $\alpha_{sk}$  fraction of the body mass concentrated in the skin compartment, dimensionless;
- $c_{p,b}$  specific heat capacity of body, with  $c_{p,b} = 3490 \text{ J} \cdot (\text{kg} \cdot \text{K})^{-1}$ ;

- $A_{DU}$  DuBois body surface area, “the total surface area of a nude person”, with  
 $A_{DU} = 0.202 \cdot m^{0.425} \cdot h^{0.725}$ ,  $m^2$ ;
- $m$  body mass, kg;
- $h$  body height, m;
- $t_{cr}$  core temperature, “the mean temperature of the thermal core of the body”, °C;
- $t_{sk}$  local skin temperature, “the skin temperature measured at a specific point of the body surface”, °C;
- $\tau$  time, s.

### Heat Losses from the Body to Outer Surrounding

Heat dissipated from the body to the outer environment [35]:

- The sensible heat loss from the skin  $C + R$  can be expressed as:

$$C + R = (t_{sk} - t_0) \cdot \left( R_{cl} + \frac{1}{f_{cl} \cdot h} \right)^{-1} \quad (3)$$

where the terms are defined according to the Standard ISO 13731:2001 [31]:

- $h$  total heat transfer coefficient, the sum between the convective heat transfer coefficient  $h_c$  and radiative heat transfer coefficient  $h_r$ ,  $h = h_c + h_r$ ,  $W \cdot (m^2 \cdot K)^{-1}$ ;
- $h_c$  convective heat transfer coefficient, “the net sensible heat transfer per unit area between a surface and a moving fluid medium per unit temperature difference between the surface and the medium”,  $W \cdot (m^2 \cdot K)^{-1}$ ;
- $h_r$  radiative heat transfer coefficient, “the net rate of heat transfer per unit area by radiation between two surfaces, per unit temperature difference between the surfaces”,  $W \cdot (m^2 \cdot K)^{-1}$ ;
- $t_0$  operative temperature, “uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment”, °C;

$$t_0 = (h_r \cdot \bar{t}_r + h_c \cdot t_a) \cdot h^{-1} \quad (4)$$

- $t_a$  air temperature, “the dry-bulb temperature of the air surrounding the occupant”, °C;
- $\bar{t}_r$  mean radiant temperature, “uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure”, °C;
- $f_{cl}$  clothing area factor  $f_{cl} = \frac{A_{cl}}{A_{DU}} \geq 1$ , “ratio between the surface area of the clothed body, including unclothed parts, and the surface of the nude body”, dimensionless;
- $R_{cl}$  thermal resistance of clothing,  $(m^2 \cdot K) \cdot W^{-1}$ .
- The evaporative heat flow at the skin  $E_{sk}$  is the sum between evaporative heat loss by regulatory sweating  $E_{rsw}$  and diffusion evaporative heat loss  $E_{dif}$ :

$$\begin{aligned} E_{sk} &= E_{rsw} + E_{dif} = w_{rsw} \cdot E_{max} + \underbrace{(1 - w_{rsw}) \cdot 0.06 \cdot E_{max}}_{\text{with regulatory sweating}} \\ &= E_{max} \cdot \underbrace{[w_{rsw} + (1 - w_{rsw}) \cdot 0.06]}_w \end{aligned} \quad (5)$$

where the terms are defined as in the Standard ISO 13731:2001 [31]:

- $w$  skin wettedness, “the equivalent fraction of the skin surfaces which can be considered as fully wet,” dimensionless;
- $w_{\text{rsw}}$  skin wettedness caused by diffusion, represents the zone of the human body which has to be wetted to evaporate the regulatory sweat:

$$w_{\text{rsw}} = \frac{E_{\text{rsw}}}{E_{\text{max}}} \quad (6)$$

- $E_{\text{max}}$  maximum possible evaporative heat flow at the skin, “the heat flow due to evaporation that can be achieved in the hypothetical case of the skin completely wetted”;  $E_{\text{max}}$  occurs when skin wettedness is  $w = 1$ :

$$E_{\text{max}} = \frac{p_{\text{sk},s} - p_a}{R_{\text{e,cl}} + (f_{\text{cl}} \cdot h_e)^{-1}} \quad (7)$$

- $p_{\text{sk},s}$  saturated water vapour pressure at skin temperature, kPa;
- $p_a$  water vapour partial pressure, “the pressure which the water vapour would exert if it alone occupied the volume occupied by the humid air at the same temperature”, kPa;
- $R_{\text{e,cl}}$  evaporative resistance of a clothing ensemble, “resistance to vapour transport of a uniform layer of insulation covering the entire body that has the same effect on evaporative heat loss as the actual clothing under (static, wind-still) conditions”,  $\text{W} \cdot (\text{m}^2 \cdot \text{kPa})^{-1}$ ;
- $h_e$  evaporative heat transfer coefficient, “net latent-heat per unit vapour-pressure difference caused by the evaporation of water from a unit area of a wet surface or by condensation of water vapour on a unit area of body surface”,  $\text{W} \cdot (\text{m}^2 \cdot \text{kPa})^{-1}$ .
- The respiratory heat flow  $q_{\text{res}}$  is the sum between the respiratory convective heat flow  $C_{\text{res}}$  and the respiratory evaporative heat flow  $E_{\text{res}}$ :

$$q_{\text{res}} = C_{\text{res}} + E_{\text{res}} = 0.0014 \cdot M \cdot (34 - t_a) + 0.0173 \cdot M \cdot (5.87 - p_a) \quad (8)$$

Because the heat balance cannot alone determine thermal comfort, there are two linear regression equations (one of the mean skin temperature, and the other of the sweat rate with data obtained from [38]) useful to obtain a connection between thermal comfort and physiological and heat flow expressions [35]:

$$t'_{\text{sk}} = 35.7 - 0.0275 \cdot (M - W) \quad (9)$$

$$E'_{\text{rsw}} = 0.42 \cdot (M - W - 58.15) \quad (10)$$

## 2.2. Approaches for Assessing Indoor and Outdoor Human Thermal Indices

The heat balance equation can be used both in moderate thermal environments, where the aim is to achieve the thermal comfort conditions, and in severe environments where the health protection of the workers to hot or cold stress is very important. The thermal environment is evaluated by using an adequate human thermal index [39]. The human thermal index can be any indicator or parameter that includes climate variables or terms that represent the state of the thermal environment, for a person or a group of persons [40].

The choice of a proper human thermal index is based on the following approaches: (a) studies in situ for making a subjective assessment of the climatic conditions; (b) analytical studies necessary to group the environmental and personal parameters in a single index; and (c) determination of the combinations of the climatic parameters to obtain the same physiological effect [39]. Blazejczyk et al. [41] made a categorisation of thermal indices as: (a) direct indices, based on direct measurements of the environmental variables, which are more user friendly and easily applicable (e.g.,

the wet-bulb globe temperature—*WBGT*, the apparent temperature, and the operative temperature); (b) empirical indices based on subjective and objective stress, difficult to be implemented for daily use due to the multitude of variables and invasive measurements (e.g., the Predicted Heat Strain—*PHS* [42]); and (c) rational indices based on the calculation concerning the heat balance of the human body, difficult to be implemented for daily use (e.g., the heat stress index for warm weather; the required clothing insulations for cold environments—*IREQ* [43]). De Freitas and Grigorieva [40] classified the human thermal climate indices according to the following criteria: (a) the thermal conditions where the index must be used; (b) for what type of metabolic states the index is applied for; (c) the environmental parameters (mean radiant temperature, air temperature, relative air velocity, humidity) considered as the input values in the block diagram of the index; (d) personal parameters (metabolic rate and clothing insulation) considered as the inputs the block diagram of the index; (e) an absolute or relative measure of thermal conditions; (f) an index of thermal environmental stress; and (g) if the index has been experimentally tested and validated.

There is a vast literature dedicated to the indoor and outdoor thermal indices. The International Standard Organisation (ISO) selected only a set of reliable indices to be published in the Standards, where: (1) moderate environments are evaluated by the Predicted Mean Vote (*PMV*) presented in the Standard ISO 7730:2005 [44]; (2) hot extreme environments are evaluated by the *WBGT* index presented in the Standard ISO 7243:2017 [45], and for transient conditions the *PHS* approach is used in the Standard ISO 7933:2004 [42]; and (3) cold extreme environments are evaluated by the *IREQ* index presented in the Standard ISO 11079:2007 [43]. Furthermore, some indices with interesting characteristics have not been used any longer after their definition [39].

The conditions of applicability of the indoor and outdoor indices have to be carefully stated and followed. For indoor conditions, the suitable indices are based on steady-state models. These indices cannot be used outdoor, where non-steady-state models are needed [46]. In fact, in outdoor conditions the external variables change more frequently than inside a building. In addition, for relatively short times (e.g., less than one hour) a thermal steady state is difficult to be reached, because of the mechanisms of thermal adaptation of the body temperatures. Moreover, the thermal expectations of the individuals can be very different from the psychological point of view.

Typically, for indoor moderate environments the *PMV* method is adopted. This method requires quasi-steady state conditions and assumes there is no heat storage variation in the human body. These assumptions are not valid outdoors. Moreover, solar radiation is present outdoors, while this term does not appear on the energy balance equation on which the *PMV* method is based. On-site measurements and questionnaires [47] have shown that, even extending the *PMV* beyond the  $[-3, +3]$  range, the actual sensation recorded by people does not agree with the expected *PMV*.

### 2.3. Fanger One-Dimensional Model

This model solves the heat balance equation between the human body and its surrounding environment [48]. The whole body is considered as a single node. The clothing system is simulated as uniform insulation over the entire body surface [49]. The heat balance is obtained taking into account physiological and physical factors, that is, the heat production by metabolism and by external work, as well as the heat loss due to evaporation, respiration, radiation, conduction and convection from the surface of the clothing and skin [50].

Fanger negatively debated the American approach concerning thermal comfort in his research [51]. The American approach related to thermal comfort considered no air motion, only one level of metabolic rate,  $t_a = \bar{t}_r$ , and one clothing type (e.g., summer). Fanger developed his equation by means of experimental studies on a large number of young subjects. The result of the experimental researches was that the *TS* could be connected to the mean skin temperature  $\bar{t}_{sk}$  and the heat loss by evaporation (both depending on the metabolic rate  $M$ ) [9]. The Fanger comfort equation is mainly focused on the thermal physiology of the human body [52]. It is applied only to subjects with a constant  $M$  exposed

to steady-state conditions in uniform thermal environments for an extended period, and is appropriate for sedentary people.

The Fanger comfort equation [3], based on the heat balance equation of the human body under particular boundary conditions, is written in the implicit form as follows:

$$f(M, I_{cl}, v_{ar}, \bar{t}_r, t_a, p_a) = 0 \quad (11)$$

where  $I_{cl}$  is the clothing insulation, defined as “the thermal insulation from the skin surface to the outer clothing surface (considering enclosed air layers)”, [clo], where 1 clo = 0.155 (m<sup>2</sup>·°C)/W;  $v_{ar}$  is the relative air velocity, or “the air velocity relative to the occupant, including body movements”, [m·s<sup>-1</sup>] [31].

Fanger’s experimental studies, based on the thermal balance model, have an important advantage by controlling all environmental parameters. The field studies developed later had shown the same purpose, namely, thermal comfort is obtained when the body temperature is maintained with the lowest effort of physiologic regulation [53].

Fanger carried out experimental studies in air-conditioned chambers in Denmark in the 1970s, on the human perception. He established that the *TS* is mainly obtained by narrow ranges of sweat evaporation rate and skin temperature, considering the activity level. He measured just physical quantities easy to be obtained by experiments. In addition, he observed that the values are correlated with the outer surrounding of the human body. The effects of diverse environmental variables (air velocities, air temperatures, and diverse humidity) are taken into account in Fanger’s model. In addition, these variables are connected to the release of the heat from the skin to the outer surrounding, without many details about the heat transfer processes developed inside the human body. The heat generated by the body activities must be totally dissipated to the outer surrounding to keep a steady state of comfort. The heat is transferred from the body core to the skin, and after that it is dissipated due to the processes of heat transfer taken into account in Fanger’s model [54].

The practical concepts that emerged from Fanger’s model are the Predicted Mean Vote (*PMV*) described below and the Predicted Percentage of Dissatisfied (*PPD*). The *PMV* index is based on heat balance studies, being considered as a reference index for buildings provided with HVAC systems in a moderate indoor thermal environment. The *PMV* index appeared in the first edition of the Standard ISO 7730:1984 [10], was accepted about 20 years later also by ASHRAE, and is currently used in various Standards such as ISO 7730:2005 [44], EN 15251:2007 [13], ASHRAE 55-2017 [1], and ISO 17772-1:2017 [55]. The *PPD* index is obtained from the *PMV* index, and gives information on discomfort or dissatisfaction. The *PMV* and *PPD* indicators predict cold and warm discomfort for the body as a whole [44]. The *PPD* index predicts the number of people who feel too cool or too warm (thermally dissatisfied) among a large group of people in a given environment [44].

Dissatisfaction is also caused by unwanted heating or cooling of one particular zone of the human body (local discomfort) [44]). Furthermore, the local thermal discomfort is caused by draught (unwanted local cooling of the body provoked by air motion) *DR*, vertical air temperature difference, warm and cool floors, and radiant asymmetry (provoked by cool walls/windows or warm ceilings)  $\Delta T_{pr}$ , which are parameters provided by the Standard ISO 7730:2005 [44] and are presented in Section 2.5.

#### 2.4. *PMV Index for Thermal Sensation Prediction*

*PMV* based on the thermal neutrality concept has been used to predict *TS* on a seven-point scale from “cold” (−3) to “hot” (+3) for a single-segment human body in a uniform environment and steady-state conditions in buildings with HVAC systems [1,55]. The *PMV* index represents the expected average *TSV*, considering that a large group of people with the same activity level and clothing insulation in a given environment express their thermal sensation vote (*TSV*). The *PMV* index

predicts  $TS$  as a function of the personal parameters and environmental parameters that affect the human heat balance.

Fanger [3] estimated the  $PMV$  index to express disequilibrium between the actual heat flow from a human body in a given environment and the heat flow required to get optimum comfort for a given activity, by the following expression:

$$PMV = [0.303 \cdot e^{-0.036 \cdot M} + 0.028] \cdot L \quad (12)$$

where  $L$  is the thermal load of the human body defined by Fanger [3] as “the difference between internal heat production and the heat loss to the actual environment for a man kept at the comfort values of the mean skin temperature and the sweat secretion at the actual activity level”.

In the thermal comfort condition,  $L = 0$ . In other environments, the effector mechanisms (vasodilatation, vasoconstriction, sweat secretion and shivering) of the body modify the sweat secretion and the mean skin temperature to keep the body heat balance. The thermal load of the human body represents an expression for the physiological strain on the effector mechanism of the body. In addition,  $TS$  at a certain activity level is connected to this strain [3].

The expression of the  $PMV$  index is presented in the Standard ISO 7730:2005 [44]:

$$PMV = [0.303 \cdot e^{(-0.036 \cdot M)} + 0.028] \cdot \{ (M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_a] \cdot 0.42 [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - \bar{t}_r) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \} \quad (13)$$

By assuming  $PMV = 0$ , different combinations of environmental parameters, activity level and clothing are predicted assuring a thermally neutral sensation [44]. The terms that appear in the  $PMV$  expression are:

- The convective heat transfer coefficient is solved by iterations and is given by:

$$h_c = \left\{ \begin{array}{ll} 2.38 \cdot |t_{cl} - t_a| & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \end{array} \right\} \quad (14)$$

- The ratio of clothed surface area  $f_{cl}$  is expressed by:

$$f_{cl} = \left\{ \begin{array}{ll} 1.00 + 1.290 \cdot I_{cl} & \text{for } I_{cl} \leq 0.078 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1} \\ 1.05 + 0.645 \cdot I_{cl} & \text{for } I_{cl} > 0.078 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1} \end{array} \right\} \quad (15)$$

The clothing surface temperature  $T_{cl}$  is a variable obtained by solving in an iterative way the implicit equation:

$$t_{cl} - 35.7 + 0.28 \cdot (M - W) + I_{cl} \cdot \{ 3.96 \cdot 10^8 \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \} = 0 \quad (16)$$

$$t_{cl} = t_{sk} - I_{cl} \cdot \{ 3.96 \cdot 10^8 \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \} \quad (17)$$

The clothing surface temperature  $t_{cl}$  is a variable very important for obtaining the  $PMV$  index. d'Ambrosio Alfano et al. [56] showed that some software applications available to calculate the  $PMV$  index are not consistent with the values reported in the Standard ISO 7730:2005 [44] (Annex E), mainly

because of missing input data and values of the clothing insulation not corrected by considering the effects of body movement and air action.

### 2.5. Psychological Factors, Adaptive PMV Index and Extended PMV Index

In addition to the physical and physiological factors, psychological factors play a key role. The identification and modelling of psychological factors are quite complex, as they depend on subjective conditions. In particular, the initial thermal state of the body, the position of the body, the rate of change of the temperature, and the duration of the thermal stimuli may have an impact on *TS* [2]. Candas and Dufour [57] reported an overview about the multisensory influence on the *TS* and comfort. To reduce the thermal disturbances an occupant must reconstruct an adequate climate around him in order to prevent the thermal discomfort. The individual judgement also depends on the presence of asymmetries resulting in different sensations in some body parts [24].

To assess the psychological response, subjective measures can be associated with a black-box approach, in which the stimulus is introduced as input, and the reaction (e.g., a *TS* or *TD* value taken from Table 1) is observed at the output. In the black-box approach, there is no need to know the internal model that describes the input-output relations, and even complex phenomena can be addressed. A limitation is a non-simple interaction with some categories of persons (e.g., very young children, sick people, or disabled) to gather the relevant information. Furthermore, in some cultures the individuals are less inclined to declare their sensations. Also, persons living in hot conditions may tend to prefer colder climates (and vice versa). Finally, the translation in different languages of the terminology used in the *TS* scale has to be accurate, to ensure that the terms used have the correct meaning in the specific language [2].

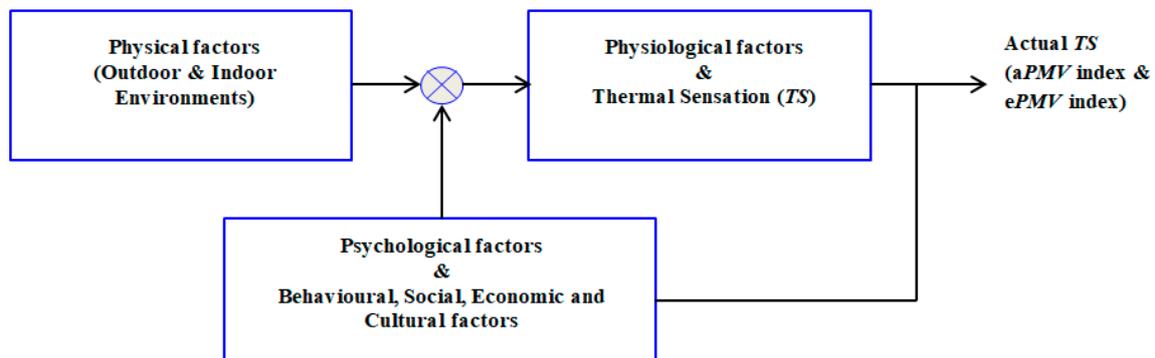
Subjective responses could also be formulated to understand whether the environment is acceptable or tolerable, or whether the individual expresses a preference for a change in the current status, e.g., to be in a warmer environment. An example is the set of subjective scales included in the Standard ISO 10551:1995 [16], which consider different types of judgements (perceptual, affective, thermal preference, personal acceptance, and personal tolerance).

Furthermore, *TS* can be assessed with a behavioural and observational approach, by observing the activity of the subjects in the environment (e.g., to put on or take off clothes, changes the thermostat set-points, change the mood or the way to speak, etc.).

The classical *PMV* is not appropriate for warm climates in buildings without HVAC systems, because studies have shown that it predicts a warmer *TS* than the persons feel [58]. The classical *PMV* is proper for buildings with HVAC systems in cold, temperate and warm climates, and is assessed over both winter and summer. For this reason, de Dear and Brager [11] proposed the adaptive *PMV* (*aPMV*) model, considered more adequate to establish thermal comfort in warm climates in buildings without HVAC systems. The adaptive model takes into account the thermal environmental conditions occurring in different periods of the year. If the occupants may have an influence on their thermal environment in these periods of time, the indoor thermal climate becomes more variable and the comfort can be improved [59].

The *aPMV* includes psychological aspects and heat balance together, while the classical *PMV* index does not take into account any psychological aspect. The optimal operating temperature is defined as the operative temperature that satisfies most individuals at a given clothing and activity level [60]. The classic *PMV* predicts optimum operative temperature by using four inputs (clothing insulation, metabolic rate, relative humidity, and relative air velocity). Instead, the *aPMV* model predicts it by using only one input (the mean monthly outdoor effective temperature) [11]. The mean monthly outdoor effective temperature at the highest value has an indirect influence on the heat balance of the human body [61]. The drawback of *aPMV* is that the thermal parameters, human clothing, and activity level, with significant impact on the heat balance of the human body and on the *TS*, are not taken into account.

Fanger and Toftum [61] introduced the *ePMV* model, suitable for buildings without HVAC systems, in warm and humid climates of regions with long summer, where the indoor air temperature considerably increases. This model considers the expectancy factor  $e_p$ , which is a correction factor to be multiplied by *PMV*, aimed to determine the corrected value of *PMV* expressing the mean *TSV* of the occupants. The  $e_p$  ranges between 0.5 and 1 and  $e_p$  is 1 for building with HVAC systems. This correction factor depends on the period of warm weather during a year, and if the buildings without HVAC systems can be compared with many buildings from the region where the HVAC systems are located [61]. In this way, it is possible to take into account that in the environments without HVAC the occupants have a reduced expectation of comfort [39]. The determination of *aPMV* and *ePMV* follows the general scheme indicated in Figure 2, in which psychological aspects are seen as a feedback coming from the individual with respect to the classical *TS* determination.



**Figure 2.** The feedback-based determination of the *aPMV* index and *ePMV* index.

## 2.6. Local Discomfort Assessment Models

Non-uniform environments are addressed with indicators of thermal discomfort (referring to radiant asymmetry, vertical air temperature gradients, warm or cold floors, or draught). For example, the Standard ISO 7730:2005 [44] defines a general expression of the percentage dissatisfied (*PD*) indicator in function of the radiant temperature asymmetry  $\Delta t_{pr}$  (“the difference between the plane radiant temperature of the two opposite sides of a small plane element” [31]), where the numerical values of the coefficients  $a_{pr}$ ,  $b_{pr}$ , and  $c_{pr}$  depend on the cause of radiant temperature asymmetry (warm ceiling, cool wall, cool ceiling, or a warm wall):

$$PD = \frac{100}{1 + \exp(a_{pr} + b_{pr}\Delta t_{pr})} + c_{pr} \quad (18)$$

Likewise, vertical air temperature gradients are addressed in the Standard ISO 7730:2005 [44] by considering the vertical air temperature difference  $\Delta t_{a,v}$  between head and feet, in [°C], to calculate *PD* with the following expression, valid for  $\Delta t_{a,v} < 8$  °C and containing the numerical parameters  $a_{a,v}$  and  $b_{a,v}$ :

$$PD = \frac{100}{1 + \exp(a_{a,v} + b_{a,v}\Delta t_{a,v})} \quad (19)$$

With local thermal discomfort caused by warm or cold floors, *PD* depends on the floor temperature  $t_f$  in [°C] and on the numerical parameters  $k_f$ ,  $a_f$ ,  $b_f$ , and  $c_f$  (for long occupancy the results are not valid for electrically heated floors):

$$PD = 100 - k_f \exp(a_f + b_f t_f + c_f t_f^2) \quad (20)$$

Concerning draught, the percentage of people predicted to be dissatisfied by the presence of draught is expressed in the Standard ISO 7730:2005 [44] as the draught rate (*DR*). The related model

for predicting draught at the neck, valid for local mean relative air velocity  $\bar{v}_{a,l} < 0.5$  m/s, local air temperature  $t_{a,l}$  from 20 °C to 26 °C, local turbulence intensity  $Tu$  from 10% to 60%, and numerical parameters  $a_{d,t}$ ,  $b_{d,v}$ ,  $c_{d,v}$ ,  $d_{d,v}$ , and  $e_{d,v}$ , is:

$$DR = (a_{d,t} - t_{a,l})(\bar{v}_{a,l} - b_{d,v})^{e_{d,v}}(c_{d,v}\bar{v}_{a,l}Tu + d_{d,v}) \quad (21)$$

This model applies for light and mainly sedentary activity, when  $TS$  for the whole body is close to neutral.

### 3. Transient Conditions

#### 3.1. Non-Uniform Energy Balance Models

Non-uniform models are based on partitioning the human body into connected components. Two types of partitioning can be identified (Figure 3):

- Body segments: the body can be represented as a single component or as a set of interconnected components called segments (e.g., head, trunk, fore arms, upper arms, fingers, hand, legs, etc.).
- Thermal nodes: each body segment can be represented by using multiple concentric layers or thermal nodes (e.g., two layers with the core part of the body and skin; three layers with core, muscles and skin; four layers with core, muscle, fat and skin). Each layer is interfaced with the adjacent one(s). Each individual thermal node (skin tissue, fat tissue, muscle tissue, bone) has different physical properties (e.g. thermal capacity, thermal conductivity, etc.) [62]. Most of the physical properties are obtained from measurements and physiological studies [63].

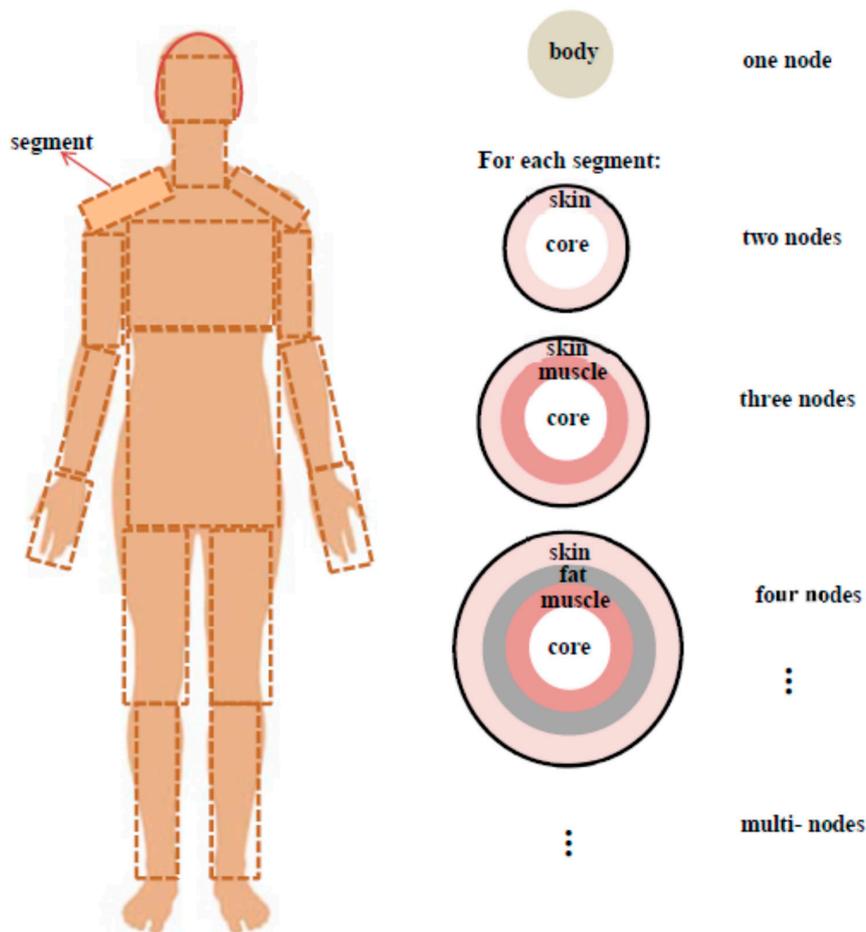


Figure 3. Body segments and examples of thermal nodes.

Thermoregulation models can simulate the local skin and body core temperatures to predict *TS* [64–67]. The input parameters used in these models are air temperature, radiation temperature, relative air velocity, relative humidity, clothing insulation, metabolic rate and their variations with the exposure time [68,69]. In general, the thermal behaviour of the human body is simulated by considering a passive (or controlled) system and an active (or controlling) system [70–74]:

- The passive (or controlled) system is affected by the heat transfer phenomena that occur inside the human body, or between the human body and the external ambient. Heat transfer in the core occurs by conduction with the skin and two convection phenomena (one with the skin due to the blood-vessels convection (blood acts as a carrier) and another with the external environment due to the breathing). In the core, the heat is generated by the metabolism and muscle work [67]. At the surface of the body-environment interface the heat exchange occurs by evaporation, convection and radiation [72]. To simulate the heat transfer phenomena, key parameters are the thermal properties of the blood, muscle, fat and bones. In addition, external sources given by electromagnetic (EM) fields are considered (Section 3.3).
- The active (or controlling) system controls the passive system to regulate the temperature of the human body in steady-state and transient environments [75]. The active system considers the human body's regulatory responses of vasodilatation, vasoconstriction, sweating and shivering. The objective is to provide thermoregulation by maintaining constant body core temperature. For this purpose, feedback signals are used to change the parameters of the passive system. The main feedback signal comes from the skin temperature. Further feedback signals come from the hypothalamic temperature variation, the skin temperature variation, and the basal evaporative heat loss from the skin [76]. Under stress conditions, the core temperature is particularly relevant in the case of hyperthermia, while the core and skin temperatures are relevant in case of hypothermia [77].

In the thermoregulation model, the control depends on the error signal given by the difference between the actual temperatures (at predefined locations, e.g., representing core and skin) and the corresponding setpoints corresponding to a thermo-neutral system. Positive error signals represent warm conditions, while negative error signals represent cold conditions at the corresponding locations. The error signals are sent to the active system, where they are processed to define the commands to be sent to the human body. For this purpose, the active system needs to set up the control coefficients to be used in the command-error equations (that combine the error signals in either a linear or a non-linear way). These control coefficients are found and validated through experiments. However, the nature of the phenomena involved in the thermoregulation is so complex that it is rather difficult to obtain the coefficients of the command-error equation, and it is not possible to account for all experimental results with a single set of control coefficients [70].

The classification of the thermal models indicated in [78] considers one-node, two-node, multi-node, up to 3-D models with thousands of nodes [24,79]. The empirical one-node model is applicable to hot environments [80] in which the thermoregulatory system is not considered [81]. 3-D models are based on partitioning the human body into segments, applying a two-node model or multi-node model to each segment.

The first transient model [82] approximated the human body by a single cylinder and divided it into four concentric layers. The Gagge model [36] considers the human body as one segment (or cylinder). The basic Stolwijk model [70] divides the human body between six segments and 25 nodes. In addition, other Stolwijk-like thermoregulation models are Tanabe's model (65MN) model [73] and the THERmoregulation MOdel for Disuniform Environments (THERMODE 193) [72]. In the 65MN model, the human body is divided into 16 segments and 65 nodes, while in the THERMODE 193 model, the human body is divided into 48 segments and 193 nodes. Table 3 summarises the number of segments and nodes included in the most used thermophysiological models, and indicates advantages and limitations of these models.

**Table 3.** Number of segments, thermal nodes, advantages and limitations of different transient thermoregulation models.

Model	Number of Segments/Elements	Number of Nodes/Layers	Advantages	Limitations	Applicability Conditions to Predict Human Thermal Responses
One-node [81]	1	1	Introduces the equations of the metabolic costs of running, walking, and carrying loads [26]	Empirical model Limited applicability range Thermoregulatory system not considered	Hot environments Considers clothing
One-node [82]	1	1/4	Two controlling centres (for heat loss and energy stored in the body) [67]	Limited applicability range Differences among body parts not considered Effect of blood flow in the heat transfer within the tissue not considered [67] Big variation of the constants in the control equations [67]	Steady-state, uniform Considers clothing
Gagge/Pierce [8,36,83]	1	2	Good mean skin temperature estimation [84] Simple model and fast calculation time [84] Easy implementation [85] Introduces the <i>SET*</i> index [86]	Limited applicability range No local body zone output [24] Limited human exposure times (<1 h) [24] Does not explain spatial non-uniformities [24] No difference between the sensation of bare skin and clothed skin [49]	Transient, uniform Moderate activity Considers clothing
KSU [87,88]	15	2	Determines <i>TS</i> directly from physiological strain [24]	Limited applicability range Not applicable in cold or hot conditions [85] Heavy computational burden Skin and fat layers modelled as one layer Heat transfer of the blood flow in large arteries neglected [85]	Transient, non-uniform, non-symmetric Sedentary activity Considers clothing
Jones, Ogawa [89]	1	2	Wide applicability range The clothing model reflects non-uniformity User-friendly interface Fast determination of the skin moisture accumulation calculations	Constraints to human exposure times	Transient, non-uniform Various environments, activities and clothing types

Table 3. Cont.

Model	Number of Segments/Elements	Number of Nodes/Layers	Advantages	Limitations	Applicability Conditions to Predict Human Thermal Responses
MSP [84]	24	2	Accurate predictions of local skin temperatures of separate body parts with normal clothing	Limited applicability range Less accurate predictions at the limb in very cold environment	Steady-state, uniform Sedentary activities Considers clothing
Crosbie [90]	1	3	Accurate human temperature regulation predictions Accurate predictions of dynamic responses to unexpected changes	Limited applicability range	Steady-state and transient, uniform Clothing is not considered
Stolwijk [70]	6	4 per segment	Accurate local skin temperature predictions [91] Gives the instantaneous temperature for all body segments [67]	Limited applicability range Less accurate predictions of body core temperature in the cold environment [92] No model of the flow in veins and individual arteries [85] Model based on limited data [93]	Transient, uniform Constant environment Clothing is not considered
Fiala thermoregulation [71,92]	15	187	Wide applicability range Accurate predictions of skin temperatures for cold, moderate and hot stress conditions Accurate predictions of body core temperature in the cold environment [92]	Less accurate predictions of skin temperatures during exercise in cold environments The model is implemented by a commercial software blind to users	Steady-state and transient, non-uniform Indoor and outdoor Different activity intensity [67] Considers clothing
Fiala UTCI [94]	12	187	Wide applicability range Accurate predictions of body thermal effects (hyperthermia and hypothermia) and local effects [92]	Time-consuming when real-time execution of the physiological model is needed [95]	Transient, non-uniform Outdoor applications including weather extremes [95,96] All scales from micro to macro, all climates and seasons [95] Whole-body and local skin cooling [77] Considers clothing
ThermoSEM [65,97]	19	Multi- node	Accurate predictions of metabolic responses to cold and mean skin temperature [98] More physiological background than in the regression model implemented in [92]	Limited applicability range The energy metabolism requires improvement in reply to mild cold [98]	Transient, close to neutral thermal environments [65] Mild cold environment [98,99] Different subpopulations (male, female) and individual characteristics (height, weight, and fat percentage) Considers clothing

Table 3. Cont.

Model	Number of Segments/Elements	Number of Nodes/Layers	Advantages	Limitations	Applicability Conditions to Predict Human Thermal Responses
UCB [100,101]	16	5	Flexibility of changing input data [20] Improvements over Stolwijk model [20] Fine segmentation for environments with local temperature variations Accurate predictions of <i>OTS</i> and <i>LTS</i> [17,20]	Extremely sensitive to the skin temperature set-point	Transient, non-uniform Considers clothing
65MN [73]	16	65	Wide applicability range	Extremely sensitive to the skin temperature set-point on each segment	Steady-state and transient, non-uniform Considers clothing
JOS-2 [74]	17	Multi- node	Considers arterial and venous circulation (improves 65MN) [67] Accurate core and skin temperature predictions	Applicable to women and elderly	Transient, non-uniform Considers clothing
AUB [85]	15	4	Accurate and realistic representation of the arterial system including blood flow pulsation Accurate predictions of heat gains/losses Improved circulatory system model Solves the asymmetry and uses anatomic positions and real dimensions of arteries	Low time step size achieved for transient simulations	Transient, non-uniform Nude and clothed subjects
THERMODE 193 [72,102]	48	193	Good prediction of mean skin temperatures and their trends in comfort and moderated discomfort cases [72,102] Possibility of using different values of clothing insulation for each body segment	Limited prediction of temperature trend in cold conditions; limited predictions for hands and feet [72] (improvements made in [102])	Steady-state and transient, non-uniform Considers clothing
HTM [103,104]	16 plus head	3200/4	Accurate predictions of the effects on the occupants under different conditions More accurate predictions than in the Fanger model [3]	Limited applicability range	Steady-state and transient, non-uniform Indoor Considers clothing

Table 3. Cont.

Model	Number of Segments/Elements	Number of Nodes/Layers	Advantages	Limitations	Applicability Conditions to Predict Human Thermal Responses
12-segment [93]	12	1 node per layer / 4 or 5 layers per segment	Accurate skin and rectal temperature predictions	Limited applicability range	Transient, non-uniform Indoor Considers clothing
Burned Patients [105]	11	4 per segment	Accurate environmental temperature predictions	Limited applicability range	Transient, non-uniform Ambient temperatures from 20 °C to 40 °C for burned patients Considers clothing
Patients during cardiac surgery [106]	19	Various tissue layers	Accurate core temperature distribution predictions Accurate predictions of heat losses in surgical interventions not experimentally evaluated in humans	Limited applicability range Uncertain initial boundary conditions lead to model sensitivity Less accurate predictions for the mean skin temperature	Transient, non-uniform Cardiac surgery patients Considers clothing
Three-Node [49]	16	2	Easy implementation due to simplifications Accurate predictions of <i>TS</i> of bare skin and clothed skin Introduces <i>TS</i> indices for bare skin, clothed skin and <i>OTS</i> of body	Clothing system simulated as an overall insulation covering the whole body	Transient, non-uniform Considers clothing
Sleeping person [107]	1	4	Acceptable accuracy to predict thermoregulatory responses Good prediction of indoor parameters (e.g., air temperature and humidity) in a sleeping environment	Limited applicability range	Transient, uniform Sleeping environments Young adults only Clothing is not considered
Human/clothing/environment [108]	6	101 nodes per half-cylinder/4 layers per segment	Wide range of environmental conditions (heat, cold, and exercise) User-friendly interface Accurate predictions of human thermal response and clothing effects on humans	Time increment restricted by numerical stability	Steady-state and transient, non-uniform Considers clothing
Clothed Infants [109]	4	7	Accurate predictions of infants' interaction with the thermoregulation system	Limited applicability range Environment temperature set to 35 °C Relative humidity set to 65%	Transient, non-uniform Clothed infants

Table 3. Cont.

Model	Number of Segments/Elements	Number of Nodes/Layers	Advantages	Limitations	Applicability Conditions to Predict Human Thermal Responses
Naked Infants [110]	4	9	Accurate core and skin temperature distribution predictions	Limited applicability range	Transient, non-uniform Naked infants
Premature Infants [111]	7	multi- node/ all segments contain multiple homogeneous layers	Accurate predictions of core and skin temperature distribution at thermal neutrality Accurate global and local physiological response predictions Accurate thermoregulatory dynamic response predictions	Limited applicability range	Transient, non-uniform, thermal neutrality Premature infants Clothing is not considered
Chinese adults [112]	14	Most segments have 4 layers with 3 sectors	Accurate predictions of mean and local skin temperature compared with the Fiala model Reduced standard deviation of predicted local skin temperatures compared to the standard Chinese model	Limited applicability range Skin surface area and body fat distribution different for Chinese adults and western people	Transient, asymmetrical Chinese young adults Considers clothing
Chinese elderly [113]	14	Most segments have 4 layers with 3 sectors	Accurate predictions of skin temperature due to the introduction of parameters like height, weight, sex and age [112]	Limited applicability range Modifications of passive and active systems Skin temperature differences between foot and thorax	Transient, asymmetrical Chinese elderly Considers clothing
Older Persons [114]	15	187	Accurate core temperature predictions	Limitations for the mean skin temperature	Steady-state and transient, non-uniform Older individuals Considers clothing
Wissler [115,116]	6 elements (15 in the improved version)	About 5300 nodes	Accurate predictions of the human body's response to the temperature changes [26]	Many equations needed to represent the temperature variation in space and the thermal flux in the boundaries	Steady-state and transient, non-uniform Cold and hot environments Hyperbaric and one-atmosphere environments Clothing is not considered
Ferreira and Yanagihara [117]	15	Multi-node/ 8 tissues	Satisfactory representation of the behaviour of the passive human thermal system	Require more segments to improve circulatory and thermoregulatory systems	Transient, uniform Clothing is not considered

### 3.1.1. Two-Node Thermal Model

The Gagge two-node thermal model [8,36,37] is based on partitioning the body into an external region formed by the skin and an internal core. In each region, the temperature is assumed to be uniform. The only temperature gradients occur between cylinders [17]. This is applicable to predict *TS* only for sedentary people in moderate levels of activity for stable environments, with human exposure times lower than one hour [103] under transient personal/environmental conditions [118]. This model takes into account the dynamic physiological reactions of the human thermoregulatory system, provoked by changes in the ambient climate.

The Gagge two-node model with single segment is used in [119] to determine the coefficients of the skin blood flow rate that minimise the difference between the experimental and computed skin and core temperatures. The single-segment model presented in [120] analyses what combinations of body core, skin and ambient temperatures satisfy thermal balance requirements in the thermoneutral zone for steady-state conditions. The thermoneutral zone model combines internal heat balance within the body with external heat balance from the body to the outer surrounding. The internal heat balance depends on the metabolic rate, skin temperature, body tissue insulation, and body core. The external heat balance depends on metabolic rate, air action, relative humidity, skin wettedness, skin temperature, operative temperature and clothing insulation.

Gagge et al. [121] consider clothing insulation  $I_{cl}$ , but neglect the effects of the body activity and air movement on the variation in the surface air insulation  $I_a$  (“thermal insulation of the boundary air layer around the outer clothing or, when nude, around the skin surface” [122]). Other contributions have taken into account the combined effects of body posture, body motion (pumping effect), wind, and clothing fit [123]. In particular, body movement and body posture affect  $I_{cl}$ , while wind especially influences  $I_a$ . Furthermore, the model of the vapour resistance of clothing has been improved with respect to the one used in Gagge et al. [121] and have been used to calculate and predict the heat strain of a person who works in warm and hot environments [124]. The Standard ISO 9920:2009 [122] considers the decrease of the vapour resistance due to the wind and body movement. Some dedicated papers estimate the effect of body motion and wind on the clothing insulation to assess the reduction of thermal insulation and vapour resistance of clothing [125–129].

The Gagge two-node model with multi-segment is used in some models of thermal interactions between human body and environment considering the effect of clothing. The relative air velocity is also examined under transient conditions [130–132]. This model has been used to predict *TS* in a vehicle [133], to examine sitting and standing postures [130], and to assess skin temperature differences in local body parts caused by the effects of high radiant temperature [134].

The two-node model converts the real environment into a “standard environment” at a Standard Effective Temperature (*SET*) [135]. It also converts the real environment into a “hypothetical environment” at a New Standard Effective Temperature (*SET\**), which is a progress over *SET* [15]. The calculation of *SET* is similar to the computation of *PMV*, with the difference that *SET* considers the two-node thermal model to obtain the mean skin temperature  $\bar{t}_{sk}$  and the skin wettedness  $w_{sk}$ . In particular:

- *SET* predicts *TS* in conditions with high airflows [136]. According to the ASHRAE Standard 55-2017 [1], *SET* is defined as the air temperature of a standard environment at 50% relative humidity (*RH*) for individuals wearing clothing that would be standard for the given activity in the real environment. *SET* considers standard climate having uniform temperature ( $\bar{t}_r = t_a$ ), relative air velocity  $v_{ar} = 0.1 \text{ m}\cdot\text{s}^{-1}$ , metabolic heat rate  $M = 1 \text{ met}$ , and clothing insulation  $I_{cl} = 0.6 \text{ clo}$ .
- *SET\** is a temperature index for uniform thermal environments [137]. *SET\** is the air temperature of a hypothetical climate at uniform temperature ( $\bar{t}_r = t_a$ ) and relative humidity  $RH = 50\%$ , where the individuals have the same physiological strain (i.e., the same  $\bar{t}_{sk}$ ,  $w_{sk}$  and heat losses to the environment) as in the real environment [138]. The standard environment has  $\bar{t}_r = t_a$ ,

relative air velocity  $v_{ar} = 0.15 \text{ m}\cdot\text{s}^{-1}$ , metabolic heat rate  $M = 1.2 \text{ met}$ , and clothing insulation  $I_{cl} = 0.9 \text{ clo}$ .

The advantage of  $SET^*$  is the possibility of carrying out thermal comparisons between environments with any combination of the physical input variables. The disadvantage is that “standard” people are required. The temperature range of  $TS$  on the  $SET^*$  scale indicated in [41] includes  $SET^*$  values  $<17$  (cool, moderate hazard),  $17 \div 30$  (comfortable, no danger)  $30 \div 34$  (warm, caution),  $34 \div 37$  (hot, extreme caution), and  $>37$  (very hot, danger).

The Jones model (or Two-dimensional model of clothing) [89] is based on the transient clothing model [139]. The core is represented by a single node. The skin is divided into arbitrary segments taking into account the angular tissue temperature variations, and is represented by several nodes. The Multi-Segmental Pierce (or  $MSP$ ) model [84] divides the body into 24 segments and two nodes to predict more accurately the local skin temperatures of individual body parts in the neutral condition.

### 3.1.2. Multi-Node and Multi-Segment Thermal Models

Multi-node thermal models consider the inhomogeneous distribution of temperature and thermoregulatory responses over the whole human body surface. They further simulate the local skin temperature of independent body parts based on vasomotion models [26].

The first multi-node thermal model in transient conditions [90] takes into account the physiological mechanism of thermal regulation [103]. The body is divided into three layers. Each layer has its energy balance equation. The core layer has one node, the other layers have several nodes.

Further multi-node models are defined with multiple segments. The Stolwijk model (or 25-node model [63,70,140]) is the first multi-node and multi-segment model of the human body under transient conditions. This model uses six cylindrical segments to describe the human body. Each segment is divided into four concentric lumped layers, where each layer represents a node. The temperature of each layer is assumed to be uniform. There are 24 tissue nodes and one central blood node. The 25th node is thermally connected to all other nodes. This model does not consider sweat accumulation on the skin surface [24,80].

Stolwijk and Hardy [141] improved the model considering the human body as a passive system or a controlling system, still neglecting the sweat accumulation on the skin surface. An improved version of the Stolwijk model is the THERMODE 193 model developed by Candas et al. [72] in cooperation with the LPPE (Laboratoire de Physiologie et de Psychologie Environnementales) of the French CNRS. THERMODE 193 was one of the first models that considered a clothed individual. The initial version of the model showed good performance in predicting with satisfactory accuracy the core temperature and local skin temperature both in standing and in sitting positions, under neutral and slightly warm conditions, with exceptions for hands and feet. The model was later enhanced by d’Ambrosio Alfano et al. [102], with a significant improvement in the active and in the passive system. The clothing model includes the correction referring to the effect of the body movement. This model, based upon an iterative procedure, is able to predict the thermal resistance of clothing for each segment from the value of the basic clothing insulation for the body as a whole ( $I_{cl}$ ).

The Stolwijk model was modified by other authors [80,142] to introduce the sweat accumulation on the skin surface, for a clothed body. The hygroscopicity of clothing materials significantly affects the human thermoregulation process. Munir et al. [91] demonstrate that the Stolwijk model is valid to predict the transient average skin temperature  $\bar{t}_{sk}$  for the “average” person under sedentary conditions. Li et al. [143] present a new simplified thermoregulation model based on the Stolwijk model and on the human temperature regulatory system model from [144]. The model accurately predicts the transient  $\bar{t}_{sk}$  in warm environments.

### Other Multi-Node and Multi-Segment Models

The Fiala model, or Dynamic Thermal Sensation ( $DTS$ ) model [145], addresses the transient response of the human thermoregulatory system to external stimuli over a period using environmental

parameters (temperature, humidity, and velocity of air at the skin surface). The model includes *DTS* in function of the simulated core temperature and  $\bar{t}_{sk}$ , and also predicts *PPD*. The Fiala model is blind to users and is implemented by commercial software. The regression analysis developed by Fiala et al. [146] for sedentary individuals demonstrate that the temperature error signal from the skin is the best predictor for *TS*. Furthermore, *TS* is better correlated with  $t_{sk}$  than with other physiological variables (sweat rate, internal temperature, skin blood flow). In the case of exercising subjects, the physiological conditions inside the human body vary without being influenced by the conditions found in the skin. Polynomial regression studies demonstrate that the temperature error signals from the head are the driving impulses with a significant influence on *TS* [146].

The extension of the Fiala model with passive and active parts [92,147] predicts *TS* from moderate to stressful cases, from low activity to high activity levels. Standard human manikins are used in [148], where a Computational Fluid Dynamics (CFD) code is coupled with the Fanger model to compute the impact of the human body on the environment, and in [149] to integrate the Fiala model with a realistic 3D figure. Van Treeck et al. [150,151] couple the model [146] with CFD to simulate the environmental impact on the human body. Fiala et al. [94] present the algorithms and methods of the multi-node dynamic Universal Thermal Climate Index (UTCI)-Fiala model of human thermal physiology. UTCI is the equivalent ambient temperature of a reference environment with the same physiological response of a reference individual like the real environment [41]. UTCI is divided into ten groups beginning from extreme cold stress (about  $-40\text{ }^{\circ}\text{C}$ ) till extreme heat stress ( $>46\text{ }^{\circ}\text{C}$ ) [152]. The ThermoSEM model, based on the *DTS* model [145], simulates body temperatures and physiological responses [97,153]. The difference between ThermoSEM and the Fiala model consists of the active part (thermoregulation) [26].

The Berkeley Comfort (UCB) model is used to simulate unlimited body segments allowing the estimation of *OTS* by predicting *LTS* in different body segments [100,154]. To obtain *LTS*, the equivalent temperature  $t_{eq}$  for different parts of the body introduced in [155] is used. To evaluate *TC* in buildings, acceptable  $t_{eq}$  ranges are identified in [156] and [157] for different zones of the body. The Fiala *DTS*, UCB and MSP models are compared in [158] with experimental data. The results show appropriate performance of the MSP model compared with the Fiala model. The MSP model is selected for coupling with the UCB model, because this combined model produces higher predictability of the skin temperature than in the Fiala and UCB models.

The Tanabe model (or 65MN model) [73] is a 3D model of a standard human manikin in the CFD tool that incorporates radiation heat transfer. The CFD technique is used to simulate the impact of the human body on the environment using empirical heat transfer coefficients. The Tanabe model predicts *TC* and *OTS* in non-uniform and transient environments. On these bases, Zhu et al. [159] propose a non-uniform thermal model to predict *TS* coupled with CFD technique and human thermal physiological model, which simulates the effects of the surrounding temperatures on the human body. Moreover, the multi-node thermal model proposed in [149] is based on a coupling system that can simulate human thermal responses in transient environmental conditions.

The Multi-node 15-segmented model, or American University of Beirut (AUB) model [85], is used to predict nude and clothed human body thermal and regulatory responses in steady-state and transient conditions. An improvement of the AUB model, described in [160], agrees well with experimental data during transitions from hot to cold, dry to humid environments, and in asymmetric radiative environments. The 12-Segment model [93] takes into account 2D heat transfer in each part of the human body for unclothed and clothed persons in transient and non-uniform environment. The results of the Three-Node Thermoregulation model [49] accurately estimate the *TS* of bare and clothed parts of the body compared with the experimental results reported in [85,161,162]. The Human Thermal Model (HTM) [104] is used to demonstrate that the operative temperature, metabolic rate and clothing insulation are the most effective boundary conditions for *TS* and *TC* [103].

Models for Patients, Children, Adults and the Elderly

The Multi-node model shown in [106], based on the Fiala model, predicts the patient temperature during cardiac surgery. The simulation results show good agreement with the experimental results of three surgical procedures. The Burned Patients Thermoregulation model [105] is used to predict the optimum environmental temperatures for the treatment of patients with burn wounds.

The thermoregulatory response is different from children to adults [163], and from adults to the elderly [164]. Table 4 indicates some differences in thermoregulation between young adults and aged persons, which strongly depend on physiological changes [165–168]. Specific models are dedicated to infants, adults and the elderly.

**Table 4.** Differences between young and aged adults.

Aspect	Characteristics	Young Adults	Aged Adults	Reference
Thermoregulation	Ability of the human body to regulate its own temperature	High	Low	[165]
Illnesses and disabilities	Increases with age	Low	High	[165]
Thermal environment	Extreme climate	<i>TS</i> depends on air temperature and skin temperature	<i>TS</i> depends on the air temperature	[166]
		Physical strain low	- Physical strain high - Physiological modifications: <ul style="list-style-type: none"> <li>• low muscle strength;</li> <li>• low blood pressure;</li> <li>• low work capacity;</li> <li>• low sweating capacity;</li> <li>• low capacity to transfer heat from the body core to the skin;</li> <li>• low hydration levels;</li> <li>• low vascular reactivity;</li> <li>• low cardiovascular stability (blood pressure).</li> </ul>	[167]
	Same climate (same clothing level)	- Low temperature preference due to high metabolism - High activity level	- High temperature preference due to low metabolism - Low activity level	[168]
	Neutral climate	<i>TS</i> of young is similar with <i>TS</i> of aged at specific temperature ranges (summer 24–28 °C, winter 22–25 °C)		[169]
	Cold environment	$\bar{t}_{sk\ aged} > \bar{t}_{sk\ young}$ (colder environment)		[170]
	Hot environment	$\bar{t}_{sk\ aged} < \bar{t}_{sk\ young}$ (warmer environment)		[171]

For infants, two models combine the Stolwijk model with the Gagge model. The Clothed Infants Thermoregulation model [109] assesses the thermal physiological response of clothed infants. The Naked Infants Thermoregulation model [110] assesses the naked infants’ thermal physiological response. Furthermore, the Newborn Premature Infants Thermoregulation model [111], inspired by [70,71,172,173], is used to predict skin and core temperatures of newborn premature infants in transient conditions and thermal neutrality.

For adults, the Four-Node Thermoregulation model [107] is based on modifications of the Gagge two-node model, to encompass the differences in the thermoregulatory responses of sleeping and awaking persons. The Chinese Thermoregulation model [112], based on the Fiala model, is used to

predict the thermal behaviour of Chinese adults. The model includes the passive and active systems, and the central nervous system provides all modifications in the muscle metabolism.

The elderly have reduced metabolism, vasoconstriction, sweating and thickness of the skin fat, the lower range of variation of skin blood flow, and different skin or core temperature thresholds at which the thermoregulatory action is activated. The thermoregulatory response in the elderly for relatively high or relatively low temperatures is more variable than for young people, because the thermoregulation ability of the elderly is lower [165]. A bio-heat model developed for the elderly should predict accurately the blood flow in the fingers. The model shown in [174] for young adults, which considers independent segments for hand and fingers, has been customised in [165] for the elderly, by incorporating the effects of the changes in physiological thermoregulation and vasomotion. The Older Persons Thermoregulation model [114], based on the modified Fiala model, includes the passive system (body structure) and the control system (the central nervous system). It predicts the core body temperature, as well as the regulatory responses of the older subjects in different environmental conditions. The thermal behaviour prediction for Chinese elderly [113], whose thermoregulation part is based on [112], uses specific inputs for height, weight, age and sex to provide results for indoor environments.

The Jointed Circulation System (JOS) model [74] is applied to women and the elderly, considering the physiological reactions to the thermal environment. The physical parameters can be modified. The results show that the thermoregulatory mechanisms (shivering or perspiration) answer to the change of thermal conditions.

### 3.1.3. Multi-Element and Multi-Segment Thermal Models

Multi-element thermal models consider the heterogeneous heat transfer boundary conditions. These models give more accurate computational results than multi-node models because the hypothesis of uniform node temperatures is not considered [103,175]. Multi-element thermal models are 3D transient thermoregulation models, in which the human body is divided into various parts without the need of an additional division in nodes [26,176] as it happens in the models with lumped parameters considered in Section 3.1.2. In this case, many geometric properties of the body are taken into account, and the temperature of each element is not uniform [26,80,103]. In this way, the multi-element models are able to provide better results than the models with lumped parameters, in particular when there are large temperature gradients in the human body [177]. The energy balance equations are determined for each body part using thermoregulatory control equations for blood flow rate, shivering, sweating constriction, and dilatation [103]. In the first multi-element steady-state model developed by Wissler [115], the human body is subdivided into six cylinders. The second Wissler model [178] is an extension of the model [82], and the body is divided into fifteen elements connected by the vascular system (arteries, veins, and capillaries).

The Kansas State University (KSU) model [87,88] is a 3000-node Finite Element Model (FEM) that improves the Wissler model. This model implements the first 3-D transient, a multi-element thermal model for the entire human body and establishes  $TS$  directly from the physiological effort. The KSU model is appropriate for sedentary conditions but not during cold or hot operating conditions [155,176]. The Fu clothing model [78] is based on [89] and [179] using 3000-node FEM, and includes a clothing layer. The model simulates the clothed human thermal response under different conditions (e.g. high-temperature, vibration, severe weather conditions). The clothing layer computes the exchange of the heat generated by the surroundings and the quantity of heat produced [103]. Some human-clothing-environment models are presented in Section 3.2.

Ferreira and Yanagihara [117] propose a 3D model of the human thermal system. The simulation results agree with the experimental data reported in [75] for the nude body model at hot exposure. Sun et al. [180] develop a more realistic human thermal model in uniform environment starting from the models [88] and [78]. The transient temperature distribution in the body segments agrees with experimental data in neutral and warm conditions [181].

Tang et al. [175] adopt a multi-scale model of behaviour and thermoregulatory system under various environmental and clothing conditions. The FEM method is applied to assess the temperature field of the 3D human body and accurately predict human thermal regulation. The model is useful for design and clothing selection to assess *TC*.

### 3.2. Considerations on the Human Clothing

#### 3.2.1. Thermophysical Properties of Clothing

The assessment of the thermophysical properties of clothing is a crucial issue in the formulation of one-node and multi-node models to predict skin and core temperatures. Clothing affects the heat exchanged with the environment and keeps the core temperature in a limited range when exposed to different environments [182].

Earlier contributions adopted an approach based on the reduction factor for latent heat exchanges due to wearing clothes  $F_{pcl}$ , defined as the “ratio of the actual evaporative heat loss to that of a nude body at the same conditions, including an adjustment for the increase in surface area due to clothing” [31]. Successively, this approach was replaced by the use of the evaporative resistance of a clothing ensemble  $R_{e,cl}$ , that is, the “resistance to vapour transport of a uniform layer of insulation covering the entire body that has the same effect on evaporative heat loss as the actual clothing under standardized (static, wind-still) conditions” [31], where the entire body includes the uncovered parts like head and hands.

The most significant parameters to predict the heat strain of an individual working in a warm or hot environment are  $R_{e,cl}$  and the insulative properties of clothing [124]. Furthermore, the total water vapour resistance  $R_{e,T}$  is defined as the “vapour resistance from the body surface to the environment (including all clothing, enclosed air layers and boundary air layers) under reference conditions, static” [122].  $R_{e,T}$  is linked to the total insulation  $I_T$  (“thermal insulation from the body surface to the environment (including all clothing, enclosed air layers and boundary air layer) under reference conditions, static” [122]) through the Woodcock permeability index  $i_m$  (introduced in [183]) and the Lewis number  $L = 1.5 \text{ K} \cdot \text{kPa}^{-1}$ , as follows:

$$R_{e,T} = \frac{I_T}{i_m L} = \frac{0.06}{i_m} \left( \frac{I_a}{f_{cl}} + I_{cl} \right) \quad (22)$$

where the right hand-side is further expressed in terms of the air insulation  $I_a$ , the clothing area factor  $f_{cl}$ , and the clothing insulation  $I_{cl}$  defined in the Standard ISO 9920:2009 [122].

Havenith et al. [123] explain how clothing insulation is affected by body posture, movement, wind, clothing ensemble, and their interactions. From the openings (e.g., cuffs and collars) in the clothing ensemble there is an air exchange with the environment. During work, the increased air exchange modifies the clothing insulation (the so-called “pumping effect”).

Furthermore, Havenith et al. [124] show that wind and movement increase the permeability index for clothing ensembles. Furthermore, with respect to a reference standing person without wind, they determine that sitting increases  $R_{e,T}$ , while walking and wind decrease  $R_{e,T}$ . Nilsson et al. [184] develop a general equation that considers the insulation reduction given by wind, air permeability and walk, in different weather conditions and activity with winter work clothing. From their results, obtained from measurements on manikins, the effect of air permeability can be neglected for wind speeds below 2 m/s. Their model has been adopted by the Standard ISO 11079:2007 [43,185].

Havenith et al. [186] discuss the effects of the clothing vapour resistance variations on the body heat loss rates, highlight the importance of correcting the clothing vapour resistance values depending on body and air movements, and present corrections equations that have been incorporated, together with other equations proposed in [187] and [188], in the *PHS* approach used in the Standard ISO 7933:2004 [42].

The models to assess the clothing vapour resistance are complex and refer to the whole body surface. The evaluation of the clothing vapour resistance for single parts of the body is even more challenging. Recently some investigations on the localised clothing vapour resistance have been presented, e.g., by using sweating manikins to assess the different effects of wind speed and body movement on the local body segments [189].

The combined effect of wind and walking on clothing insulation is addressed in Havenith and Nilsson [126]. From experimental investigations, updated equations are proposed to correct the previously adopted equations for the total insulation in such a way to ensure that for wind speeds equal to the reference wind speed the correction factor is equal to 1. Further experimental tests that consider wind and walking have been carried out with movable sweating manikins. For example, Qian and Fan [190] develop a regression model to predict the clothing thermal insulation and the vapour resistance with wind and walking on the basis of the values of the same quantities measured on an individual standing in “still air”. Havenith et al. [191] provide many clothing thermal insulation results for non-Western (and mainly indoor) clothing ensembles, with the aim of extending the database of insulation values of non-Western clothing in the relevant International Standards. With respect to the Standards, the investigation carried out by d’Ambrosio Alfano et al. [129] shows significant differences between the results of the algorithms proposed in two different Standards – ISO 9920:2009 [122] and ISO 7933:2004 [42] to correct the static values of the thermophysical properties of clothing. These differences raise a warning to avoid the use of the new equations introduced in the Standard ISO 9920:2009 [122] in the revision of the Standard ISO 7933:2004 [42]. At the same time, these differences highlight a need to harmonise all the Standards concerning the Ergonomics of the Thermal Environment.

In these studies, the clothing insulation refers to the surface of the whole body, and the coefficients included in the equations are defined empirically. Recent contributions have presented empirical equations to estimate the total clothing insulation in function of the relative air velocity and walking speed [128], as well as correction equations for each part of the body [192]. The definition of equations for clothing insulation valid for the single parts of the body is a challenging open field of research.

### 3.2.2. Human Clothing Models

The human-clothing-environment models combine the human thermoregulatory model with a clothing model to predict skin and core temperatures. The human thermoregulatory model determines the thermoregulation and heat transfer within the body, while the clothing model simulates heat and moisture transfer from the human skin to the environment [193]. Clothing establishes how much heat is exchanged with the environment and keeps the core temperature in a limited range when exposed to different environments [182].

Various clothing models simulate the heat and mass transfer in clothing layers, considering phenomena like diffusion, evaporation, condensation, and sorption [194–197]. In particular, Fan et al. [162] and Fan and Wen [198] introduce the dynamic clothing model of heat and moisture transfer considering sorption and condensation in the porous clothing layer. The results show that condensation is reduced in clothing assembly. Khatoon and Kim [195] test different ventilation schemes in a car. Ghali et al. [199] develop a mathematical model for the heat and mass transfer through the air spacing layer and the fibre clothing system. Fan et al. [196] describe an improved model of [198] using experimental data, taking into account the condensates in fibrous insulation. Zhu et al. [197] establish a fractal model for the coupled heat and mass transfer in porous media considering moisture sorption/desorption and evaporation/condensation.

The human-clothing models presented in [200] are useful for the analysis of dynamic thermal stress problems. Three dynamic predictive clothing insulation models are tested in [201] to obtain improved *TC* estimation by considering that the occupants adjust their clothing during time depending on the thermal conditions. The heat transfer modelling through the clothing [202] based on [203] considers a clothing ensemble with different layers of material and air, inside which condensation occurs as well. The effect of two-layer clothing ensemble in thermoneutral conditions and extreme

ambient conditions is analysed with or without an EM source. The magnitude of the blood temperature elevation is influenced much more by environmental conditions (e.g., temperature and  $RH$ ) and type of clothing than by the EM source.

Some dynamic human-clothing-environment models are presented in [108,178,204,205], with numerical results validated by experimental data. In particular, the human clothing model [108] is valid in both steady-state and dynamic conditions (heat, cold, exercise, clothing and transient phases). The model used in [204], based on the Tanabe model, takes into account the dynamic heat and moisture transfer through clothing, including liquid water transport and clothing ventilation. The transient model [205] of heat and mass transfer through clothing layers containing phase change material (PCM) packets is integrated with a segmental bio-heat model to predict the instantaneous response of the human body. In [193] the thermoregulatory model is coupled with a clothing model to simulate the effects of the air gap and fabric properties on human thermal responses.

### 3.3. Anatomical Models

Starting from an initial condition with acceptable temperatures in different parts of the body, if the body is subject to an external source such as the absorbed electromagnetic (EM) radiation, the body temperature increases. The Specific Absorption Rate (SAR) index used in the radio-frequency (RF) protection standards represents the power per unit mass absorbed by the human body from an EM source. The SAR index is used to assess the safety of the human body exposed to different frequencies [76].

The blood flowing in the body introduces conduction and convection effects. The tissue and blood temperatures can be directly obtained by measurements in a discrete number of points of the human body [206]. However, a mathematical model to calculate the tissue and blood temperatures provides more general information.

There is a vast literature on anatomical models, whose complete review is outside the scope of this paper. Some conceptual aspects are recalled here. Explicit and implicit methods have been formulated to solve the bio-heat transfer equation. Explicit models are based on the Finite Difference Method (FDM) or the Finite Element Method (FEM) representation of the body [207]. Implicit models are based on the inversion of a sparse matrix, with a computational burden that increases for larger dimensions of the domain. The use of an alternate-direction-implicit (ADI) technique reduces the computational burden by making the matrix inversion more efficient, as in the ADI-FDM [208] and the ADI technique introduced in [209].

Further models have been developed in non-equilibrium conditions. The generalised dual-phase lag bio-heat equations proposed in [210] are based on dividing the biological tissue into vascular and extravascular regions, to consider different temperatures for each region. Then, only one temperature (blood or tissue) is considered as an unknown, by eliminating the other temperature from the model. The generalised dual-phase-lag model of bio-heat transfer has been used in various applications, including magnetic hyperthermia treatment [211]. Furthermore, the local thermal non-equilibrium (LTNE) method is used in [212] to represent the bio-heat transport through the body tissues in RF hyperthermia treatment, studying the SAR of the body tissues when the EM field is imposed.

The thermoregulatory system has a strong influence on decreasing the elevation of the blood temperature almost uniformly in all body regions. The analysis of the thermoregulatory response is particularly important to study prolonged exposures to external sources (e.g., more than two minutes), or exposure to EM fields in extreme thermal environments [213]. Without thermoregulation, important blood temperature elevations are observed. For this reason, the thermoregulation model implemented in [76] has been included into the bio-heat equation to calculate the blood temperature elevation and the distribution of the power absorption inside a human body exposed to a uniform plane wave, in function of frequency. The thermoregulatory response provides an essential reduction of the temperature elevation, in particular in the body core. A limitation of including the thermoregulation model into the bio-heat equation is the high computational cost [206].

Furthermore, the temperature rise in a human body exposed to RF may depend on adverse environmental conditions (e.g., high ambient temperature, strong humidity, and the effects of clothing) [202]; the preliminary results obtained do not envisage changes needed to the existing safety standards and guidelines.

### 3.4. Models to Predict the Local and Overall Thermal Sensation

The local thermal sensation (*LTS*) considers the individual body segments, while the overall thermal sensation (*OTS*) summarises the local effects into a unique indicator. Corresponding acronyms are used for local thermal comfort (*LTC*) and overall thermal comfort (*OTC*).

The local environment establishes which body parts are relevant [214]. The *LTS* for one body segment could affect other segments [215]. The multi-segment physiological models presented above are used to predict the local temperatures necessary to determine *LTS* and *LTC*.

*LTS* depends on the local skin temperature  $t_{\text{skloc}}$  and the overall thermal state. In [181], *LTS* is written as a logistic function of the skin temperature:

$$LTS = f(t_{\text{skloc}}; t_{\text{skloc}_{\text{set}}}; \bar{t}_{\text{sk}}; \bar{t}_{\text{set}}; t_{\text{core}}; \mathbf{r}) \quad (23)$$

where  $t_{\text{skloc}_{\text{set}}}$  is the local skin set point temperature,  $\bar{t}_{\text{set}}$  is the mean whole-body skin set point temperature,  $t_{\text{core}}$  is the core temperature, and  $\mathbf{r}$  is the vector that contains the body-part regression coefficients.

Starting from the local thermal sensation  $LTS_j$  for the body segment  $j = 1, \dots, n$  and from the average local sensation  $\overline{LTS}_j$  (arithmetic mean of  $LTS_j$ ), the following weighting coefficient  $s_j$  is computed:

$$s_j = \vartheta \cdot (LTS_j - \overline{LTS}_j) \quad (24)$$

where  $\vartheta$  is the slope of the linear model considered.

The *OTS* expression, applicable in steady-state and transient conditions for cooling and heating, is estimated according to the UCB model considering the weighted average of all the local sensations [103,216]:

$$OTS = \left( \sum_{j=1}^n s_j \cdot LTS_j \right) \cdot \left( \sum_{j=1}^n s_j \right)^{-1} \quad (25)$$

This formulation can also be retrieved in the models reviewed in [30], in which *LTS* is denoted as *TSV*, and *OTS* is denoted as Mean Thermal Sensation Vote (*MTSV*).

The *OTS* expression has also been written by introducing a constant term  $s_0$ , using the multiple stepwise regression methods to show how the local body parts affect *OTS* in a HVAC environment in summer [217]:

$$OTS = \sum_{j=1}^n LTS_j \cdot s_j + s_0 \quad (26)$$

The results show that the head has a significant influence, followed by calf and foot. A negligible effect is observed at chest and back.

A linear regression equation of *OTS* is used in [214] to analyse *LTS* at different parts of the body:

$$OTS = f(LTS_{\text{arm}}, LTS_{\text{hand}}, LTS_{\text{calf}}, LTS_{\text{back}}, LTS_{\text{foot}}) \quad (27)$$

The results show that high velocity and low air temperature close to the floor strongly influences the *OTS* of the individuals.

In the model for non-uniform transient environments described in [181], *OTS* (and *OTC*) are variable over the time  $\tau$  and depends on  $t_{\text{skloc}}$  and  $t_{\text{core}}$ , and on their change rates  $\frac{dt_{\text{skloc}}}{d\tau}$  and  $\frac{dt_{\text{core}}}{d\tau}$ , for example:

$$OTS = f\left(t_{\text{skloc}}, \frac{dt_{\text{skloc}}}{d\tau}, t_{\text{core}}, \frac{dt_{\text{core}}}{d\tau}\right) \quad (28)$$

The experimental results obtained in [181] confirm that the overall response to cooling is more significant than the overall response to heating. Moreover, a body portion with the same  $t_{\text{skloc}}$  feels relatively warmer when other body portions are colder, and vice versa.

Different evaluations under transient conditions are conducted in [218], obtaining an empirical equation of *OTS*:

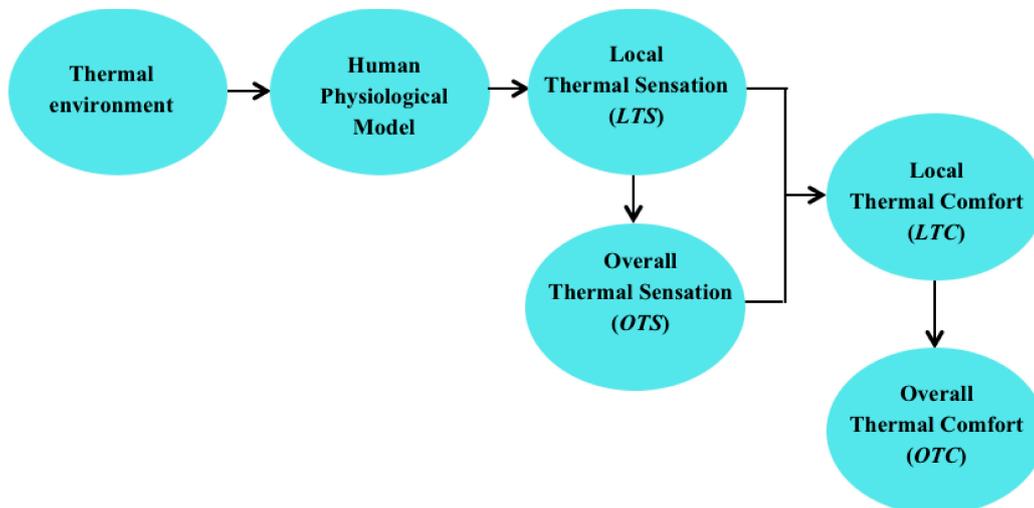
$$OTS = 0.0152 \cdot t_a - 0.0726 \cdot D_a + 0.676 \cdot v - 3.66 \quad (29)$$

where  $D_a$  is the supply air temperature difference in °C. A definite benefit is obtained by taking into account the simulated airflow from a ventilation system. In this case, the free term of the equation becomes 3.51 and corresponds to a reduction of *OTS*. Jin et al. [216] start from [219] and develop a weighting factor model for *OTS* under local cooling conditions by statistical analysis. In [219], the weighting factors are constant when cooling different body parts, while in [216] the body parts are cooled independently by local ventilation. In [220], *OTS* is affected by *LTS* of various body parts (head, chest, back, calf, and foot) varying at different seat positions in aircraft cabins. From the experimental analysis presented in [221], the most significant influence on *OTS* refers to the superior part of the body, then the head, and finally the inferior part of the body. A simplified three-node model is used in [49] to assess *LTS* of the bare and clothed parts of the body, as well as *OTS*.

For the prediction of *LTS*, *OTS*, *LTC* and *OTC*, the model for non-uniform transient environments shown in Figure 4 (adapted from [181]) contains the expression that links human body physiological parameters (skin and core temperatures and their change rates) and thermal response. Successive refinements of the model presented in [181] have been introduced in [222–224], up to the version presented in [225] that includes computational details. In particular, in [222] the body has been divided into 19 parts, *LTS* models applicable in non-uniform and transient environments have been developed for each body part in function of thermo-physiological parameters like skin and core temperatures, and have been validated separately in an automobile testing facility. The concepts presented in [225] include the distinction between the so-called “no-opposite-sensation” condition (when no body part feels significantly opposite thermal sensation with respect to the other body parts) and the “opposite sensation” condition (when there are body parts that feel significantly opposite thermal sensation with respect to the rest of the body parts). For each condition, a specific model represents the *OTS* for sedentary activities in different environments (uniform and non-uniform, for steady-state and transient). In the model, the individual parts of the body are weighted in different ways for warm and cool sensations, so that strong local thermal sensations dominate the *OTS*. In [225] the best agreement between the predicted and actual *OTS* is found for the UCB model. The Dymola/Modelica coupled model of human physiology for non-uniform and transient environmental conditions [226] combines the modified Tanabe model [73] and the model presented in [181,223–225], with better results for warm environments than for cold environments. The predictions of the Dymola/Modelica coupled model successfully predict *TC* compared with the predictions of the Fiala model. Starting from the model [181], successful comparisons with experimental results are shown in [227] from the 65MN model combined with a CFD code.

Some references address the correlation between *OTS* and *LTS*. From the results shown in [228], the *LTS* and skin temperature of hands and arms are significant for *OTS* in the case of women, while for men are not so important. In [65] the ThermoSEM model for predicting the *TS* in a non-uniform environment, correlated with the UCB model, gives a reasonable *OTS* prediction in steady-state conditions. The results of the experiments carried out in a climate control chamber in [30] indicate in which parts of the body the *LTS* is warmer or colder than the *OTS*. In particular, the *LTS* of chest and back has a strong linear correlation with the *OTS* and values higher than the *OTS*. The other parts of

the body exhibit poorer correlation with the *OTS*. Starting from a substantial agreement between *OTS* and *LTS* in uniform environmental conditions [229], fast temperature changes are introduced in [230], showing a strong correlation between *OTS* and *LTS* also in non-uniform environments.



**Figure 4.** Block diagram for computing local and overall thermal sensation and thermal comfort.

The correlation between *OTS* and *OTC* is addressed in [231]. The *OTS* and *OTC* models are obtained through multiple linear regressions. According to the regression models, the *LTS* of different body parts affects *OTS* and *OTC* to different extents. A significant influence on *OTS* is obtained for head and hand, a small influence for leg and foot, and a negligible influence for the other body parts. Regarding the impact on *OTC*, only head and leg demonstrate significant influences. These results are in line with the findings of [232], in which the forehead and arm are indicated as appropriate local spots for *OTS* estimation. In [30] the main effect on *OTS* comes from the upper body.

The *LTS* and *OTS* results are used to define further indicators. The General Percentage Dissatisfied (*GPD*) in non-uniform environment is determined in [219] as:

$$GPD = \underbrace{100 - 95 \cdot e^{-(0.03353 \cdot OTS^4 + 0.2179 \cdot OTS^2)}}_{\text{uniform term}} + \underbrace{7.27 \cdot \Delta TS^2 + 6.64 \cdot \Delta TS_{\max}}_{\text{non-uniform term}} \quad (30)$$

where  $\Delta TS_{\max}$  is the maximum thermal sensation difference between the body parts. The authors of [219] observe that the face has a more significant influence on *OTS* than other parts of the body. The new thermal acceptability (*nTA*) model, suitable for both neutral and warm situations in uniform and non-uniform environments, is proposed in [233] from an experimental study. The *nTA* model depends on a uniform term, in function of *OTS*, and a non-uniform term, in function of  $\Delta TS_{\max}$ :

$$nTA = \underbrace{-0.41 \cdot OTS + 0.58}_{\text{uniform term}} + \underbrace{-0.27 \cdot \Delta TS_{\max}}_{\text{non-uniform term}} > 0 \quad (31)$$

The relation between *TS* and *TC* for steady and uniform conditions is shown in the new Thermal Comfort *nTC* model reported in [234], written as:

$$nTC = \underbrace{(-0.80 \cdot OTS + 1)}_{\text{steady -state conditions}} + \underbrace{(-0.56 \cdot TS_{CS})}_{\text{steady and transient conditions}} \quad (32)$$

where  $TS_{CS}$  is the thermal sensation changing with space. The results show that  $TS_{CS}$  is an essential factor in determining *TC*.

#### 4. Conclusions

This paper has reviewed a number of models used to study various aspects of the thermal sensation in steady-state and transient conditions. These models differ because of their structure, with the partitioning of the human body into segments and the further consideration of nodes to represent external and internal parts of the body by using lumped parameters. With the availability of increasingly higher computational capability, the models have been detailed by resorting to the finite element method, where the human body is represented through a large number of points. The finite element method enables the development of transient models with a growing level of detail and accuracy in the representation of the temperature gradients. However, the increasingly higher detail of the numerical model has to be accompanied by an effective formulation of the thermoregulation model. In this respect, the validation of the thermoregulation models is still difficult, because the reliability of physiological experimental data is affected by the accuracy of the measurement techniques and by insufficient information on the clothing parameters. The existing approaches, also adopted by International Standards, are based on the definition of model equations corrected on the basis of the results of experimental investigations. Some differences emerge in the existing Standards, and the discussions on the possible convergence of the models used in various Standards are under way. Furthermore, most of the thermoregulation models currently used are not accessible to the users or are implemented in commercial software tools (e.g., the Fiala model, not available for free). This does not help the research on further improvements. In this context, the open source approach used in Stolwijk-like models is still very important to advance the research in the field and facilitate comparisons among the results obtained by different research teams.

Clothing models are further introduced to represent the heat and mass transfer in clothing layers. The assumptions used in the definition of the models make them suitable to be exploited in different conditions. In early models, the application was limited to uniform environmental conditions. The most recent models may be applied in non-uniform and transient conditions. In particular, the availability of models in which the human body is represented with multiple segments is essential to assess the thermal response of the body in non-uniform conditions with natural or forced ventilation, also taking into account the posture and clothing. The assessment of the thermophysical properties of clothing is one of the key points still under development.

The outcomes of the thermal sensation assessment also depend on the psychological response of the subjects and further social, cultural and behavioural factors. These factors are taken into account by introducing a feedback on the outcomes of the physiological model, to represent the thermal sensation more comprehensively.

The most recent research is enhancing the models and indicators to assess global and local thermal sensation. In particular, the local thermal sensation is becoming more and more significant, taking into account in which segment of the human body the worst conditions occur, as well as the temperature differences among the body parts, in case of slowly or rapidly changing external conditions. The comparisons of the results obtained from more sophisticated models with respect to simpler models provide hints on the limitations of the simple models and on the need to resort to more detailed models to analyse specific situations. The advances in progress also concern the effectiveness of predicting the thermal sensation and use the predicted results into thermal comfort models. In this respect, suitable information to refine the models comes from the correlation between thermal sensation and thermal comfort indicators, and from the correlation among the physiological parameters of different parts of the human body and the outcomes of thermal sensation and thermal comfort assessment. Some thermal sensation models are used in the Standards concerning the design of indoor spaces. Extended information to drive the upgrade of the Standards come from the availability of more refined tools that consider human responses in transient conditions under asymmetrical environments, together with the experimental results gathered from practical applications.

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