ANNEX 69

EBC

Energy in Building and Communities Programme

International Energy Agency

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (EBC Annex 69)
Deliverable 2: Models and Criteria for the Application of Adaptive Thermal Comfort in Built Environment

Energy in Buildings and Communities Technology Collaboration Programme

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Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (EBC Annex 69) Deliverable 2: Models and Criteria for the Application of Adaptive Thermal Comfort in Built Environment

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 31 member countries and 11 association countries, and to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)

The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.

At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

- reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
- improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
- the creation of 'low tech', robust and affordable technologies;
- the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
- the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

- the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
- benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
- improving smart control of building services technical installations, including occupant and operator interfaces;
- addressing data issues in buildings, including non-intrusive and secure data collection;
- the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO_2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO_2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
Annex 62: Ventilative Cooling (*)
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Annex 68: Indoor Air Quality Design and Control in Low Energy Residential Buildings (*)
Annex 69: Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (*)
Annex 70: Energy Epidemiology: Analysis of Real Building Energy Use at Scale
Annex 71: Building Energy Performance Assessment Based on In-situ Measurements (*)
Annex 72: Assessing Life Cycle Related Environmental Impacts Caused by Buildings
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Annex 88: Evaluation and Demonstration of Actual Energy Efficiency of Heat Pump Systems in Buildings
Annex 89: Implementing Net Zero Emissions Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes

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Preamble

Reductions in energy use and provision of comfortable indoor environment to occupants are both key objectives of the building sector all around the world. However, establishing the appropriate balance between these often competing issues is challenging. Is it possible to achieve thermal comfort in buildings without increasing energy use?

The key point is to understand the occupants' real thermal demand. To maintain the indoor environment variables within narrow range is known to consume copious energy, but is the steady iso-thermal environment with minimal variations really necessary for thermal comfort? Previous studies have shown that staying in a steady thermal environment for long time periods may actually be harmful to human body, since it weakens the physiological thermoregulatory resilience and acclimation when people are finally exposed to heat stress. We now have enough evidence to show that tight control of indoor temperatures drives high energy costs and greenhouse gas emissions, and may not always provide benefit for occupant comfort and health. The current indoor environment standards for mechanically heated and cooled buildings are based on the PMV-method for specifying an acceptable comfort temperature range. The same standards also include an adaptive approach for office buildings relying on operable windows instead of mechanical cooling systems (ISO 7730, 2005; CEN 15251, 2012; e.g. ANSI/ASHRAE, 2013).

The Annex 69 project was approved unanimously at the XXth Executive Committee Meeting of the IEA Energy in Buildings and Communities Programme, held on 14th November 2013 in Dublin, Ireland. The Annex will focus on the fundamental question of how to describe the mechanisms of occupant adaptive thermal comfort in buildings, as well as the application of the thermal adaptation concept in design, evaluation and control of built environments in order to reduce energy use. The participants will collaborate to establish a worldwide database of building performance, to develop and improve the adaptive method in indoor thermal environment standards, and to propose guidelines for using the adaptive approach in low energy building design, operation, refurbishment, and new personal thermal comfort systems. The project has three subtasks:

Subtask A: Collecting field data on comfort and occupant responses, and research into models of adaptation

Subtask B: Criteria and guidelines for adaptive comfort and Personal Thermal Comfort Systems in standards

Subtask C: Case studies - Practical learnings from exemplary adaptive buildings, supporting Subtasks A & B

In total 14 countries organizations including universities and research institutes have participated in the project. Preparation phase started in January 2015 and lasted until December 2015. The

Working phase started in January 2016 and lasted for three years. The Reporting phase started in January 2019 and plans to end in December 2019.

Through Annex 69, we hope to provide scientific description and clear understanding of how to develop quantitative description of occupants' adaptive thermal comfort in buildings, which is a fundamental science question related to the appropriate design, evaluation and control methods of indoor environment in order to reduce building energy use.

1. Introduction

Thermal comfort attracts more and more attention as a result of the developments in human society. Meeting the basic requirements of housing is no longer the goal, but the pursuit of high-quality indoor environment is the purpose. Since the beginning of studies on indoor thermal comfort, the existence of thermal adaptation has been noticed. By comparing the field survey data, Nicol and Humphreys found that the indoor comfort temperature in UK, USA and other countries has been increasing in the past 20 years. Also, a difference between the comfort temperatures of naturally ventilated and air-conditioned buildings was recorded (Humphreys, Nicol and Raja, 2007; Nicol and Humphreys, 2002). De Dear and Brager proposed an adaptive thermal comfort model based on a large amount of survey data and established a relationship between the neutral temperature and outdoor temperature. The model attracted extensive attention in the thermal comfort community and was applied popularly (De Dear and Brager, 1998). In the past twenty years, the proposal of adaptive thermal comfort theory has provided a new perspective on the relationship between the human body and the ambient environment. De Dear et al. put forward the concept of “Alliesthesia” which believed that people's active adaptation to environmental changes can produce some thermal pleasure. A stable and neutral environment was not necessarily the best environment (de Dear, 2011). Schrauwen et al. provided physiological evidence showing that cold or hot exposure could improve the ability to adapt to a changeable climate and benefit health (Schrauwen, van Marken Lichtenbelt and Spiegelman, 2015). The breakthrough on mechanisms and the update on the methodology are driving new progress on thermal comfort modelling.

Thermal comfort models aim to describe the influence of thermal environmental parameters on human responses. The model written into standard and used in direction of building design is usually established based on basic heat balance calculation and a large amount of subjective feedback, such as the commonly used PMV model and the adaptive thermal comfort model (De Dear and Brager, 1998; Fanger, 1970). PMV model had been revised by many studies because of its low accuracy in practice in natural ventilation buildings and in some non-neutral conditions (Ole Fanger and Toftum, 2002; Yao, Li and Liu, 2009a; Kim et al., 2015). Also, the scope of application of adaptive model was challenged, many researchers had developed the adaptive thermal comfort model which was suitable for their climate types and regions (Singh, Mahapatra and Atreya, 2011; Van Hoof and Hensen, 2007). As the individual control and comfort was proposed, more complex model which reflected human thermal physiological regulation and the heat transfer with the environment was developed, so as to acquire more details about physiological parameters to define the human thermal state (Huizenga, Hui and Arens, 2001; Tanabe et al., 2002).

In line with the activities within IEA-EBC Annex 69 Subtasks A, B, and C, the present report includes four main sections, namely comparison of existing standards, new research related to adaptive mechanisms, prediction and modelling of adaptive mechanisms, and assessment of the accuracy of models.

In section 2 existing international standards are compared with respect to their way of incorporating adaptive thermal comfort, which is followed by section 3, which gives an overview of latest developments in standardization efforts.

Section 4 presents a study assessing implications of applying two different control strategies (a prescriptive thermal comfort control based on the Predicted Mean Vote model and an adaptive thermal comfort control) on energy consumption based on simulation study and a summary of energy implications when considering personal comfort systems.

In section 5, new research related to adaptive mechanisms is presented, which includes methodological aspects such as differences in the perception of scales used to assess thermal perception or the value of alpha in the running mean outdoor temperature. New findings are presented related to long-term clothing trends and a novel approach to create thermosensitivity maps of individual body parts.

Section 6 outlines new approaches for modelling individual adaptive mechanisms in the context of heat balance models, which includes the adaptive thermal heat balance approach applied to the predicted mean vote (PMV), standard effective temperature (SET) and thermoneutral zone (TNZ), as well as the PTS-model based on SET.

In section 7, methods to assess the accuracy of thermal comfort models are summarized and first applications described. This section and report conclude with a comment on the true value in the assessment of the accuracy of existing and new thermal comfort models.

2. Comparison of existing standards

2.1. Introduction

Energy efficient design and operation of indoor environment in buildings as well as evaluation of indoor environments rely on appropriate guidelines and recommendations. To this end, detailed criteria for indoor environment conditions that can be considered as acceptable to a majority of building occupants are specified in a range of national and international standards. Most of these standards are based on consensus reached among stakeholders comprising experts from industry, consumer associations, academia, NGOs and government.

Across standards there may be discrepancies in the criteria used to specify optimal thermal conditions. This will affect not only occupant comfort, but also the amount of energy required to heat and cool buildings to maintain comfortable temperatures, as the energy use of climatic systems depends on the set-points for heating and cooling, which are mandated by national or international standards. The energy consumption of buildings accounts for 40 % of the total energy consumption and is responsible for 36 % of the CO_2 emissions in the European Union (Directive 2010/31/EU). Worldwide, the building sector consumed 20.1 % of the total delivered energy in 2016 (U.S. Department of Energy, 2016) and climatic systems accounted for 11 % of the total electricity use in the European Union in 2007 (Knight, 2012). Specification of set-points for control of heating and cooling systems therefore impact significantly the energy use and the carbon footprint of the building sector.

Several methods are used to define thermally comfortable conditions, typically based on either a heat balance equation of the human body or on the adaptive hypothesis of thermal comfort. Adaptive thermal comfort relies to a higher degree on behavioral adjustment and psychological adaptation and therefore may specify different comfort temperatures, which ultimately will affect the energy used to climatize buildings. Also, factors such as climate, building typology, demographics, or culture may be difficult to address universally due to regional differences, which may limit the general feasibility of the criteria specified in different indoor environment standards.

This section reviews and compares the criteria to the thermal indoor environment across different comfort models in selected national and international standards and how these influence building energy use.

2.2. Objectives

To compare criteria to indoor thermal environmental and personal factors as specified in selected national and international standards. The comparison will account for both adaptive and heat balance based comfort models and quantify the influence of standards' criteria on the amount of energy used to maintain comfortable temperatures in buildings located in different climate zones.

2.3. Publishers of standards

A range of different standards bodies oversee the development of standards on national and international levels. The current comparison was based on selected standards available in English and published by ISO (International Organization for Standardization), CEN (European Committee for Standardization), ASHRAE (American Society of Heating, Ventilating, and Air Conditioning Engineers), ISHRAE (Indian Society of Heating, Refrigerating and Air Conditioning Engineers), and National Standard of the People's Republic of China (Ministry of Housing and Urban-Rural Development). Table 1 shows the scope of each of the standards that were compared. For completeness and because some standards address several aspects of the indoor environment, also other factors than those related with the thermal indoor environment are included in the table.

Table 1: Scope of the compared standards.

Standard	*EN 15251* (2012)	*EN 16798-1* (2019)	*ISO 17772-1* (2017)	*ISO 17772-2* (2018)	*ISO 7730* (2005)	*ASHRAE 55:2017* (2017)	*ISHRAE 10001* (2016)	*GB/T 50785* (2012)
Overall Thermal comfort	x	x	x	x	x	x	x	x
Local thermal discomfort		x	x	x	x	x	x	x
IAQ and ventilation rate	x	x	x	x			x	
Humidity	x	x	x	x		x	x	x
Artificial lighting	x	x	x	x			x	
Daylight		x	x	x			x	
Acoustics	x	x	x	x			x	

*EN 16798 supersedes EN 15251. EN 16978 and ISO 17772 are almost identical documents.

Table 2 lists thermal comfort related elements that are also covered by the different standards.

Table 2: Thermal comfort related elements covered by the standards.

Standard	*EN 15251* (2012)	*EN 16798-1* (2019)	*ISO 17772-1* (2017)	*ISO 17772-2* (2018)	*ISO 7730* (2005)	*ASHRAE 55:2017* (2017)	*ISHRAE 10001* (2016)	*GB/T 50785* (2012)
Temperature transients				x	x	x		
Adaptive thermal comfort*	x	x	x	x	(x)	x	(x)	x
Personalized comfort systems		x		x				
Computer program for calculating PMV/PPD					x	x		x
Increased air velocity to compensate for increased air temperature			x			x		
Values of metabolic rates for various activities		x			x	x		x
Values and calculation methods to determine clothing insulation					X	x		x
Estimation of exceedance of criteria	x	x		x				

*Adaptive thermal comfort: EN 15251 defines criteria for the indoor operative temperature based on the outdoor temperature, stating that if those criteria are to be used, occupants must be able to adapt their clothing. prEN 16798 gives the same criteria for operative temperature, but calls it the adaptive method. ISO 7730 describes adaptive occupant behaviors, but without being equally specific.

2.4. Description of quality categories used in the standards

An indoor environment standard does not aim to specify conditions that provide comfort for everyone, as the sensitivity to indoor environment exposures varies between individuals and because individuals may have different preferences (Fanger, 1975). In the same space with uniform environmental conditions individual differences between occupants may cause some to prefer lower and other to prefer higher temperatures. Thus, standards' criteria rely on probability-based exposure-response associations describing the percentage of occupants expected to feel uncomfortable (be dissatisfied) as a function of the parameter(s) in question. The percentage of dissatisfied, which is found acceptable, is then used to establish the corresponding limit for the environmental parameters.

Some standards specify conditions to achieve compliance (ASHRAE, 2017), while others specify categories for criteria that address the desired quality of the indoor environment. The highest category is typically associated with a high level of expectation or with sensitive or fragile individuals that require particularly careful control of the indoor environment (e.g. the elderly or young children). The medium category is associated with a so-called normal level of expectation and is targeted new buildings or renovations. Lower categories are associated with acceptable or minimum acceptable conditions corresponding to a low level of expectation or conditions outside the recommended categories. A poorer quality category usually means a wider interval of comfortable temperatures and thus lower use of energy to condition a building. The number of categories varies between standards and not all standards suggest categories for all parameters.

2.5. Indoor thermal environment

Criteria for the thermal indoor environment are typically based on thermal comfort for the body as a whole and on local discomfort factors, the latter being related with thermal asymmetries such as draught or radiant temperature asymmetry. Analytical methods can be used to specify comfortable operative temperatures in a wide range of clothing insulation or metabolic rate. One of the most widely applied analytical models is the Predicted Mean Vote (PMV) index. Both prescriptive and empirical methods assume certain activity levels or that occupants have some adaptive opportunities available, such as access to openable windows. For example, the adaptive model of thermal comfort applies to occupants of spaces without mechanical cooling who are engaged in near sedentary activity (1–1.3 met), are able to freely adapt their clothing to the indoor and/or outdoor thermal conditions and who can regulate their thermal conditions by opening and closing of windows (De Dear and Brager, 1998).

Comparison of operative temperature limits across standards requires definition of reference levels for environmental and personal parameters that may vary depending on the season or the type of building (e.g. residential or commercial). The temperature limits shown in Figure 1 and Figure 2 refer to low air velocity (typically less than 0.2 m/s), clothing insulation of 0.5 clo for summer and 1 clo for winter, sedentary activity and air humidity around 50%. Figure 1 and Figure 2 compare operative temperature ranges for these reference levels during the cooling and heating season, respectively.

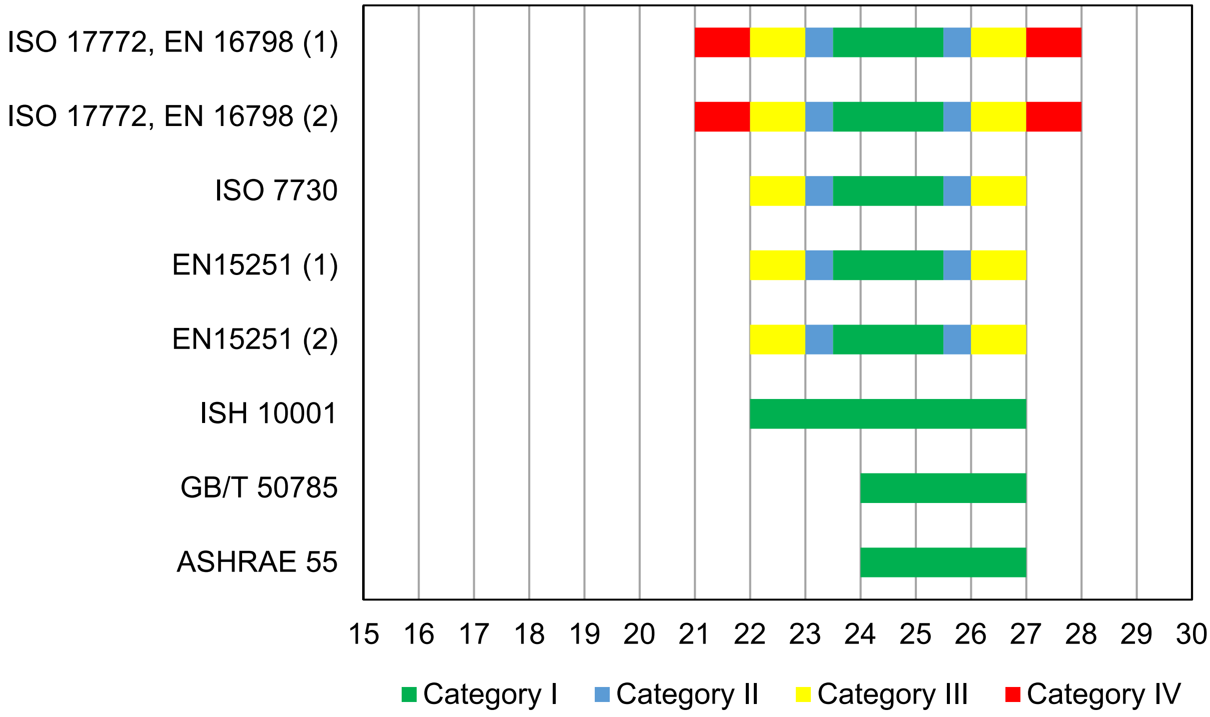

Figure 1: Categories for acceptable operative temperature ranges during the cooling season. (1) residential settings, (2) offices.

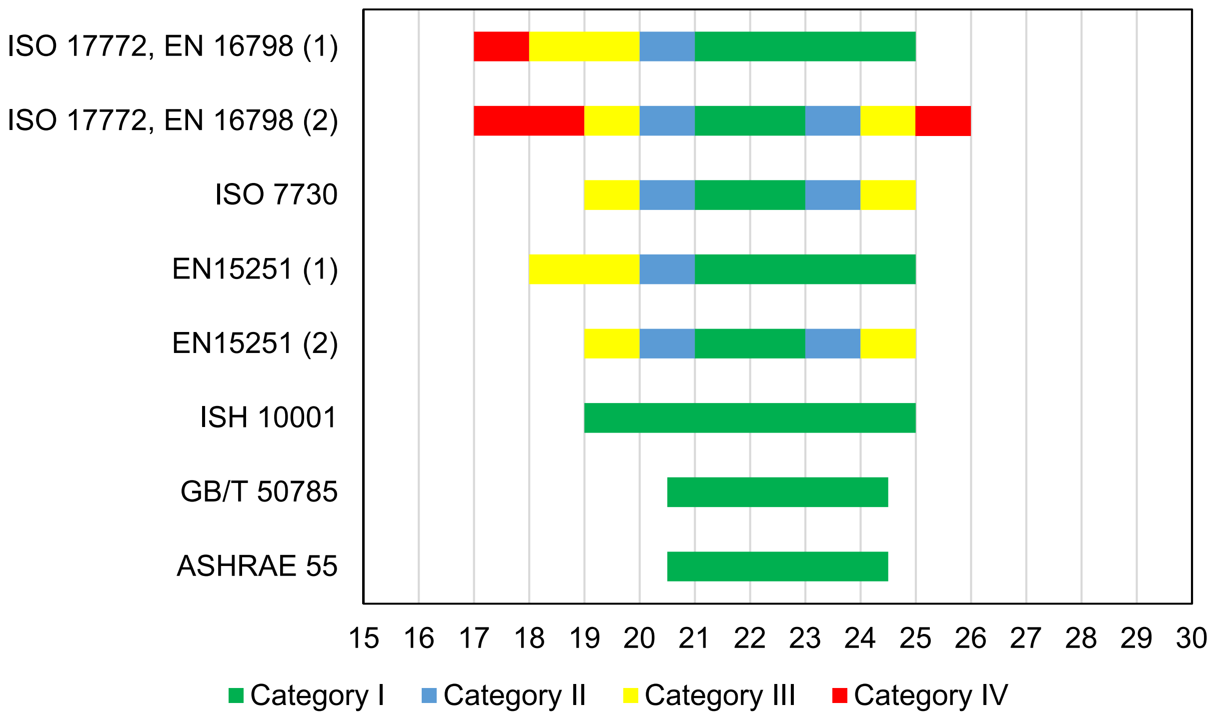

Figure 2: Categories for acceptable operative temperature ranges during the heating season. (1) residential settings, (2) offices.

Several standards specify requirements to the buildings and conditions under which adaptive comfort models may be applied. For example, ASHRAE 55 specifies that the adaptive model may only be applied in occupant-controlled, naturally conditioned spaces, where no mechanical cooling is installed, no heating system is in operation, occupants' metabolic rates are in the range between 1.0 met and 1.3 met, occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions with a clothing insulation that ranges from 0.5 clo to 1.0 clo, and where the outdoor temperature falls in the range 10°C to 33.5°C (ASHRAE, 2017; Carlucci et al., 2018). EN 15251 (2012) and prEN 16798-1 (2017) specify that the adaptive comfort model should mainly be applied to office buildings and other buildings of similar type, not equipped with mechanical cooling systems, where occupants are engaged in sedentary physical activity and can freely adapt their clothing to the indoor/outdoor conditions (Carlucci et al., 2018; CEN 15251, 2012; CEN 16798, 2017). The outdoor temperature range for application of the adaptive model is 10°C to 30°C (CEN 16798, 2017). Outside this range, mechanical cooling or heating systems should be installed and operated according to set-points calculated with the PMV equation (Carlucci et al., 2018).

Adaptive thermal comfort models rely on the outdoor temperature to determine ranges for comfortable indoor temperatures. Temperature limits are therefore not fixed as in Figure 1 and Figure 2, but vary according to season and prevailing outdoor climate. Standards suggest different methods to determine an arithmetic average or a running or prevailing mean average outdoor temperature. ASHRAE 55, EN 15251 and prEN 16798-1 define the mean monthly outdoor air temperature as the arithmetic average of the mean daily minimum and mean daily maximum outdoor air temperatures for the month in question (ASHRAE, 2017; CEN 15251, 2012; CEN 16798, 2017). The running or prevailing mean outdoor temperature is based on a weighting of the form

$$t_{rm(out)} = (1 - a)\cdot[t_{e(d-1)} + a\cdot t_{e(d-2)} + a^2\cdot t_{e(d-3)} + a^3\cdot t_{e(d-4)} + \ldots] \quad (1)$$

in which more distant days are weighted less.

In the equation, a is a constant in the range 0 to 1 and $t_{e(d-n)}$ is the daily mean external air temperature for n days prior to the one in question. ASHRAE 55 2013 suggests an a = 0.9 where the temperature variation is minor (e.g. humid tropics) and a lower a = 0.6 where the temperature variation may be more pronounced (ASHRAE, 2017). prEN 16798 (2017) recommends an a = 0.8 (Carlucci et al., 2018; CEN 16798, 2017).

ISO 17772-2 (2018) suggests another approximate formula to calculate the running mean outdoor temperature based on six preceding days (ISO 17772-2, 2018):

$$\theta_m = \frac{(\theta_{ed-1} + 0.8\cdot\theta_{ed-2} + 0.6\cdot\theta_{ed-3} + 0.5\cdot\theta_{ed-4} + 0.4\cdot\theta_{ed-5} + 0.3\cdot\theta_{ed-6} + 0.2\cdot\theta_{ed-7}}{3.8} \quad (2)$$

Figure 3 shows the upper and lower operative temperature limits based on the adaptive comfort models of ASHRAE 55 (2013), EN15251 (2007) and prEN16798 (2017) (ASHRAE, 2017; CEN 15251, 2012; CEN 16798, 2017).

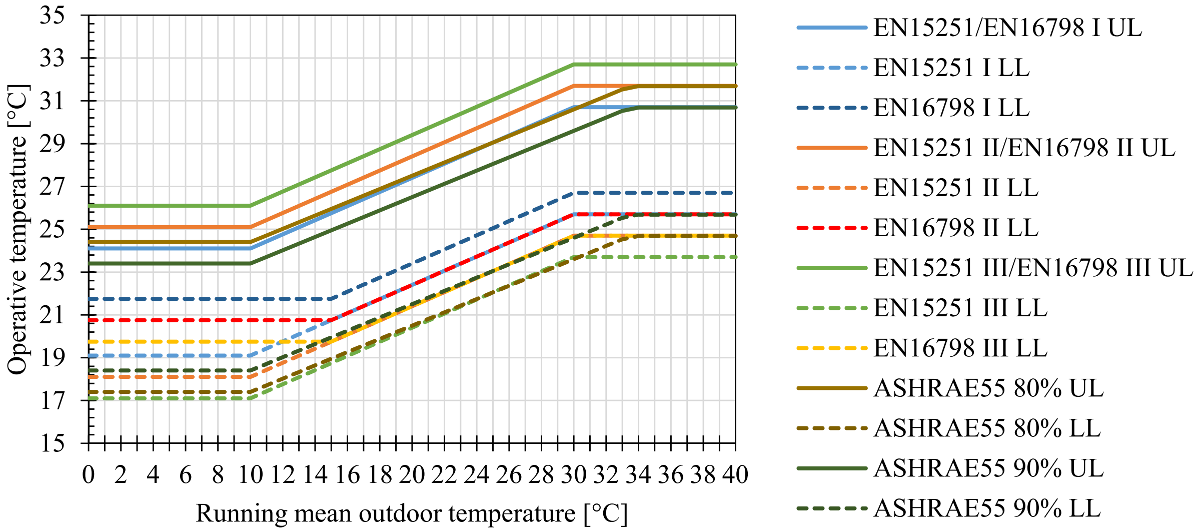

Figure 3: Adaptive thermal comfort zones for non-mechanically conditioned buildings. UL: Upper limit, LL: Lower limit.

Table 3 shows adaptive comfort models in the form of regression equations used to determine the comfort zones in Figure 3.

Table 3: Regression equations for the adaptive comfort zone and their applicability range (modified from (ISO 7730, 2005).

Standard	Categories	T_{op} (°C), upper limit (UL)	T_{op} (°C), lower limit (LL)	T_{op} (°C), applicability range
ISO 17772, EN 16798	I	$0.33*T_{rm}+20.8$	$0.33*T_{rm}+15.8$	10-30
	II	$0.33*T_{rm}+21.8$	$0.33*T_{rm}+14.8$	10-30
	III	$0.33*T_{rm}+22.8$	$0.33*T_{rm}+13.8$	10-30
EN 15251	I	$0.33*T_{rm}+20.8$	$0.33*T_{rm}+16.8$	10-30
	II	$0.33*T_{rm}+21.8$	$0.33*T_{rm}+15.8$	10-30
	III	$0.33*T_{rm}+22.8$	$0.33*T_{rm}+14.8$	10-30
ASHRAE 55	acceptable (80%)	$0.31*T_{rm}+21.3$	$0.31*T_{rm}+14.3$	10-33.5
	acceptable (90%)	$0.31*T_{rm}+21.3$	$0.31*T_{rm}+15.3$	
GB/T 50785	I^d	$0.77*T_{rm}+12.04$	$0.87*T_{rm}+2.76$	18-28
	II^d	$0.73*T_{rm}+15.28$	$0.91*T_{rm}-0.48$	16-28 (30)
	I^e	$0.77*T_{rm}+9.33$	$0.87*T_{rm}-0.31$	18-30
	II^e	$0.73*T_{rm}+12.72$	$0.91*T_{rm}-3.69$	16-28 (30)

3. Latest developments in standardization efforts

ASHRAE Standard 55 has been actively implementing new approaches to sustainable buildings based on recent research on comfort in both laboratory and in actual buildings. In the period 2015-2019, many changes (addenda) were made to Standard 55 to encourage sustainable (defined as being both thermally comfortable and energy-efficient) building designs and operating practices. The changes provide new approaches to designing for the occupant, including encouraging the use of occupant adaptation and behavior. The changes were based on new research contributions in the technical literature, and have spurred follow-on research to develop design applications.

Providing the occupant with adaptive control solutions addresses the most important source of discomfort in modern buildings, the large inter- and intra-personal variability in thermal comfort requirements. Adaptive measures are usually more energy-efficient than centralized HVAC control, and should in principle be encouraged. The Standard's addenda address potential comfort-influencing effects inherent to low-energy HVAC, such as non-uniform elevated air movement, thermal stratification, and draft at the ankles, in order to appropriately reward good practice.

Below we summarize the broad themes being addressed in Standard 55, and list the research papers on which the new Standards features are based. We also list papers that extend the use of the standard by developing design applications (e.g., the Zani solar papers, and many ceiling-fan-airflow papers).

3.1. ASHRAE Thermal Comfort Field Study Database (aka 'Comfort Database')

One of whose major purposes of the Comfort Database is developing and validating comfort standards. The original Adaptive Model adopted by ASHRAE Standard 55 in 2004, was developed from a collection of field study data assembled by Richard de Dear and Gail Brager ('Database 1'). Annex 69 supported a project sponsored by ASHRAE in 2013-8 to collect and organize all possible subsequent field studies, resulting in a greatly expanded database of real-world comfort (Földváry Ličina et al., 2018). The new database also includes analysis and visualization tools[1] that allow the field studies to be compared, and statistics such as percent dissatisfied curves to be calculated for a wide range of comfort parameters (Pigman et al., 2014;

[1] https://cbe-berkeley.shinyapps.io/comfortdatabase/

Földváry Ličina et al., 2018). Database 2 is already in active use and can be downloaded[2]. So far there have been 682 downloads and 44 citations[3].

It has been used to test metrics and models such as the PMV/PPD (Cheung et al., 2019) and and the ISO/EN thermal environmental classification schemes (Li et al., 2019). It has been used to revisiting the original adaptive comfort model and suggesting nudges to theory, standards, and practice (Parkinson, de Dear and Brager, 2020).

3.2. The ASHRAE/CBE Thermal Comfort Tool

The **ASHRAE/CBE Thermal Comfort Tool** incorporates all calculations involved in determining the current PMV+SET-based comfort zone, and the Adaptive-Model comfort zones. In preparing the tool, all underlying calculation models were vetted, coding errors corrected, and validation tables prepared. This effort was assisted by team members of Annex 69. The changes are now included in the Standard 55 normative standard, and the web-based Tool[4] has been adopted by ASHRAE as the official calculation engine and embodiment of the Standard's comfort zones. It is in wide use by designers allowing comfort conditions to be evaluated and compared in real time (Schiavon, Hoyt and Piccioli, 2014; Hoyt et al., 2017).

3.3. Air movement considerations

The most promising solutions to adaptive comfort in neutral-to-warm environments involve air movement cooling the occupant. In the 2010 edition of Standard 55, the cooling effects of air movement began to be evaluated using the model SET, supplemented by an empirical relationship for acceptability limits developed from analysis of Comfort Database 1. The new approach applies to both air-conditioned and naturally-ventilated building types. Previous draft risk provisions were simplified based on evidence from field studies. Some refinements have been made to these provisions since 2010, such as raising the threshold of the still-air zone from 0.15 to 0.2 m/s to accommodate draft models, ASHRAE's ADPI index, and design practice. The new standards provisions have attracted a great deal of interest, with much new research underway on how to create effective air movement within rooms, primarily addressing ceiling fans at this point (Huang et al., 2014; Zhai et al., 2017, 2015b, 2013; Gao et al., 2017; Wang et al., 2019; Lipczynska, Schiavon and Graham, 2018; Chen et al., 2018; Raftery et al., 2019; Present et al., 2019; Liu et al., 2018a; b; Yang et al., 2015).

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[2] http://www.comfortdatabase.com/

[3] https://datadryad.org/stash/dataset/doi:10.6078/D1F671

[4] https://cbe.berkeley.edu/project/thermal-comfort-tool/

3.4. Solar control

Solar radiation on occupants indoors almost always results in discomfort. In addition, most low-energy design strategies cannot succeed in inappropriately shaded buildings. However, up until 2017, indoor solar radiation was not addressed in any thermal comfort standard. An addendum containing SolarCal model and prescriptive compliance approaches was added to Standard 55 in 2017. Direct and diffuse shortwave gain on occupants are now evaluated in order to predict the extent of solar shading needed in building design. The standard requirements encourage both architects and engineers to be engaged in shading design. The orientation of representative occupants and their surrounding furniture geometry become elements of the design. The model is incorporated in the CBE/ASHRAE Thermal Comfort Tool (Arens et al., 2015; Zani et al., 2018).

3.5. Thermal Environmental Control Classification

Addendum C of the Standard (published 2020) assigns credit to the degree of individual comfort control available to the occupants. Following strong evidence that achieving high rates of thermal satisfaction requires individual control, a five-level classification scheme rates the degree of control by the number of control options provided to occupants. The options include personal comfort systems, and their eligibility in the Standard is determined by their comfort-correcting power measured in degrees temperature. The new classification approach is designed to be adopted by building rating systems such as LEED and WELL, and by real-estate managers, in ranking the quality of office environments. Basing the classification of availability of occupant control options is a promising new approach in comfort standards, in that it takes advantage of occupant adaptive behavior to provide more comfortable and more energy-efficient design solutions.

The new classification is in contrast to the ISO PMV-based classification system (in which narrow temperature deadbands are rated as providing superior environments). Conforming to the ISO system is strongly energy-intensive. More importantly, numerous, large scale studies in the literature show that the higher classification levels do not actually improve occupant comfort. This is mostly because narrow room temperature control cannot solve occupants' interpersonal variation in thermal comfort requirements. Recent research consistently points to deficiencies in predictive value of PMV and PPD, the measures underlying the ISO classification system (Zhang, Arens and Zhai, 2015a; Li et al., 2019; Luo et al., 2018a; Zhang et al., 2015).

3.6. A clothing insulation model

A clothing insulation model was added in 2015 to give designers a standard way of incorporating seasonal clothing behavioral changes in their designs. Clothing insulation on a given day is based on outdoor air temperature at 6 AM (Schiavon and Lee, 2013a; Lee and Schiavon, 2014).

3.7. Ankle draft risk model,

An ankle draft risk model was approved and published as Addendum A on October 2017. Draft, unwanted local cooling caused by air movement, is a major issue for displacement ventilation (DV) and underfloor air distribution (UFAD) systems. The earlier draft risk model developed by Fanger et al. (1988) overestimated risk for such systems. Since DV and UFAD deliver conditioned air from the floor level, exposing feet and ankles to cold air, the new model predicts percentage dissatisfied with ankle draft as a function of whole body thermal sensation and air speed at ankles (Schiavon et al., 2016; Liu et al., 2017).

3.8. The vertical thermal stratification

The **vertical thermal stratification** limit is currently being increased. The traditional limit of 3 K between 0 and 1.1 m has been proven to be too conservative. This limit had a serious adverse effect on the design and operation of displacement ventilation and underfloor air distribution systems. Extensive human subject tests spurred by this problem have found the acceptable gradient to exceed 5 K (Liu et al., 2017). A 5 K limit is under consideration by the Standards Committee and an addendum is being prepared as of February 2020.

3.9. Evaluating comfort in operating buildings

Standard 55 addresses operation in normative and informative sections (Section 7 and Informative Appendix L) that were incorporated in the 2013 Standard, including:

- Evaluation approaches based on 1) physical measurements and models, and 2) occupant surveys, and criteria and examples for each.
- Exceedance metrics for comfort and acceptability as measured over time. These include the definition of exceedance-hours specified in the normative standard, and the definition of other measures (weighting by severity of temperature exceedance, thermal sensation exceedance, rate-of-change exceedance, and numbers of discomfort episodes) are specified in the Standard's informative appendix H.
- The ASHRAE Performance Measurement Protocols for measuring indoor environmental quality were prepared for ASHRAE in 2012 using the above methods outlined in the Standard.
- Since 2013 there has been considerable work done on exceedance assessment in actual buildings, encouraged by Annex 69 (Heinzerling et al., 2013; Parkinson, Parkinson and de Dear, 2019; Karmann, Schiavon and Arens, 2018; Carlucci, 2013; Borgeson and Brager, 2011).

3.10. Metabolic rates and comfort of occupants in transition

Arriving occupants have different activity levels and thermal states from those who have been indoors longer, and they may experience discomfort during the transition. These transitions occur in outdoor-to-indoor transitional spaces, like lobbies, stores, and restaurants, but they also continue in interior destination spaces such as offices. It is challenging to condition such spaces to suit the comfort requirements of all the occupants, and there are energy and economic consequences to the methods employed.

Our focus here is on summer or warm-climate conditions, for reasons explained later.

People:

1. enter buildings with elevated body temperature obtained from the outdoor environment.
2. change from walking to sitting activity, during which their metabolic rate decreases.

When people enter buildings, body heat from outdoor exposure and elevated metabolism has to be removed from the skin before it can cause discomfort indoors. Unfortunately, outdoor wind levels and the self-generated wind from walking usually decrease when a person enters a building. This causes their skin temperature and sweat rate to spike as the body compensates for the lost convective cooling. The resulting discomfort can persist for over an hour. During this time the occupant might reset the thermostat.

In addition there are spaces like restaurants in which some occupants (servers) continuously have higher metabolic rates than others (diners) and require different levels of cooling.

The environmental control options for removing body heat differ greatly in their effectiveness. Recent research studies show that indoor air movement is far more effective than cooled temperature, both for maintaining comfort throughout transitions from outdoors to indoors, and during the metabolic downstep when a person sits down. When operative temperature alone is used to remove body heat, both subjective comfort votes and physiological responses respond much more slowly. (Zhai et al., 2019a; b, 2018, 2015a; Gao et al., 2018; Luo et al., 2018c).

This research result has important practical implications for the design and operation of buildings, one of them related to comfort and one to energy efficiency.

1. Comfort: conditioning with cooled air inherently covers large areas which may have multiple occupants, some of whom are not experiencing the thermal transient and do not need the cooling. Air movement in contrast can be directed into smaller areas that do not overcool longer-term sedentary residents of the space.
2. Energy: transition spaces at the indoor/outdoor boundary (stores, lobbies, transit stations) inevitably leak their cooled air to the outdoors, and the colder that these spaces are maintained, the greater the energy loss. Air movement cooling provides equivalent comfort at warmer interior temperatures, so less energy is lost from leaked air.

The research results suggest that we can quantify the combinations of air movement and temperature that are most effective at keeping people comfortable thoughout the time they are in lobbies, stores, and other transition spaces. We can also quantify the combinations needed by newly arrived occupants once they arrive in long-term sedentary spaces like their office workstations and conference rooms.

Translating these environmental conditions into design, transition zones should be capable of providing sufficient elevated air movement so that an occupant's transient period is comfortable throughout. Office workplaces should have personally controlled air movement sources available to deal with the transition to sedentary in spaces whose temperatures are not under the control of the occupant. The operational goal in both cases should be to avoid overcooling the space temperature, but to maintain it at an appropriately warm level to provide the most effective draft-free convective cooling.

3.11. Applying the adaptive model in mixed-mode buildings and air-conditioned buildings incorporating personal comfort systems.

The ASHRAE Standard 55 committee is as of February 2020 preparing an addendum to its provisions for the adaptive model, addressing the application of the model to: 1) mixed-mode buildings, and 2) air-conditioned buildings that incorporate personal comfort systems to supplement the building system. This activity followed from the following research on the adaptive model done using the new ASHRAE Database II.

A detailed examination of the first generation adaptive comfort standards (ASHRAE 55 and EN15251) was undertaken using the large dataset in Database II. The analytical procedure used to develop the ASHRAE 55 adaptive standard was replicated on 60,321 comfort questionnaire records with accompanying measurement data Parkinson et al. (2019). Results validated the standard's current adaptive comfort model for naturally ventilated buildings, while suggesting several potential nudges relating to the adaptive comfort standards, adaptive comfort theory, and building operational strategies. Adaptive comfort effects were observed in all regions represented in the new global database, but the neutral temperatures in the Asian subset trended 1-2 °C higher than in Western countries. There were sufficient data to develop an adaptive model for mixed-mode buildings, which is seen to closely align to its naturally ventilated counterpart. The paper presents evidence that adaptive comfort processes are relevant to the occupants of all buildings, including those that are air conditioned, as the thermal environmental exposures driving adaptation occur indoors where we spend most of our time. This affords significant opportunity to transition air conditioning practice into the adaptive framework by programming synoptic- and seasonal-scale set-point nudging into building automation systems.

4. Energy consumption assessment

4.1. Introduction

In order to maintain indoor environmental conditions in a comfortable range, energy is used whenever the combination of outdoor conditions, properties of the building envelope, and indoor activities does not lead to comfortable conditions in the free-running mode. Differences in the properties of the building envelope, the HVAC-system as well as the chosen indoor environmental conditions will have an impact on occupant comfort, but also on the energy consumed by heating, ventilation and air conditioning systems. The following subsections summarize studies quantifying such effects.

4.2. Comparison of energy consumption between prescriptive and adaptive control strategies based on existing standards

The application of indoor environment standards enables the appropriate design of indoor environments and operation of building systems, increasing energy efficiency and occupant comfort and well-being. The criteria defined in standards are based on consensus between industry, academia, NGOs, governments and consumer associations. Therefore, it is expected that there will be discrepancies across standards in terms of the specifications for optimal thermal conditions.

There are two main models for thermal comfort assessment defined in the standards: predicted mean vote (PMV) and the adaptive model. The PMV is based on a semi-empirical heat-balance model of the human body, whereas the adaptive model suggests a linear relationship between an estimation of the prevailing outdoor temperature and comfortable indoor temperatures (Fanger, 1970; De Dear and Brager, 1998).

This section compares thermal comfort criteria included in different national and international standards, presenting the implications of their application in terms of thermal conditions and building energy consumption.

4.2.1. Methodology

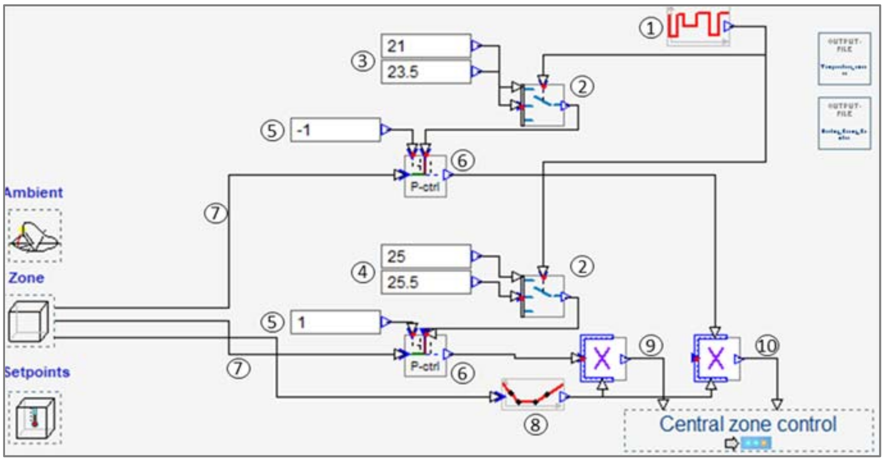
The energy consumption assessment was performed through dynamic simulations, using the software IDA-ICE (IDA-ICE, 2019). The aim was to compare the energy consumption when two different control strategies were applied in simulated building models: a prescriptive thermal comfort control (PTC) based on the PMV model and an adaptive thermal comfort control (ATC) defined by the adaptive model. The indoor environment requirements for both control approaches considered the criteria defined in three international standards: EN15251 (CEN 15251, 2012), ASHRAE 55 (ASHRAE, 2017) and EN16798 (CEN 16798, 2017). The analysis accounted for eight locations reflecting different climatic zones, according to the Köppen-Geiger classification (Peel, Finlayson and McMahon, 2007). The locations were: Copenhagen, Denmark (CPH); Tromsø, Norway (TOS); Athens, Greece (ATHB); Beijing, China (BJ); Mumbai, India (MUM); New Delhi, India (ND); Abu Dhabi, UAE (AUH); and Miami, USA (MIA). The weather data from each location was taken from ASHRAE IWEC (International Weather for Energy Calculations) (ASHRAE, 2018).

4.2.2. Simulation models

The simulations were performed in three different building types: a school, an office and a residential building. The residential building was an apartment with a 24 m² living room and a 16 m² bedroom located in a multi-family building. The school building was based on a 50 m² single classroom for 25 occupants. The office building comprised a 10 m² single-office and a 100 m² open-plan office for 10 occupants. The envelope characteristics of the models were designed based on the Danish Building Regulation BR15 (Trafik- Bygge- og Boligstyrelsen, 2015). Only one building code was used for all locations to avoid analyzing the discrepancies between regional building regulations. Occupant schedules and internal gains were based on EN16798 (CEN 16798, 2017).

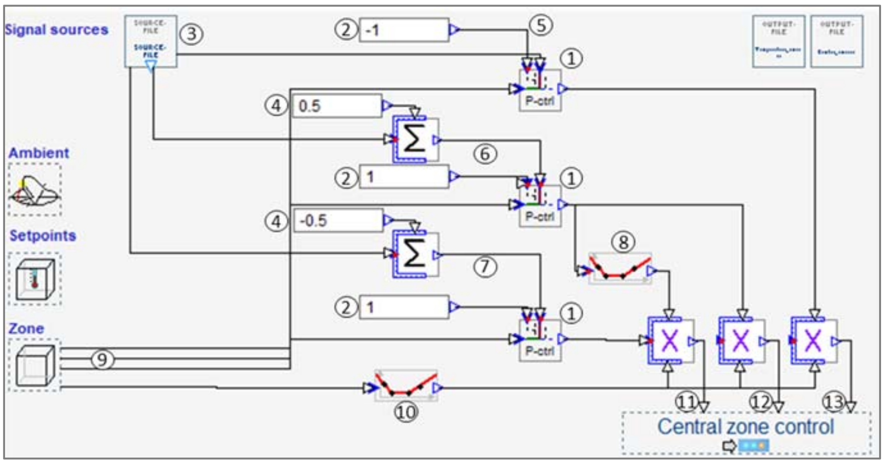
A CAV mechanical ventilation system was applied for all the simulated models. The airflow rates were calculated based on the criteria defined in EN15251 Category II for a low polluting indoor environment (CEN 15251, 2012). Space heating was provided in all models by applying the lower temperature limits of the adaptive model for the ATC and the heating set point described by the PMV (using I_{cl} =1 clo, M = 1.2 met) for the PTC. For space cooling, the PTC adopted the cooling set point defined by the PMV for the cooling season (using I_{cl} = 0.5, M =1.2 met) (Figure 4-a). The ATC approach used a mixed-mode control strategy, i.e., combined natural ventilation and mechanical cooling (Brager, 2006). In this case, the set point for opening windows corresponded to a temperature 0.5°C below the upper limit of the adaptive model. When the indoor operative temperature reached a level 0.5°C above the set point, all windows were closed and mechanical cooling was applied (Figure 4-b). All models used ideal heaters and ideal coolers for space conditioning (i.e., equipment that responds instantly to thermal demands), governed by proportional controllers with a dead-band of 1°C.

a)



1. Schedule for heating/cooling season
2. Switch ON/OFF for heating/cooling season
3. Heating set points
4. Cooling set points
5. Dead band
6. Proportional controller
7. Room operative temperature
8. Occupancy signal
9. Cooling output
10. Heating output

b)



1. Proportional controller
2. Dead band
3. Operative temperature limits from adaptive model
4. Offset
5. Heating set point
6. Coolers' set point
7. Window opening set point
8. Coolers' ON/OFF signal
9. Room operative temperature
10. Occupancy signal
11. Window opening output
12. Cooling output
13. Heating output

Figure 4: Room HVAC control system using the PTC approach (a) and ATC approach (b).

4.2.3. Results

The adaptive model defines a linear regression between comfortable indoor temperatures and the prevalent outdoor temperature. The temperature range in which the regression is valid varies depending on the specifications given by different standards.

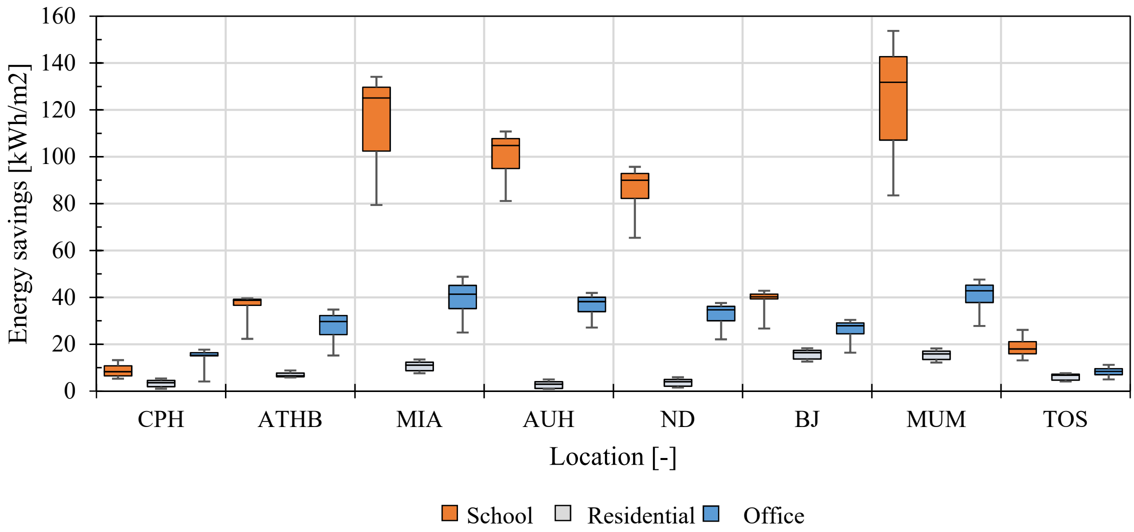


Figure 6: Energy savings (heating, cooling and HVAC auxiliary energy) using the ATC approach instead of the PTC for the three building models analyzed.

Figure 5 shows aggregated values of the running mean outdoor temperatures at the different locations. Figure 6 shows the energy savings of using the ATC instead of the PTC in the different building types at the included locations. Locations with lower outdoor temperatures showed moderate energy savings compared to those with temperatures within the limits of the adaptive model. Moreover, the results suggested that buildings with higher internal gains (e.g. school building), consumed less energy when applying the ATC approach.

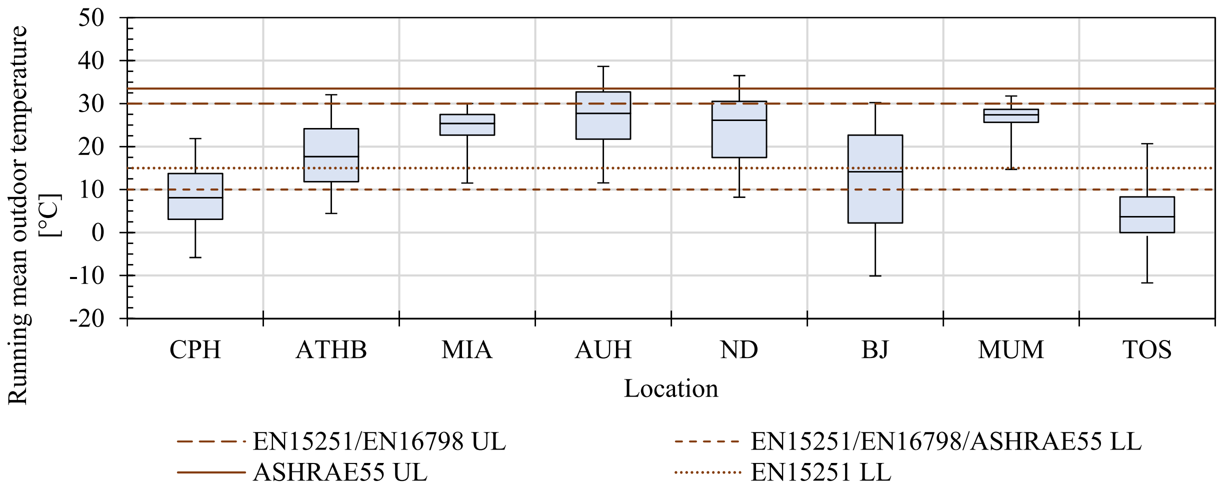


Figure 5: Variability of the running mean outdoor temperature on each location from a representative year and the limits where the ATC regression is valid on each standard. UL: Upper limit, LL: Lower limit

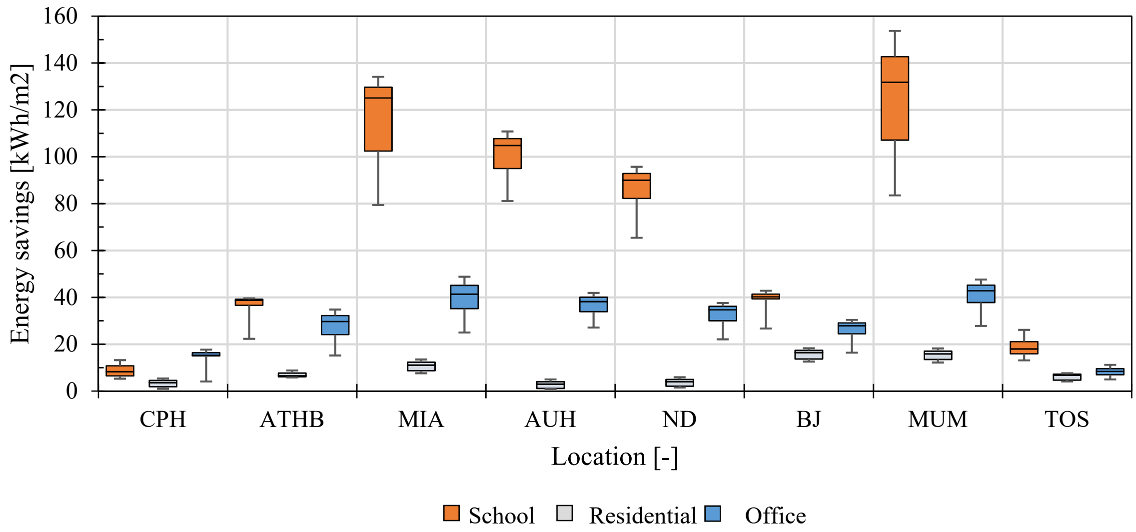


Figure 6: Energy savings (heating, cooling and HVAC auxiliary energy) using the ATC approach instead of the PTC for the three building models analyzed.

Table 4 shows that application of the ATC approach increases the time in which occupants are exposed to temperatures higher than 27ºC. In hot climates such as Abu Dhabi and Mumbai, the number of hours within a year that the operative temperature exceeded 27°C increased more than four times when applying the ATC approach instead of the PTC approach.

Table 4: Percentage of hours within a year when the operative temperature was above 27°C, comparing the ATC and PTC approaches for each location and building type. The results are given in: % hrs.>27 for School/Residential/Office building.

Location	ATC	PTC
CPH	3% /26% /15%	6% /20% /17%
ATHB	45% /48% /57%	20% /23% /21%
MIA	93% /99% /98%	21% /23% /21%
AUH	95% /82% /99%	21% /23% /22%
ND	77% /94% /88%	21% /24% /22%
MUM	100% /100% /100%	21% /26% /23%
BJ	39% /53% /48%	20% /22% /21%
TOS	0% /9% /3%	1% /21% /16%

4.2.4. Discussion and future analysis

The preliminary results showed that applying the ATC instead of the PTC resulted in a significant reduction in the energy consumption in the simulated buildings. The energy savings gained by using ATC depended considerably on the outdoor temperature and the building type. Cold climates had a lower potential to reduce the energy consumption as compared with climates with higher outdoor temperature. Moreover, the differences between the calculated energy savings for the residential, school and office building models were partially explained by the magnitude of the internal heat gains. Depending on the building type and the outdoor climate, the energy savings using the adaptive model varied from 0 to 150 kWh/m².

Nevertheless, applying the ATC approach also caused considerably longer periods with temperatures higher than 27°C at several of the included locations. In the warmer climates, occupants will be exposed to temperatures above 27°C during almost the entire year.

Future analyses within this study will consider a more detailed evaluation of each model. This will contemplate a comparison of the energy savings when using the adaptive model defined in different standards. The analysis will also account for an assessment of the energy consumption implications of using different thermal environment categories.

4.3. Implications on energy consumption when widening setpoint ranges by applying adaptive strategies

The more tightly the indoor temperature is controlled, the more energy is used (Hoyt, Arens and Zhang, 2015) (see Figure 7). In order to save energy, one needs to find ways to relax today's typically tight temperature setpoint ranges. In order to have wider ranges that are comfortable, the occupants must have adaptive opportunities such as personal and group access to controls, windows, fans, personal comfort systems, etc – summarized as personal comfort systems (PCS). The energy savings of widened ranges are truly substantial; 1K setpoint extension in either direction results in about 10% total annual HVAC energy savings, which is true for US residences as well. In PCS and fan field studies, observations energy savings range up to 40-60% repeatedly, in case the setpoint temperature range can be extended (Zhang et al., 2015).

The effect of fans, personal comfort systems, etc. was quantified in terms of 'corrective power', describing the delta ambient temperature offset by the device (Zhang, Arens and Zhai, 2015b; Luo et al., 2018a). Typical PCS devices have fixed corrective powers of 2-4K and appear to be additive (Luo et al., 2018a). These are measured preferably in human subject tests but also using manikins; they cannot be simulated with PMV. SET is also not fully appropriate but has been found to work for fan cooling over the upper half of the body (Huang et al., 2014). Thus the feasible setpoint extensions and related potential reduction in energy use are a simple function of the adaptive corrective powers furnished by the PCS or other adaptive opportunities.

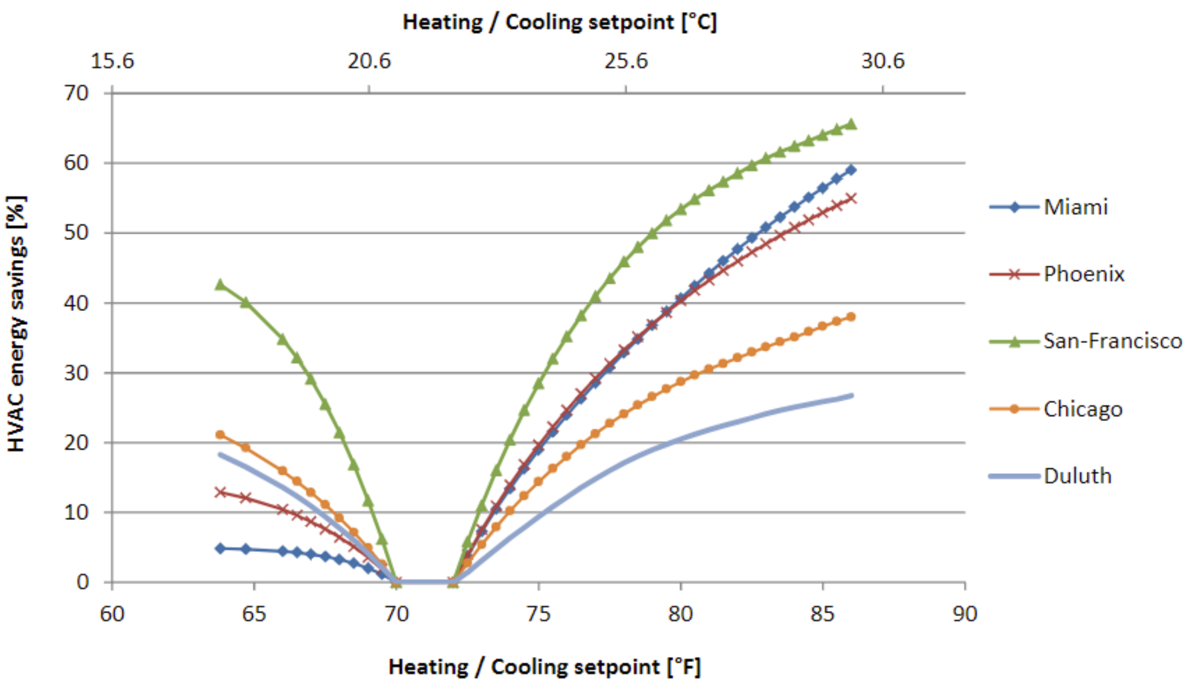


Figure 7: Average annual HVAC savings for commercial buildings with setpoint extension (Hoyt, Arens and Zhang, 2015)

5. New research related to adaptive mechanisms

5.1. Introduction

Research related to adaptive thermal comfort and adaptive mechanisms is attracting more and more researcher over the last years. The SI on adaptive thermal comfort organized within Annex 69 attracted more than 100 submissions and will have more than 30 accepted articles presenting new results. These can be grouped in three large areas.

The first group of papers addresses methodological questions related to adaptive mechanisms or analyses available data sets such as the Global comfort database (Földváry Ličina et al., 2018) with new analysis approaches. In this line researchers continue questioning existing methods such as the Griffith constant (Schweiker et al., 2012; Ryu et al., 2020). Zhou et al. (2020) present a machine learning approach to analyse the available comfort databases, similar to the approach by Kim et al. (2018). Teilelbaum et al. (2019) enhance the well-known psychrometric chart with individual dimensions for radiation and convection. More fundamentally, the reliability of items used to assess thermal perception (Schakib-Ekbatan, Lechner and Schweiker, 2019) and the way the verbal anchors are perceived (Schweiker et al., 2020a) (see also section 5.2) have been challenged as well. The original findings by de Dear and Brager (1998) leading to the adaptive comfort model implemented in ASHRAE 55 are challenged through repetition of the same analysis methods applied to a much larger datasets by Parkinson et al. (2020)

In the second group, research can be found, which conducts further research in the area of adaptive thermal comfort theory related to new or so far less researched climatic regions, building types, activites, or personal characteristics. Thereby, data from India (Tewari et al., 2019) and China (Yan et al., 2019) is analyzed and the effect of long term history on actual perception shown based on a large field study in the United Kingdom (Jowkar, de Dear and Brusey, 2020). Kim et al. (2019) question the applicability and operation mode of mixed-mode buildings and comfort during sleeping hours investigated (Xia et al., 2020; Nicol, 2019). building type or. In addition, Xia et al. (2020) looked at thermal requirements and adaptation of people with high age.

The third group of paper is dealing with individual aspects of adaptation and the adaptive theory. Related to physiological aspects, Filingeri at al (Filingeri, Zhang and Arens, 2017) addressed adaptation mechanisms, at the psychophysical and neural substrate levels, determining whether the thermoneutral zone shifts along the temperature continuum depending on adaptation to a preceding thermal state. Repeated local warm and cool stimuli (14 mm diameter) to human subjects' palm and forearm of a warm produced local neutral sensations with a range of 8.5°C. The paper also quantifies associated temperature detection thresholds, and the differences between thermal insensitivity and thermal neutrality in both warm and cool conditions. These results support the adaptation theory, and suggest that thermal comfort models must adopt shifting neutral setpoint temperatures, rather than using fixed values as at present (Zhao et al., 2014). With respect to behavioral adaptation, Wang et al. (2020) studied the effects of clothing insulation distributions between body-halves and found significant influences of the clothing distribution, presented as distribution index (DI), on thermal perception. Related to psychological adaptive mechanisms, a new appraoch in the analysis of expectation is presented by Schweiker et al. (2020), confirming the importance of this aspect for thermal perception shown also in earlier studies (Luo et al., 2018b; Cândido et al., 2010; Rajkovich and Kwok, 2003). Beyond considering adaptation as an isolated concept, Schweiker et al. (2020b) compare the concept of adaptation and alliesthesia and present results from an experimental study leading to the introduction of the concept of seasonal alliesthesia.

The following subsections present additional findings from research conducted within the framework of IEA EBC Annex 79 in more detail, covering methodological aspects such as differences in the perception of scales used to assess thermal perception (section 5.2) or the value of alpha in the running mean outdoor temperature (section 5.3), presenting new findings related to long-term clothing trends (section 5.4), a novel approach to create thermosensitivity maps of individual body parts (section 5.5) and findings from cold climates (section 5.6).

5.2. Contextual influences on the perception of scales

The second part of the widely used definition of thermal comfort by ASHRAE states that thermal comfort “is assessed by subjective evaluation” (ASHRAE, 2017). Such subjective response is most often assessed by using rating scales. These scales request respondents to describe their level of thermal sensation, comfort, and acceptability.

The analysis of data collected by means of scales assumes specific distances between verbal anchors. A second assumption considers that relationships between verbal anchors from different dimensions that are assessed (e.g. thermal sensation and comfort) do not change (see (Schweiker et al., 2017) for a longer discussion on the first two assumptions). Third, the responses on scales is considered independent of the context in which they are applied (e.g. the climate zone, season, etc.).

Recent findings suggest, that these three assumption lack validity and need to be assessed themselves (Fuchs et al., 2018; Al-Khatri and Gadi, 2018). Therefore, a large international collaborative questionnaire study was conducted within the framework of IEA EBC Annex 69 in 26 countries, using 21 different languages, which led to a dataset of 8225 questionnaires. The dataset together with an extensive description of its development is published open-access (Schweiker et al., 2019).

Cluster analysis of the dataset showed that only a subset of the respondents perceived the thermal perception scales in accordance with the first two of above described assumptions (Schweiker et al., 2020a). Groups of participants differed significantly in their perception of the scales, both in relation to distances between verbal anchors of a single scale as well as in the relationships between scales. The third assumption was challenged as well, because contextual factors, such as climate, season, and language, influenced the interpretation of scales. In conclusion, context-dependent factors need to be considered when interpreting and reporting results from thermal comfort studies or post-occupancy evaluations. Further work is necessary in order to validate and if necessary modify the use of rating scales and the analysis methods applied to datasets from thermal comfort studies.

5.3. The value of alpha (α) in running mean outdoor temperature

The basic concept of adaptive comfort is that the comfort zone, or range of acceptable indoor temperatures, drifts upwards in warm weather and downwards in cool weather, particularly in environments where occupants have a variety of adaptive opportunities at their disposal. The adaptive comfort model suggests that neutrality of building occupants corresponds to the broad climatic experience to which they have become adapted.

Adaptive comfort theory emphasizes the temporal variability of building occupants' 'comfort set-point,' particularly as it responds to changes in the atmospheric environment outside the building. Our thermal comfort optimum drifts in the direction of the climate to which we have been exposed; as winter turns to summer, so does our comfort optimum move from cool to warm. The thermal adaptive processes are complex and operate on several levels, including physiological (also known as acclimatization), behavioral, and psychological (also known as expectation). Presumably each level of climatic adaptation has its own time-constant, and so the seemingly simple task of fixing the definitive adaptive "exposure time" turns out to be quite complex.

The input variable in the adaptive model is the prevailing mean outdoor air temperature $T_{pma(out)}$, which is based on the arithmetic average of the mean daily temperatures over some period of days. The prescribed expression for $T_{pma(out)}$ in international thermal comfort standards, such as ASHRAE 55 (ASHRAE, 2017) and EN15251 (DIN EN 15251, 2012), is an exponentially weighted, running mean of a sequence of mean daily outdoor temperatures prior to any given day. $T_{pma(out)}$ is expressed as:

$$T_{pma(out)} = (1- \alpha)\ \{T_{t-1} + \alpha T_{t-2} + \alpha^2 T_{t-3} \ldots + \alpha^{n-1}\ T_{t-n}\} \quad (3)$$

where α is a constant (<1) and T_{t-1} is the mean daily outdoor temperature for the previous day, the day before (T_{t-2}), the day before that (T_{t-3}), and so on. Since α is less than unity, this equation emphasizes recent days' temperature more heavily than days further in the past. As α approaches unity the rate of decay in daily temperature weighting coefficients approaches zero, and the calculated value approaches a simple monthly mean temperature. EN15251 recommends an α = 0.8 because, according to Nicol and Humphreys (Nicol and Humphreys, 2010), it maximizes correlation with neutralities for free-running buildings in the SCATs database. ASHRAE 55 recommends values between 0.9 and 0.6 for α, representing a slow- and fast response running mean, respectively. Therefore, while $T_{pma(out)}$ are deemed useful in describing occupant neutralities or changes in clothing in response to prevailing weather conditions, the "true" value of α is debatable.

With an aim to derive the optimal value of α, the IEA-EBC Annex 69 Subtask C database was utilized. In Annex 69 Subtask C, fourteen office buildings from eight countries were studied employing the consistent measurement protocols across all case studies. During the longitudinal monitoring period of at least six months, indoor and outdoor environmental conditions were monitored, and then paired with *right-here-right-now* thermal comfort questionnaires.

In the present statistical analysis, firstly, $T_{pma(out)}$ was calculated using various weights for α (i.e. α =0.6, 0.7, 0.8 and 0.9) for each sample in the database. Then, the calculated $T_{pma(out)}$ values were correlated with (1) the neutral temperatures (calculated by the Griffiths method with G value of 0.5, i.e. $T_n = T_o - TSV/G$, where T_o = indoor operative temperature, TSV = Thermal Sensation Vote) and (2) clothing insulation (*clo*) values. Table 5 presents the correlation of either the neutral temperature (n=8,311) or clothing insulation (n=9,958) with $T_{pma(out)}$ calculated using the four different α values.

Table 5: Correlation of running mean outdoor temperature $T_{pma(out)}$ (calculated using different values of α) with neutral temperature T_n (calculated using the Griffiths constant of 0.5) or clothing insulation (*clo*). $^{**}p < 0.01$

	$T_{pma(out)}$ using α = 0.6	$T_{pma(out)}$ using α = 0.7	$T_{pma(out)}$ using α = 0.8	$T_{pma(out)}$ using α = 0.9
Neutral temperature T_n (n=8,311)	0.548**	0.549**	0.550**	0.550**
Clothing insulation (*clo*) (n=9,958)	-0.585**	-0.586**	-0.588**	-0.589**

The optimum value of α can be determined by inspecting the correlation coefficients. Table 5 indicates that $T_{pma(out)}$ with α = 0.9 maximizes the correlation with both the neutral temperature (0.550) and clothing insulation (0.589). However, the differences are negligible, with the maximum increment in correlation coefficient of only 0.002 (neutrality) ~ 0.004 (clo). The result suggests that the value of α is not critical in the calculation of the prevailing mean outdoor temperature. Indoor neutral temperature and occupant clothing behavior were not particularly sensitive to $T_{pma(out)}$ calculated with different α values. The values of α currently prescribed in the thermal comfort standards seem to be reasonable (satisfactory) predictor of indoor thermal comfort.

5.4. Long-term clothing trends

Our selection of what clothing to wear on any particular day represents an adaptive behavior in response to, and in anticipation of our thermal environment. The clothes we wear in indoor environments are selected on the basis of our expectations of the indoor climates of specific built environments. For example, previous experience of overcooled Australian cinemas prompts me to bring an additional layer of clothing insulation, usually in the form of a sweater which I can remove when I leave the cinema.

But apart from expectations of specific building's indoor climate, a major determinant of clothing insulation behavior is the external climatic environment which operates on various timescales, from diurnal scale (hours), through synoptic scale (days), through to seasonal (months). This nexus between outdoor weather and indoor clothing insulation provides a very useful predictive capability. Indoor clothing levels on any particular day can be predicted with useful levels of skill based on outdoor temperatures which are also predictable with useful levels of skill for short lead-times (hours-to-days).

The quantitative expression of clothing insulation, *clo* units (0.155 m^2•K W^{-1}) is one of the six key inputs to contemporary heat-balance models of thermal comfort, namely PMV/PPD and SET. Whilst not explicitly declared as an input to modern adaptive comfort models, clothing insulation is *implicitly* accommodated in the adaptive models' independent variable (prevailing outdoor temperature). Clothing insulation is difficult to measure accurately (thermal manikin is required), and therefore current engineering practice is based on simplistic look-up tables for "typical summer and winter clothing ensembles" that are appended to the major comfort standards. A default value of 0.5 *clo* is often assumed for summer clothing, while 1.0 *clo* is the default wintertime estimate.

A more climatically nuanced approach to predicting the clothing insulation worn by building occupants is based on a statistical clothing model such as that found in ASHRAE Standard 55 (ASHRAE, 2017) (Figure 8). That particular model has the structure of an adaptive comfort model, with a climatic input parameter on the x-axis, and an estimated clothing insulation value (*clo* units) as the dependent y-axis variable. The model was based on analysis performed by Schiavon and Lee (Schiavon and Lee, 2013b) using clothing observational data contained in the first thermal comfort field study database (ASHRAE RP-884) which comprised field studies from the 1980s and 90s (de Dear, 1998).

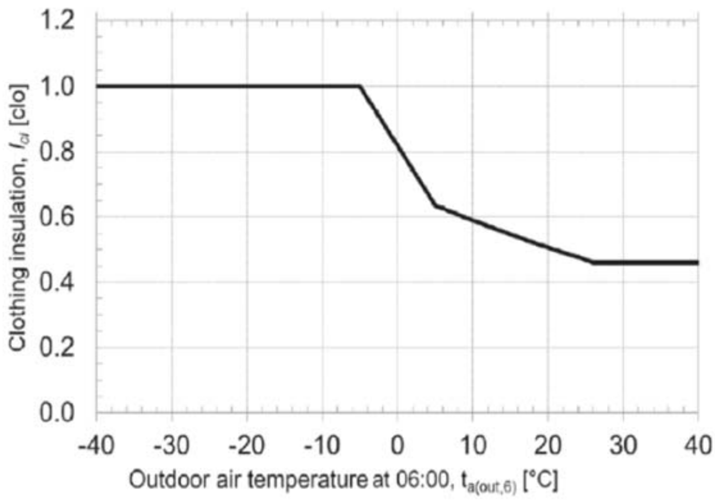


Figure 8: Standard clothing insulation prediction model (source: ASHRAE Standard 55-2017)

The **aim** of the present study in Sydney Australia was to develop a predictive clothing model based on a comprehensive clothing database for Sydney. A longitudinal field study was conducted to develop a database of clothing levels of Sydney office workers. Sydney is located in the humid subtropical climate zone where summer daily maximum temperature falls between 26-28°C and winter daily maximum temperature falls around 17°C.

The **method** was based on unobtrusive observations of clothing worn by office workers at their workstations. The clothing garment lookup table in ASHRAE Standard 55-2017 was used throughout this study. Although chair insulation is recorded in the observation, the clothing value in this study excludes the chair insulation to allow comparison with the previous model built by Schiavon and Lee (Schiavon and Lee, 2013b). Observations were conducted during office hours for a large financial institution located in the Sydney Central Business District from May 2018 until December 2018 to observe late autumn, winter, spring, and summer clothing levels.

Throughout the observation period, daily minimum and maximum outdoor temperatures forecasted by the Australian Government Bureau of Meteorology website on the day of the observations were recorded. Indoor operative temperatures within the zones of subjects observed in this study were recorded at 10am on each day of the survey period.

Results indicate a significant correlation between forecast 6am outdoor air temperature for the day of clothing observations and the clothing insulation worn by office workers. Figure 9 illustrates the current sample of clothing insulation estimates against outdoor 6am temperature, as well as the *clo* level predictions from the existing ASHRAE Standard 55-2017 clothing model for comparison. Clearly the ASHRAE model under-predicts indoor clothing insulation levels worn by Sydney office workers.

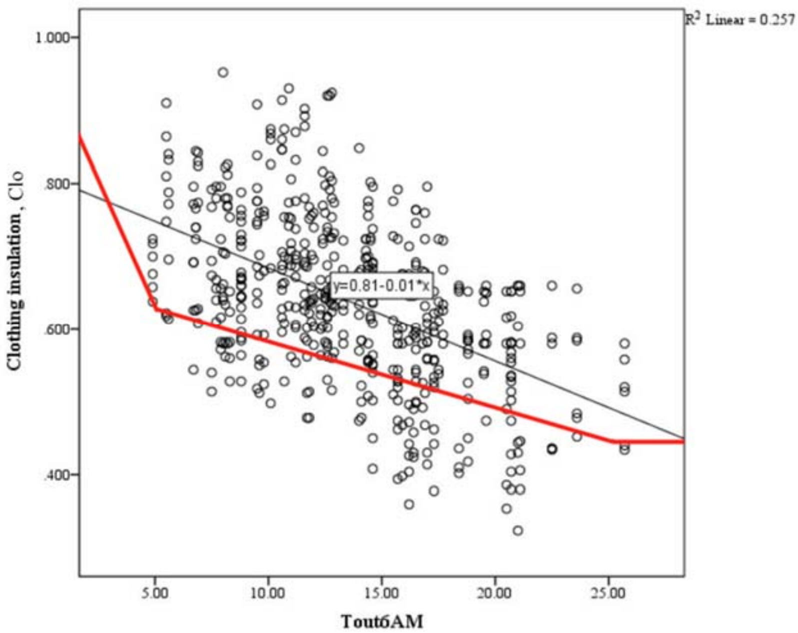


Figure 9: Comparison between the ASHRAE 55-2017 clothing model (in red) and the clothing insulation level (*clo*) observed in a Sydney office building

Whether this discrepancy between Sydney and the ASHRAE clothing model is the result of cultural differences between Sydney office workers and the subjects represented in the ASHRAE

Comfort Database, or simply differences in clothing behavior and fashions between the 1980s/90s and the present, remains moot.

5.5. Thermosensitivity maps for individual body parts

In order to efficiently apply local heating and cooling to the human skin, we performed a series of studies to examine thermal sensitivity to small-scale warm and cool stimuli. We began with a sensitivity analysis of hand and foot (Filingeri, Zhang and Arens, 2018), provided warm and cool sensitivity mapping for hand and foot, and then mapped the entire body (Luo et al., 2020). These papers show a wide variation in thermal sensitivity across the body. The results can be used for the efficient personal comfort system designs, or heated and cooled wearables.

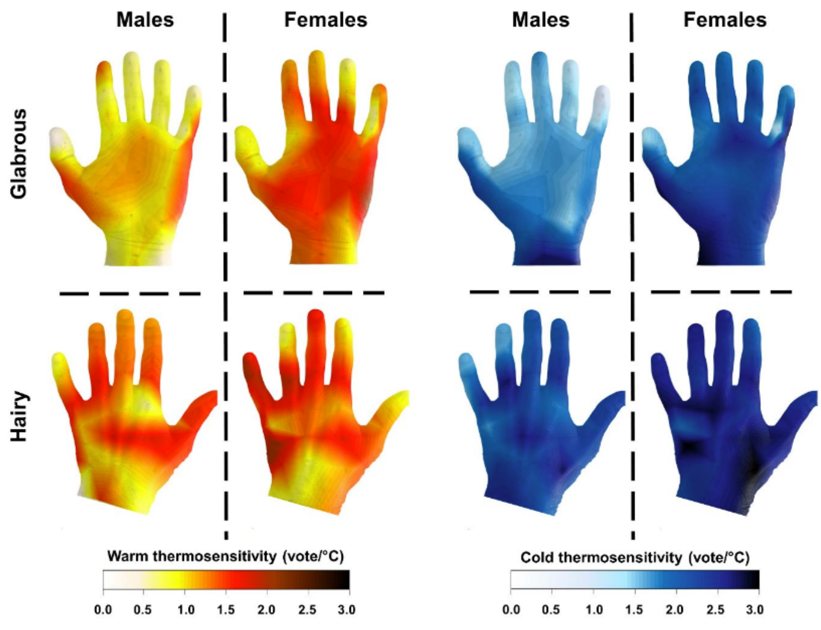


Figure 10: Warm and cold thermosensitivity maps for hand and foot of males and females (Filingeri, Zhang and Arens, 2018)

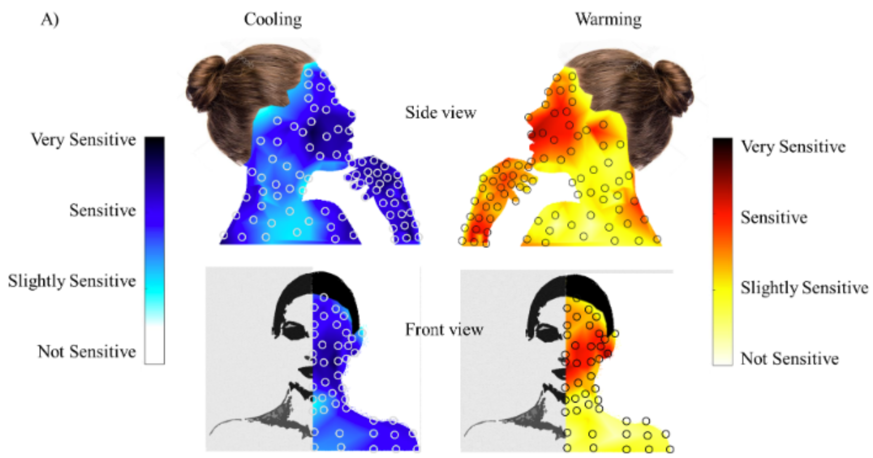


Figure 11: Warm and cold thermosensitivity maps for head and neck (Luo et al., 2020)

5.6. Cold climates

While the large majority of research related to thermal adaptation focusses on adaptation to warm conditions, adaptation in cold climates is another important field of research. Therefore, this section summarizes findings related to cold climates.

5.6.1. Acclimatization

Wang and Ji (2016) found that people easily accept cool indoor environment with lower expectation when the outdoor temperature is decreasing. Therefore, they feel warmer at the same indoor temperature. When the outdoor temperature is similar, the skin temperatures and heart rates of the subjects drop as the indoor temperature decreases. When the indoor temperature is constant, the arm skin temperatures and heart rates of the subjects increase as the outdoor temperature decreases. This indicates that the subjects have thermal adaptation in cooler environment when the outdoor temperature is lower. The experiment provides a supportive evidence for psychological adaptation and physiological acclimation of people in severe cold zone.

Due to the low outdoor temperature in severe cold area, people spend most of time in the room. Therefore, the indoor thermal environment in winter has a greater impact on short-term acclimatization. Wang et al. (2018) carried out a long-term field study on human thermal adaptation in winter in the severe cold area. They found that the participants were more sensitive to temperature variations at the early heating phase (EH). From EH to late heating phase (LH), they are acclimatized to higher temperatures. Therefore, although the occupants felt warm, they would not like the indoor temperature reduced

In the same climate, different building environments also contribute to the physiological acclimatization. For example, Yu et al. (2012) found that compared with people living in air-conditioned (AC) environments, people living in naturally ventilated (NV) environments had a higher skin temperature in neutral environment, faster skin temperature regulation speed and higher sweat rate in the process of 'heat shock'.

5.6.2. Thermal history

Seasons also contribute to the human thermal history. Wang et al. investigated thermal comfort of types of building environments in severe cold area in different seasons. The neutral temperature in different seasons were different. It was noteworthy that the neutral temperature in summer and spring were higher than those in winter (Wang et al., 2010, 2014). And the neutral temperature was close to the average indoor temperature (Wang et al., 2014; Wang, 2006).

Ning et al. (2016) conducted a field research on thermal adaptation in university dormitories in Harbin. The results showed that when participants adapted to a high indoor temperature physiologically and psychologically during space heating, they were thermally sensitive to indoor temperature fluctuations. Furthermore, they were more sensitive to the temperature reduction.

Ning et al. (2016a) investigated two types of residential heating environments in Harbin, respectively warm exposure and cool exposure environments, to discover relation between different indoor heating temperatures and human thermal responses. They found occupants could actively adapt to indoor heating environments. The neutral temperature was 1.9℃ higher in warm exposure than cool exposure sample after clothing insulation standardization, which suggests the possible effects of physiological and psychological adaptation.

Wang et al. (2017) studied the thermal adaptability of residents in the whole heating season. The results showed that the thermal neutral temperature had an upward tendency with the increasing indoor air temperature.

Climate and indoor environment affect human adaptability together. Field study in dormitory by Ning et al. (2016) suggested that the past indoor and outdoor thermal experiences have influence on human thermal adaptation. In the early heating period, human thermal adaptation was mainly affected by the outdoor climate. From mid heating period to late heating period, thermal adaptation was mainly affected by the indoor thermal environment.

5.6.3. Expectation

Luo et al. (2016, 2018b) carried out online questionnaires successively to collect the comfort expectations of people in the north and south of China for indoor thermal environment in winter. They found that Long-term comfortable thermal experiences lift occupants' thermal expectation, while non-neutral thermal environment can stimulate thermal adaptation. Wang et al. (Wang, Ji and Su, 2018) compared voting results of human thermal response in different heating stages in severe cold area. It was found that the frequencies of expecting “no change” at warm side were higher than cool side, which indicated that people living in the warm environment had high expectation for thermal environment.

5.6.4. Non-uniform thermal environment

Wang et al. (2013) found that, in the slightly cool and neutral asymmetrical cold radiation conditions, the head and back thermal sensation had no significant difference; while the hand, arm, lower leg and overall thermal sensation were different. In the neutral non-uniform condition, overall thermal sensation votes were lower than those in the uniform condition, although the mean indoor temperature of the former condition was higher. The temperature difference between head and foot increased for the subjects near the exterior window and wall because of cold radiation, which led to the people felt cold at their legs and the overall thermal sensation and comfort decreased.

The cold radiation from the outer window might result in the decreases of local skin temperatures, especially for calf and back. The mean skin temperature is 33.0℃ when subjects felt thermally neutral for the whole body. With the increase of the distance between the subjects and the window, the votes of skin temperature, thermal sensation and thermal comfort will increase. The changes of legs in thermal sensation and thermal comfort were most significant. Overall thermal sensation, mean skin temperature and heart rate showed a good linear relationship (Wang et al., 2013).

5.6.5. Influence of different heating modes on human thermal comfort

Wang et al. (2015) investigated human thermal physiological and psychological responses under different heating environments. The subjects' skin temperatures, heart rate and blood pressure were significantly affected by the type of heating environment. Ankle temperature had greatest impact on overall thermal comfort relative to other body parts, and a slightly cool FH condition was the most pleasurable environment for sedentary subjects. The overall thermal sensation, comfort and acceptability of floor heating (FH) system were higher than that of radiant heating (RH) system. However, the subjects of FH felt drier than that of RH, although the relative humidity in FH environments was higher than that of the RH environment.

Cao et al. (2014) conducted a winter field study in Beijing, focusing on the comparison of thermal comfort between district heating (DH) and individual heating (IH) residences. They found that the thermal sensation of DH users changed to a greater extent compared to IH users when the thermal environment deviated from the neutral condition.

Table 6: Regression equations.

		Equation	R^2
Wang (2018)	Residence	$MTS\ (EH) = 0.2327\ t_a - 5.0232$	0.4382
		$MTS\ (MH) = 0.1456\ t_a - 3.4144$	0.3953
		$MTS\ (LH) = 0.1733\ t_a - 3.9993$	0.4412
	Office	$MTS\ (EH) = 0.3163\ t_a - 6.6555$	0.7696
		$MTS\ (MH) = 0.1743\ t_a - 3.2717$	0.4266
		$MTS\ (LH) = 0.1242\ t_a - 2.2489$	0.3426
	Dormitory	$MTS\ (EH) = 0.4245\ t_a - 9.1086$	0.7143
		$MTS\ (MH) = 0.1676\ t_a - 3.6265$	0.4003
		$MTS\ (LH) = 0.1674\ t_a - 3.6601$	0.1606
	Classroom	$MTS\ (EH) = 0.1435\ t_a - 2.5939$	0.4856
		$MTS\ (MH) = 0.1480\ t_a - 2.8380$	0.7920
		$MTS\ (LH) = 0.1452\ t_a - 2.7782$	0.5913
Ning (2016)	Late autumn(LA)	$MTS = 0.198\ t_a - 4.249$	0.665
		$PMV = 0.280\ t_a - 6.431$	0.985
	Early heating period(EH)	$MTS = 0.340\ t_a - 7.106$	0.724
		$PMV = 0.245\ t_a - 5.639$	0.984
	Mid heating period(MH)	$MTS = 0.176\ t_a - 3.867$	0.561
		$PMV = 0.244\ t_a - 5.535$	0.986
	Late heating period(LH)	$MTS = 0.132\ t_a - 2.798$	0.448
		$PMV = 0.227\ t_a - 5.332$	0.953
	Early spring(ES)	$MTS = 0.248\ t_a - 5.603$	0.581
		$PMV = 0.277\ t_a - 6.615$	0.964
Ning (2016b)	Cool exposure	$AMV = 0.1848\ t_a - 3.7411$	0.6865
	Warm exposure	$AMV = 0.1374\ t_a - 3.1281$	0.6794
Cao (2014)	Individual heating(IH)	$TSV = 0.172\ t_a - 3.204$	0.8120
	District heating(DH)	$TSV = 0.211\ t_a - 4.647$	0.8821

6. New approaches for modelling individual adaptive mechanisms

6.1. Introduction

Halawa & van Hoof (2012) and Parsons (2014) state, that there is a need to combine the adaptive and heat balance approach to increase the predictive capability of thermally comfortable conditions. In line with this statement, several attempts have been published previously. Fanger and Toftum (2002) introduced an expectancy factor to adjust for discrepancies between observed and predicted sensation votes. As such, their extended PMV (ePMV)-model considers psychological adaptive processes and ignores the behavioral and physiological adaptive processes. V.d. Linden et al. (2008) found that adjusting the clothing level according to the outdoor conditions as given by de Carli & Olesen (2007) combined with the PMV-approach explains the adaptive comfort equation for a moderate climate. Parsons (2014) presents the Equivalent Clothing Index, which represents the equivalent effects of various behavioral opportunities in terms of the clothing parameter in the heat balance equation and is focused on behavioral adaptation as well. Yao et al. (2009b) developed the adaptive PMV (aPMV) model, which is a "black box" approach to incorporate all three processes into one factor in a similar way as done by ePMV, by introducing an adaptive coefficient. Orosa et al. (2011) attempted to combine the PMV model with the adaptive model based on the field survey data to make up for the deficiency of lacking heat balance calculation in the existing adaptive thermal comfort model. Gao et al. (2015) introduced the eSET and aSET-models, which are applications of the concepts of ePMV and aPMV to the SET-model by Gagge [**Fehler! Verweisquelle konnte nicht gefunden werden.**]. Schweiker & Wagner (2015) proposed a framework of the adaptive heat balance model which presented ideas how to connect the PMV model and the three adaptive mechanisms (physiological, psychological and behavioral) mentioned in the thermal adaptation theory, so that they can be analyzed separately.

Regarding the above, all of these studies have some enlightening significance. Still, the direction of thermal comfort model in the future is a crucial issue requiring further work. In the following, recent approaches to implement individual adaptive processes into existing heat balance models are described.

6.2. The adaptive thermal heat balance model (ATHB) based on PMV and SET

The ATHB approach (Schweiker and Wagner, 2017, 2015) offers a framework to include individual processes of thermal adaptation (behavioral, physiological, psychological) into the heat balance approaches by Fanger (Schweiker and Wagner, 2015), $ATHB_{PMV}$, and the SET model by

Gagge (Schweiker and Wagner, 2017, 2015), $ATHB_{SET}$. Thereby, the original equations and calculation routines remain unchanged. Previous approaches, aiming to bridge adaptive comfort model and heat balance approach, such as ePMV (Ole Fanger and Toftum, 2002) and aPMV, (Yao, Li and Liu, 2009b) adjusted the output of the PMV calculation. In contrast, the ATHB approach adjusts the input values according to the level of adaptation per adaptive mechanism. In short, Schweiker and Wagner (Schweiker and Wagner, 2015) modeled

a) behavioral adaptation by adjusting the clothing insulation level based on the running mean outdoor temperature (T_{rm}) according to

$$CLO_{adapt} = 1.252594 - 0.03 * T_{rm} \; with \; 0.46 < CLO_{adapt} < 1 \quad (4)$$

b) physiological adaptation by adjusting the metabolic rate related to the given activity (MET_0) based on T_{rm} through

$$MET_{adapt} = MET_0 - 0.017756 * (T_{rm} - 18) \; with \; MET_{adapt} \geq MET_0 \quad (5)$$

c) psychological adaptation by adjusting the metabolic rate either based on a fixed value related to a specific and fixed psychological effect such as the number of persons in a room or a variable value depending e.g. on indoor operative temperature.

Figure 12 shows the effect of applying the ATHB approach to PMV. The PMV (without adjusting clothing level) predicts a neutral operative temperature independent from the running mean outdoor temperature (line a)). Adding step-by-step the individual adaptive mechanisms, the curve bends and finally follows a similar trend as the adaptive model in its version from (CEN 15251, 2012). At the same time, it is possible to show the effect of variations in all indoor environmental parameters included in the PMV model (i.e. air temperature, radiant temperature, relative humidity, and air velocity) individually or in combination. Exemplarily, Figure 13 shows variations of air velocity. It should be noted, that the derivation of above equations and their consequences was not based on the objective to "fit" the ATHBPMV to the adaptive regression curve. The equations were formulated based on theoretical thoughts and the coefficients based on analysis of empirical data from experimental data. At the same time, more research is necessary to validate the model and to improve parts of its assumptions, e.g. related to the effect of psychological adaptation.

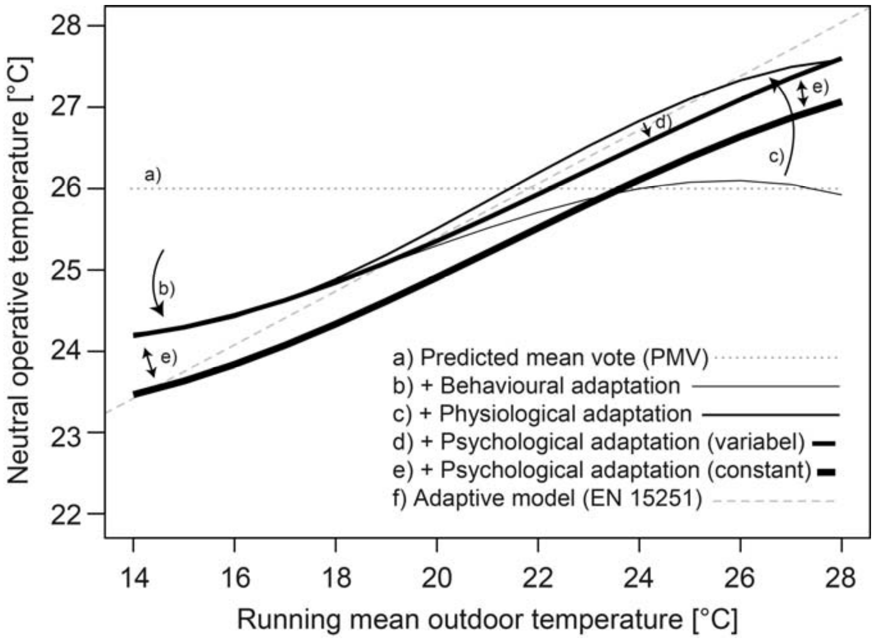


Figure 12: Effect of step-wise application of the $ATHB_{PMV}$ approach based on (Schweiker and Wagner, 2015).

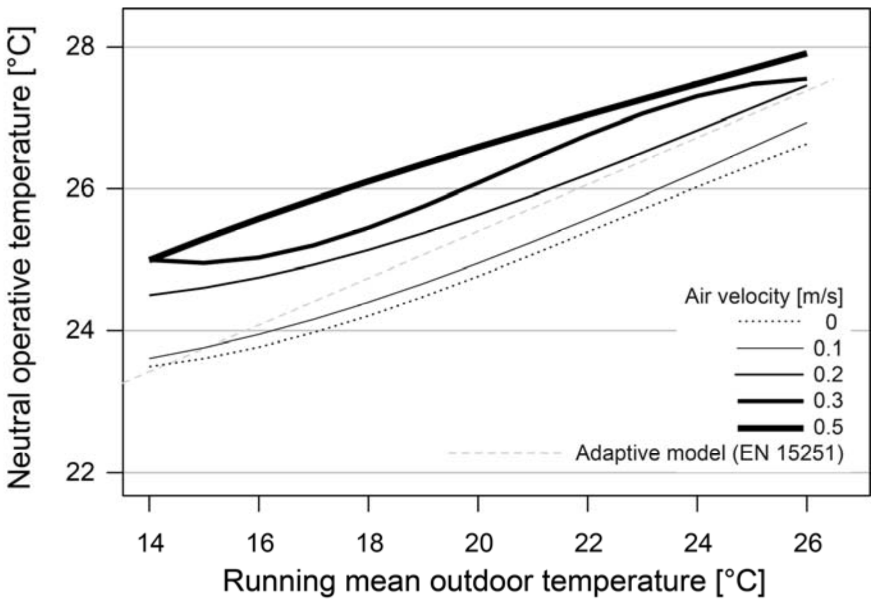


Figure 13: Effect of variations in air velocity on the predicted neutral operative temperature by the $ATHB_{PMV}$ approach (Schweiker and Wagner, 2015).

6.3. Thermoneutral zone (TNZ) and ATHB

The thermoneutral zone (TNZ) model (Kingma et al., 2014) is a steady state heat balance model, which combines internal (within body), and external (from body to environment) heat balances. The TNZ model can be used to find the combinations of body core temperature, skin temperature and operative temperature that 1) support both internal and external heat balance, and 2) are physiologically feasible. These combinations then form the traditional physiological thermoneutral zone, that is, “the range of ambient temperature at which temperature regulation is achieved only by control of sensible (dry) heat loss, i.e. without regulatory changes in metabolic heat production or evaporative heat loss”.

Heat production, body tissue insulation, body core, and skin temperatures affect the internal heat balance, while heat production, clothing insulation, air speed, skin wettedness, relative humidity, skin and operative temperatures affect the external one. The definition of physiologically feasible solutions considers body core temperature within a specific range (e.g. 36.5°C to 37.5°C), and constrains body tissue insulation to be within thermoregulatory bounds (e.g. highest body tissue insulation for maximal vasoconstriction and lowest body tissue insulation for maximal vasodilation). Previous research introduced the distance ($dTNZ_{op}$) of the actual (measured) operative temperature (T_{op}) to the operative temperature in the center of the TNZ ($T_{op\ centroid}$) and suggests a relationship between $dTNZ_{op}$ and the thermal sensation vote (Kingma et al., 2017; Schweiker, Kingma and Wagner, 2017).

In the same way, input values for PMV and SET could be adjusted to include the effect of individual adaptive mechanisms (see section 6.2), the TNZ model offers similar opportunities. At the same time, additional input parameters such as age, sex, and body tissue insulation can be varied when using the TNZ model. Therefore, a combination of the ATHB approach and the TNZ approach might offer the potential to look at the combined effects of individual differences and adaptive processes in thermal sensation and thermal satisfaction.

Such combination was recently discussed by Schweiker et al. (2018), who showed, that the probability density functions based on predictions by the ATHB*TNZ approach are able to replicate individual differences found in field studies and the adapted $T_{op\ centroid}$ aligns with the adaptive regression curve.

6.4. The Predicted Thermal Sensation model (PTS) based on SET

A new model is proposed based on the Standard Effective Temperature (SET), namely the Predicted Thermal Sensation (PTS) model. Since Gagge modified many versions of SET, the most popular version issued in 1986 (Gagge, Fobelets and Berglund, 1986) was selected for calculation here. Actually, the concept of PTS was first presented by McIntyre (1980) but without receiving much attention. It revealed that there was a linear relationship between thermal sensation and SET. It is brought up again here and committed to some further development and enrichment. The thermal sensation vote (TSV) from large amounts of survey data was used to build the relationship with SET. So a more reliable thermal prediction can be applied under the premise of a heat balance calculation with higher accuracy. Figure 14 shows the hypothetical figure of PTS model.

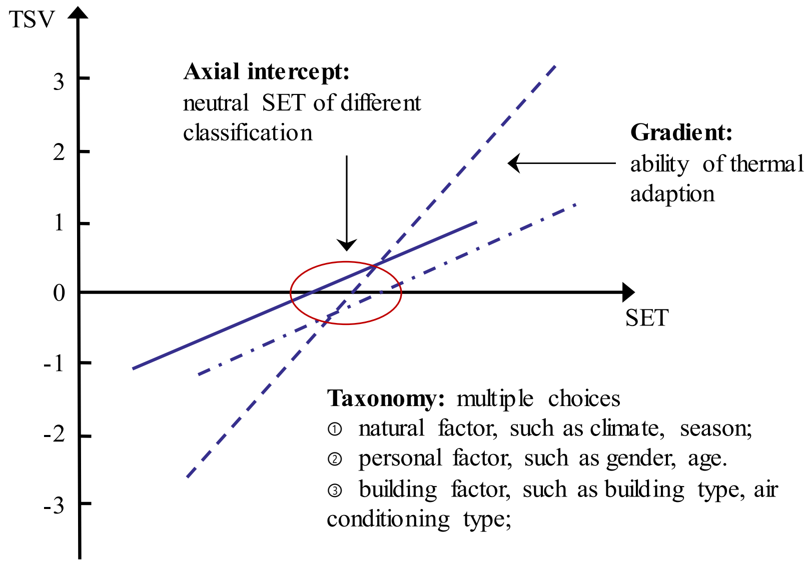


Figure 14: The hypothetical figure of PTS model.

Unlike the traditional PMV model in which the relationship between parameters and TSV are constant, the new PTS model has the advantage of reflecting independent characteristics of different classifications such as natural, personal, and building related factors. It can present the adaptability differences of different populations. TSV is supposed to have a linear relationship with SET here. It's worth noting that the fitted line can give a clear physical definition. The slope of the line can represent the thermal adaptive ability of corresponding classified populations. The smaller the slope is, the narrower the range of TSV variation within the same SET range, and the stronger the adaptive ability is. Conversely, the bigger the slope is, the weaker the adaptive ability is. In addition, the horizontal intercept of the line can reflect the neutral SET, which is equal to the commonly used neutral temperature if other parameters are of standard values.

The PTS model is flexible in taxonomy. For example, three types of categorical factor can be considered: natural factor, personal factor and building factor. It can reflect the thermal adaptability of people who acclimated to a specific climate if it is classified according to the climatic zones. It can reflect the characteristics of different groups if it is classified according to gender or age. And it can present the influences of different air conditioning types on thermal sensation if it is classified according to the air conditioning. The actual demand is the one which decides the classification criteria of the PTS model. Users can be provided more choices and focused on some personalized evaluation.

To explore the PTS models of worldwide major climate classifications, all data in ASHRAE Global Thermal Comfort Database I were included because of the high quality of data with SET and TSV in pairs and the relatively comprehensive details. After initial filtration, 24,020 samples covering 12 climate types were further analyzed. The data were from office buildings with air conditioning, natural ventilation or running in mixed-mode, which, however were not distinguished here. It referred to nearly the main climate type worldwide in Köppen climate classification. Table 7 shows the sample size of each climate classification and the source of data. As TSV involved in the survey was a classified variable, the minimum sample size with an error of 5% under 95% confidence interval was calculated to be 384 according to Kotrlik and Higgins (2001). The sample size of each group of data met the requirement. The linear regression was exerted on the raw data of each climate type. And the PTS models of different climate types and the distributions of data are shown in Figure 15, in which the similar climate types are put together for comparison.

Table 7: Sample size and data source of different climate classifications.

Climate classifications	Sample size	Data source: countries and regions
Desert	2014	Karachi Pakistan, Quettar Pakistan
Hot arid	1214	Kalgoorlie-Boulder Australia
Semi-arid high altitude	1116	Saidu Pakistan
Semi-arid midlatitude	1069	Peshawar Pakistan
Tropical savanna	6962	Honolulu Hawaii, Townsville Australia, Darwin Australia, Bangkok Thailand
Humid subtropical	946	Brisbane Australia, Sydney Australia
Humid midlatitude	1927	Ottawa Canada, Grand Rapids MI USA
Wet equatorial	812	Jakarta Indonesia, Singapore
Continental subarctic	869	Montreal Canada
Mediterranean	4560	Athens Greece, San Francisco Bay Area USA, San Ramon CA USA, Antioch CA USA, Auburn CA USA
Temperate marine	1058	Melbourne Australia
West coast marine	1473	South Wales UK, Merseyside UK, Oxford UK

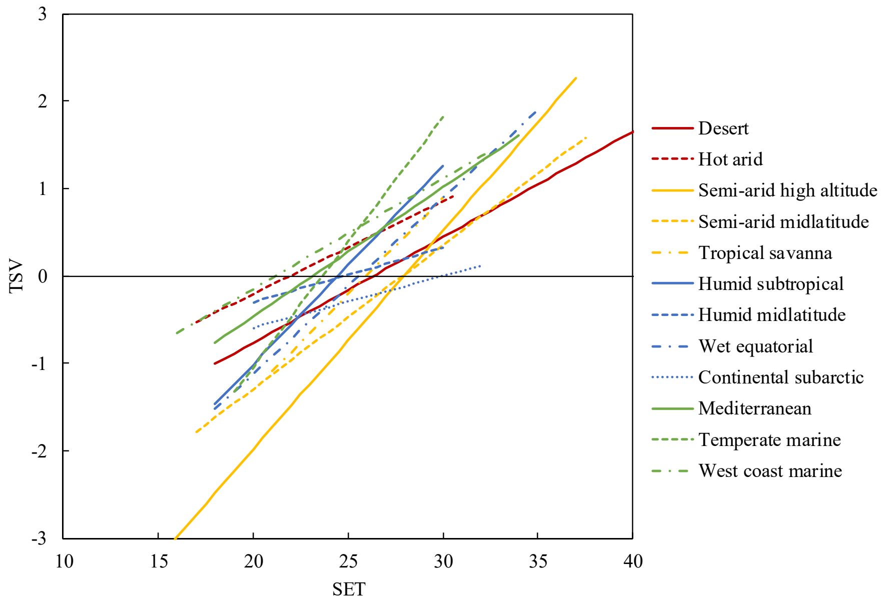


Figure 15: PTS models of different climate classifications

7. Assessing the accuracy of new models

As described in section 6, the number of alternative approaches and models to adaptive thermal comfort is increasing. This raises questions towards the accuracy of these models and the benefits of new modelling approaches for the prediction of comfortable conditions. This section outlines previous research to assess the accuracy of existing models together with recommended procedures for the assessment of future models together with a case study. This section ends with a discussion on the true value for the assessment of any models accuracy.

7.1. Assessing the accuracy of thermal comfort models

Assessing the discrepancy between observed and predicted thermal sensation votes is usually done for a study proposing a new concept or regression line based on statistical parameters of the regression model. At the same time, few studies looked at external validation processes, i.e. analyzing the performance of a thermal comfort model on data not used to apply such model.

Among those few studies, Humphreys & Nicol (2002) analyzed the mean bias between observed and predicted thermal sensation vote:

$$meanBIAS_j = mean(PSV_{j,i} - ASV_i) \quad (6)$$

with j denoting the thermal sensation index and i the individual vote. Their analysis showed substantial bias of the PMV model, which led them to question its applicability for the ranges of input values described in (ISO 7730, 2005).

Schweiker & Wagner (2015) calculated the true positive rate (TPR), for thermal sensation votes predicted by PMV and their $ATHB_{PMV}$, as well as the TPR, true negative rate (TNR), and the accuracy (ACC) predicted by PMV, $ATHB_{PMV}$, and adaptive comfort model. The dataset used was their own dataset as well as data from the ASHRAE RP-884 database. For their own dataset, PMV and $ATHB_{PMV}$ had a similar TPR for thermal sensation around .5, while the TPR of PMV was around .3 (i.e. 30% of votes predicted correctly) and that of $ATHB_{PMV}$ around .35 for ASHRAE RP-884. For thermal acceptance, TPR was highest for the adaptive comfort model for their own dataset and the subset of ASHRAE RP-884 with the natural ventilated (NV) buildings, but highest for $ATHB_{PMV}$ for the air-conditioned (AC) buildings. In contrast, the TNR was lowest for the adaptive comfort model for their own dataset and NV data, but highest for AC data.

Recently Cheung et al. (2019) also found a low accuracy around .3 of PMV based on the data from ASHRAE Global Thermal Comfort Database II.

7.1.1. *Accuracy of Predicted Thermal Sensation model (PTS) based on SET*

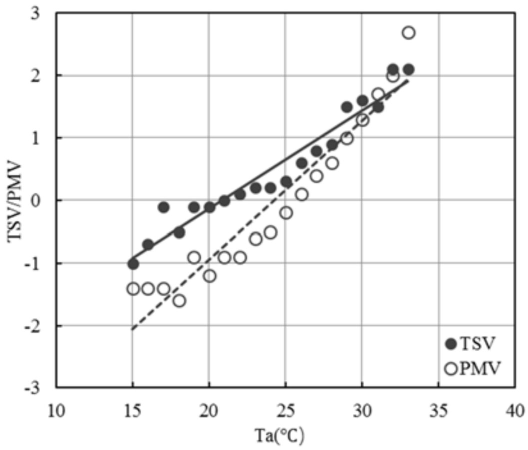
In order to verify the accuracy of PTS models of different climate types, field studies from different countries in four continents were chosen as the representative cases of four climate types. All the data of TSV, PMV and SET were acquired from the ASHRAE global thermal comfort database II. And data for these four cases data were not included in the establishment of the PTS model of different climate classifications. The relationship between TSV and PMV, as well as the relationship between TSV and PTS were compared, so as to illustrate the advantage of PTS model in practical application. Figure 16 shows the comparison results of the case validation. To make the results more concise and clear, the data were divided by 1 ^{o}C air temperature interval in the figures used PMV prediction, while the data were grouped by 1 ^{o}C SET interval in the figures used PTS prediction. The average values of TSV and PMV in each temperature/SET interval were used for the comparison. And the PTS value was calculated with the corresponding regression model, which has a general expression:

$$PTS = a \times SET + b \quad (7)$$

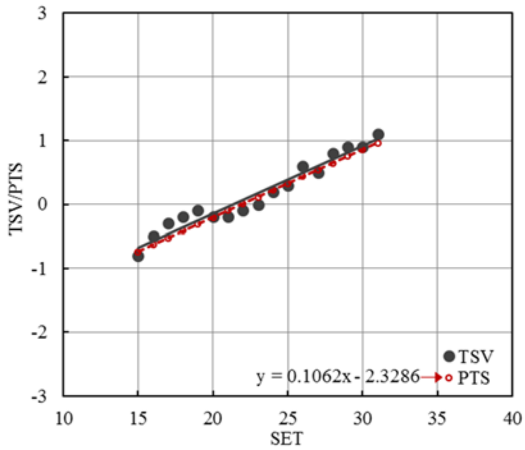
where "a" is the gradient of the fitted line, "b" is the intercept which is usually negative.

In most cases, PMV was difficult to effectively predict TSV, especially in some extreme climates. The PMV values were small in the climate types of desert and humid subtropical; they were large in the climate type of semi-arid midlatitude; while there was a scissors difference between PMV and TSV in Mediterranean climate. However, the PTS model which has a higher flexibility could make more accurate prediction of TSV whatever the climate type it was. It is obvious shown in Figure 16 that the predicted value is almost identical with the actual value, which gives supports for the accuracy and practicability of this model. It is of great significance to provide guidance to the thermal sensation prediction in an actual indoor environment.

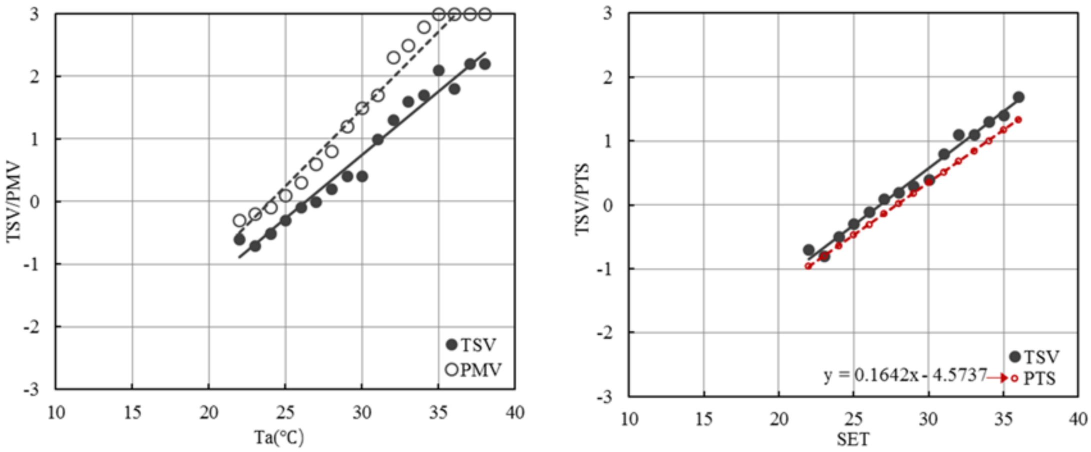
The relationship between TSV/PMV and T_a



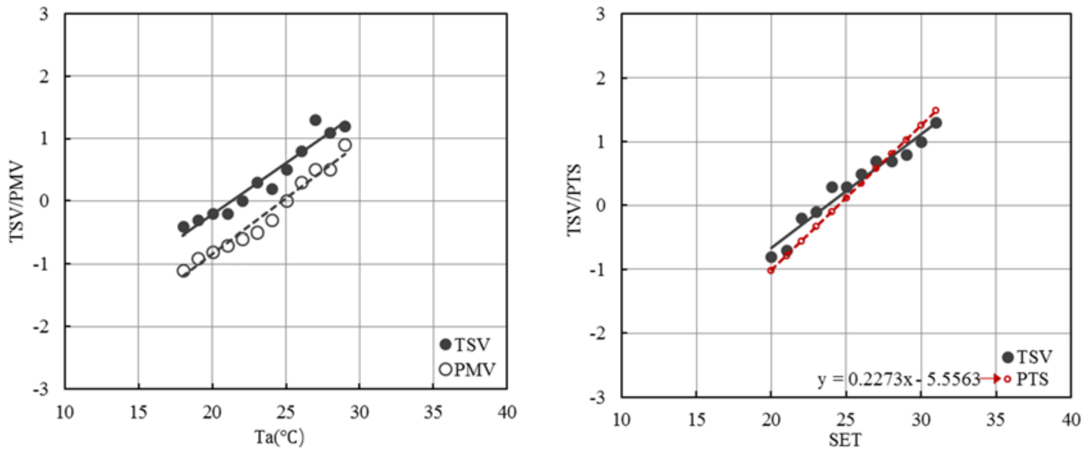
The relationship between TSV/PTS and SET



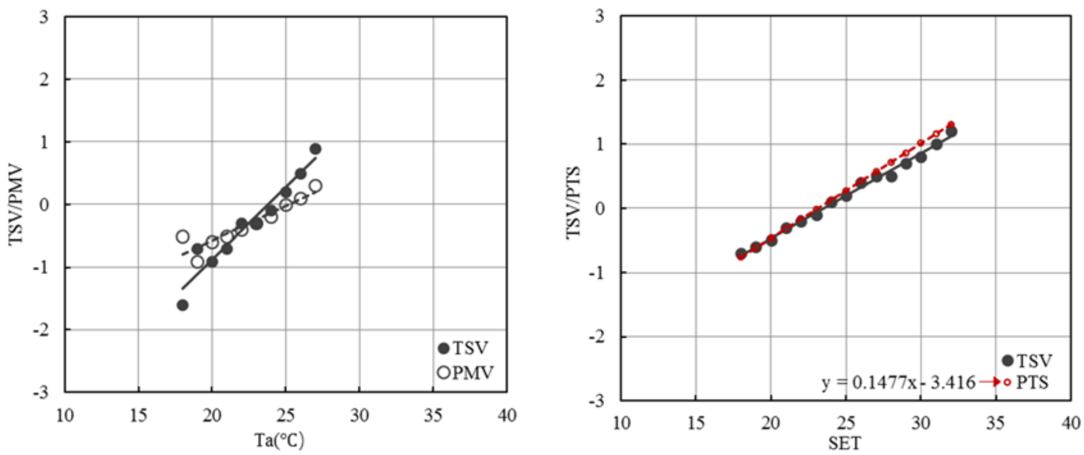
Hot arid climate, Tunisia (Bouden and Ghrab, 2005)



Semi-arid midlatitude climate, India (Indraganti et al., 2014)



Humid subtropical climate, Australia (Tartarini, Cooper and Fleming, 2018)



Mediterranean climate, UK (Oseland, Reardon and Langkilde, 1998)

Figure 16: Case validation of PTS model and the comparison between PTS model and PMV model

7.1.2. Comparison of accuracy between several existing and new comfort indices

Schweiker & Wagner (2017) compared the accuracy of 9 thermal sensation indices, PMV, PMV_{adj}, aPMV, ePMV, $ATHB_{pmv}$, PTS, aPTS, ePTS, and $ATHB_{pts}$. They calculated two different evaluation parameters in order to compare the predicted sensation votes (PSV) to the actual sensation votes: the mean bias based on Humphreys & Nicol (2002) and the true positive rate (TPR).

The true positive rate presents the proportion of the true predicted cases, where the actual sensation vote was equal to the binned predicted sensation vote (Schweiker and Wagner, 2015) and was calculated according to

$$TPR_j = \frac{\sum_{i=1}^{k} TP_k}{n} \quad (8)$$

with j denoting the thermal sensation index, k the categories of the sensation scale (e.g. cold), n the total number of votes, and TP those cases, where the binned predicted sensation vote is equal to the actual sensation vote.

In this way, the mean bias is a measure of performance how well an index predicts the sample mean, while the true positive rate is a measure how well the index predicts individual thermal sensation votes.

The analysis of field data from 2 naturally ventilated and 4 mixed mode office buildings showed, that the ATHB-indices either based on Fanger's PMV (ATHBpmv) or Gagge's SET (ATHBpts) outperform the other 8 indices in terms of predicting thermal sensation. The effect of false assumption is larger for PMV-based models compared to SET-based models. In addition, customization revealed no clear distinction between naturally and mixed mode buildings, which suggest other factors to be more influential.

7.2. Short review of methods used for uncertainty estimation

7.2.1. Sources of uncertainties

According to JCGM 100 (2008a) the notion of 'uncertainty' means there is a doubt about the reliability of obtained model's input and/or output. The three main sources of uncertainties can be categorized as follows:

1. model framework uncertainty: result from incomplete data or insufficient knowledge about the factors that determine the system's behaviour. These uncertainties may be the case when the model is oversimplified, and some important interrelations or factors have been assumed as insignificant and excluded from the model.
2. model input uncertainty: result from measurement error (systematic or random error), averaging or any further processing of the data used as the input data model.

3. model niche uncertainty: result of misuse of the model, i.e. using the model for the cases it is not supposed to be used or without taking into consideration conditions or assumptions, the model was based on. These uncertainties can also take place when several models are combined to form a new one without amendments made to the scales, ranges and etc.

The existence of one type of uncertainty does not necessarily implies that it is the only one. A model might have all three types of uncertaincy.

Assuming the model is correctly used, i.e. no model's niche uncertainties, there will be a relationship between model framework uncertainty and model input uncertainty. As the model becomes more complex (i.e. increase in the number of input), the framework uncertainty decreases but there is an increased in input uncertainty. Therefore, there is an optimal level of model complexity, which can be ascertained through sensitivity and uncertainty analysis.

7.2.2. Methods used for uncertainty estimation

Model uncertainty analysis may combine the results of the model sensitivity analysis and the input uncertainty to ascertain the output uncertainty. The model sensitivity analysis will determine which input have the greatest and the least impact on the output.

There are two methods for estimating output uncertainty.

The first method is described by Saltelli et al. (2009). The result of global sensitivity analysis, 'mean ± one standard deviation' ($\mu \pm \sigma$) can be used as a measure of uncertainty in the output. The value of standard deviation (σ) tells how the data is spread around the mean (μ), i.e. any single value has an uncertainty equal to the standard deviation. Usually, two-thirds of all values fall into plus/minus one standard deviation. Therefore $\mu \pm \sigma$ uncertainty can be used as an estimate of the true mean of the distribution.

The second method is described in GUM JGGM 101 (2008b). The output uncertainty may be estimated by applying either propagation of input uncertainties values or propagation of input distributions.

Propagation of uncertainties method 'propagates' the existing uncertainty $u(x_1), u(x_2), \dots, u(x_N)$ associated with each of the input quantities $x_1, x_2, \dots, x_N$ on the total output uncertainty $u(y)$. These values are usually obtained from the reliable study (standard deviation) or from calibration certificate. The contribution of each input is based on the value of uncertainty of associated measurement.

Propagation of distributions method uses the preselected probability distribution function (PDF) $g(x_1), g(x_2), \dots, g(x_N)$ to each input quantity as a source of uncertainty associated with each quantity. If appropriate representative PDF was selected, it is considered it already contains the information of all possible uncertainties associated with the input variable.

In summary, though the propagation of distributions method provides more information on sources of uncertainties and their shares in total uncertainty, the value of standard deviation can be used as a first evaluation before performing a propagation of uncertainties analysis.

7.3. Preparations

7.3.1. Ascertain the model to be assessed: review of existing thermal comfort indices and their dependent, independent and latent variables

All thermal comfort models described in Section 2 and 6 have dependent, independent and latent variables. To assess these models' uncertainties, these variables will need to be assessed. The independent and latent variables may bring model input uncertainties, while latent variables may create model framework uncertainties. This section will use the PMV model as described in ISO 7730 (2005) as an example. Similar review may be applied to other models.

The predicted model described in ISO 7730 has the following variables:

- Six independent variables, defined as air temperature (t_a), mean radiant temperature (t_r), relative humidity (RH), relative air velocity (v_{ar}), metabolic rate (M) and clothing insulation (I_{cl}).
- Latent variables, including heat transfer coefficients and body surface area.
- One dependent variable: Predicted Mean Vote (PMV)

With regard to the six input variables, two of them, M and I_{cl}, are usually estimated from screening or observations, while the other four variables are usually obtained from measurements. As described in ISO 8996 (2004), screening has a '*very great risk of error*', while observation has a '*high error risk*' with estimated accuracy of $\pm 20\%$. As described in ISO 7726 (1998), the four environmental variables will have associated measurement uncertainties. Further uncertainties will be in the location of the environmental sensors with respected to the location of the participants.

With regard to the latent variables, many assumptions have been made in the PMV model, namely the definition of metabolic rate. Metabolic rate reflects how much heat is produced within the body to maintain the core temperature constant. Thus, to describe the metabolic rate a new unit 'met' is used to describe how much heat is produced per unit of skin. 1 met is equal to 58 W/m^2, whereas the average heat produced by the male adult in rest is 100 W and the average male body surface area is equal to 1.8 m^2 (ASHRAE, 2009). 1 met should then be equal to 55 W/m^2. The assumptions taken for the values of the latent variables will bring further input uncertainties to the PMV model.

Besides, important variables or interrelations between variables may have been excluded from the PMV model; for example, contextual, physiological and psychological factors. These exclusions of latent variables or oversimplification will bring framework uncertain to the PMV model.

In addition to the above, the PMV model has prescribed ranges for its independent and dependent variables; for example, the model '*should be used only for values of PMV between -2 and +2*' and t_a should be between 10 and 30 °C (ISO 7730, 2005). If the PMV model was used for cases it is not supposed to or without taking into consideration these prescribed ranges, then this will result in niche uncertainties.

In summary, the PMV model might be subject to one, two or all three form of uncertainties.

7.3.2. Verification of the code of the assessed model

When analyzing the accuracy of a new or modified model in comparison to existing models, it is crucial to verify the code used to calculate thermal comfort indices for the new and existing model. Especially for the calculation of the widely used comfort models such as the PMV- and SET-models, numerous tools exist. However, their code is not always accessible. In contrast, tools such as the CBE comfort tool (Schiavon, Hoyt and Piccioli, 2014; Hoyt et al., 2017) or the package comf (Schweiker et al., 2016; Schweiker, 2016) for R (R Development Core Team, 2012) permit line-by-line verification of the code[5]. Once the code is verified (if possible), potential differences need to be evaluated and potentially discussed with the authors of such tools.

In the next step (or the first step in case line-by-line verification of the code is not possible), the output of the tool should be verified based on published verification tables or available materials. For PMV, ISO 7730 (2005) and the original publication by Fanger (1970) offer extensive tables with a variety of input parameters and the corresponding output values. These tables are also coming together with the R package comf (Schweiker et al., 2016). For SET, ASHRAE 55 (2017) provides reference tables, which are also available in the R package comf.

7.4. Results from sensitivity analysis

As described in section 7.2, sensitivity analysis aims to uncover the degree of influence of each independent variable on the dependent variable. Furthermore, a sensitivity analysis will be the first step of an uncertainty analysis, enabling a crude estimation of output uncertainties as the value of one standard deviation. There are two broad types of sensitivity analysis, local and global sensitivity analysis, described as follows (Saltelli, Chan and Scott, 2009). Local sensitivity analysis (LSA) implies repeated simulations by varying a different input each time while maintaining the other input constant. The limitations of this method lies in:

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[5] CBE comfort tool: https://github.com/CenterForTheBuiltEnvironment/comfort_tool; R package comf: https://cran.r-project.org/package=comf

1. Establishing a base level for all input, as the justification for these chosen inputs values remains questionable.
2. Assuming that the model is linear or additive.
3. Assuming that the input variables are independent from one another.

The second method, global sensitivity analysis (GSA) implies that all input variables vary simultaneously within defined inputs' range. According to Hopfe et al. (2007) and Saltelli et al., (2009), GSA can be applied by undertaking the following three steps:

1. Selection of the ranges and distribution for the input parameters.
2. Generation of a random sample represented as a matrix with all input variables.
3. Evaluation of the model and computation of the outcome distribution.

The main limitation of GSA is that the sensitivity of the output to variation in individual input changes is hidden (as the inputs are varied simultaneously).

This section will use the PMV model as described in ISO 7730 (2005) as an example. Similar LSA and GSA analysis may be applied to other thermal comfort models.

7.4.1. GSA Inputs: selection of the ranges and the distributions

The Predicted Mean Vote (PMV) model has four environmental input variables (t_a, t_r, RH, v) and two personal input variables (M, I_{cl}). There are two methods to determine the ranges and the distributions of the six inputs, from standards and from data.

In the 'standard' method, no prior knowledge is assumed. The ranges are defined in ISO 7730 (Section 4.1), the values within these ranges are defined by established inputs' resolution (ISO 7726, 1998), finally all inputs' distributions are assumed uniform (Gauthier, 2013).

In the 'data' method, prior knowledge is assumed. Databases, such as the SCAT project, ASHARE database I and II, may be used to infer the six inputs' ranges and distributions. Then, Sobol sequence is applied to generate quasi-random values for all input within these distributions (Movchan et al., 2020).

7.4.2. GSA Output: evaluation of the model

As described in Gauthier (2013), the results of the 'standard' method shows that the PMV model is most sensitive to the two personal variables. As described in Movchan et al. (2020), the results of the 'data' methods shows that the PMV model is most sensitive to ambient temperature, followed by radiant temperature and then metabolic rate. These divergent results may be explained by the difference in the inputs' variances, as in databases personal variables are often given constant values.

7.4.3. LSA: review of latent variables

LSA may be applied to review the influence of individual latent variable on the output of model. As described in Movchan et al. (2020), this method was applied to explore the influence of body surface area on PMV. Results shows that the constant value given to body surface area may lead to the underestimation of PMV. Greater variations may be experienced by women.

In summary, sensitivity analysis is an essential tool to understand a model. In particular, the influence of each independent variables and latent variables on the dependent variable.

7.5. The true value in the assessment of the accuracy of thermal comfort models

Thermal comfort models are used by planners and designers in order to design buildings and to predict their thermal behavior in order to provide comfort indoors. In addition, they are used to define boundaries for the operation of buildings. As shown above, there is a gap between predicted and actual comfort votes, while more and more thermal comfort indices and variations of existing thermal comfort indices appear(ed) in the literature (see chapter 6). Practitioners assume a certain precision in prediction. However, the „performance“ of these indices is hardly analyzed (Gauthier, 2013; Schweiker and Wagner, 2017; Schweiker, Kingma and Wagner, 2017). Furthermore, the interpretation of models by researchers and practitioners can differ from the intended use of the model or the intended interpretation.

The overall objective should be to quantify the mismatch between prediction and vote/perception and analyze underlying reasons. However, already the quantification is not as straightforward as one may think. This chapter showed methods, but also discussed the difficulties to evaluate the accuracy of thermal comfort models. An additional aspect not mentioned so far is the difficulty to determine the true value of thermal comfort. Above approaches consider the obtained votes by human beings as the true value for the assessment of a models' accuracy. Difficulties arise in the moment, when the accuracy of models with different output should be compared, e.g. the accuracy of PMV and adaptive comfort model. While PMV predicts a mean thermal sensation vote, the adaptive comfort model predicts comfortable conditions, hence the true value differs between both models. But which of these true values is the true value for assessing the suitability to predict "optimal" conditions for the design or operation of a building? Such discussion is still to be done among researchers within the field of thermal comfort together with practitioners and most important: the users of buildings. .

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Reference

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ANNEX 69

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