3 Introduction into thermal comfort in buildings

The previous chapter reviewed the environmental impacts of courtyards. One of the background research questions of this dissertation is related to thermal comfort standards that are applicable for this research. To investigate thermal comfort in courtyard buildings, a choice for a comfort standard needs to be made. This chapter looks back to the history of thermal comfort and reviews the current standards with emphasis on adaptive comfort standards: the American (ASHRAE-55 2010), European (EN-15251: 2007) and Dutch (ATG). For each standard, the corresponding database, equations and comfort boundaries are discussed. At the end, these standards are compared through a case study in the Netherlands.

A review into thermal comfort in buildings[1]

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Abstract

Thermal comfort has been discussed since 1930s. There have been two main approaches to thermal comfort: the steady-state model and the adaptive model. The adaptive model is mainly based on the theory of the human body's adapting to its outdoor and indoor climate. In this paper, besides the steady-state model, three adaptive thermal comfort standards are comprehensively reviewed: the American ASHRAE 55-2010 standard, the European EN15251 standard, and the Dutch ATG guideline. Through a case study from the Netherlands, these standards are compared. The main differences discussed between the standards are the equations for upper and lower limits, reference temperatures, acceptable temperature ranges and databases.

Keywords

Thermal comfort, ASHRAE 55, EN15251, ATG

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§ 3.1 Introduction

One of the more unfortunate aspects of modern global development has been the introduction and widespread acceptance of the use of mechanical means for providing desired comfortable temperature for building users. This phenomenon has led to a huge energy consumption in the building stock, and nowadays, around one third of fossil fuels is consumed in buildings [1]. In this regard, thermal comfort boundaries are limitations which help building physicists to estimate to what extent buildings should be heated or cooled. Thermal comfort is defined as '*that condition of mind which expresses satisfaction with the thermal environment.*'[2]. Prediction of the range of temperatures for this comfort condition is complicated and apart from cultural influences it depends on environmental and personal factors. Chronological review of current knowledge on thermal comfort shows two different approaches: climate chamber tests and field studies. The former, which is based on heat exchange processes of the body, has led to steady-state laboratory thermo-physiological models and standards (ASHRAE 55-1992, ISO7730 and …). The latter has concluded to adaptive thermal comfort models and standards: the American ASHRAE 55-2010 standard, the European EN15251 standard, and the Dutch ATG guideline. Today, these standards are increasingly used in research and in practice within the field of thermal comfort. The current chapter tries to clarify the differences behind the mentioned standards through a Dutch case study.

This chapter first reviews the development of the ideas of thermal comfort, starting with the laboratory studies conducted by Fanger and his co-workers. In the next step, field studies which were done on naturally ventilated (and in a non-steady-state situation) and air conditioned buildings will be explained. Then, three adaptive thermal comfort standards are presented with their equations. In section 5, a Dutch representative city will be presented as a case study. In this regard, each one of the adaptive thermal comfort standards provides an estimate of the temperature range for thermal comfort. Through the results of the estimations, the standards will be compared and discussed.

§ 3.2 Development of the concept of human thermal comfort

Research in thermal comfort integrates several sciences such as physiology, building physics, mechanical engineering and psychology. According to Nicol [3], there are three reasons for understanding the importance of thermal comfort:

- To provide a satisfactory condition for people,
- To control energy consumption (elaborated by [4, 5],
- To suggest and set standards

Furthermore, Raw and Oseland [6] suggested six aims for developing knowledge in the field of thermal comfort:

- Control over indoor environment by people,
- Improving indoor air quality (dicussed comprehensively by Khodakarami and Nasrollahi [7], [8, 9])
- Achieving energy savings,
- Reducing the harm on the environment by reducing CO_2 production,
- Affecting the work efficiency of the building occupants (discussed by Leyten, Kurvers [10]),
- Reasonable recommendation for improving or changing standards.

Our current knowledge of human thermal comfort is developed by engineers and physiologists. The first concept began by a British physician in 1774. Afterwards, engineers and physiologists developed different indices relating temperature to comfort, and now, building physicists use different thermal comfort standards. Apparently, their endeavours were through two basic methods; steady-state studies and field studies. Most of the steady-state studies were prior to the field studies.

In the past, there have been two general approaches for determining thermal comfort: a) climate chamber studies, and b) field studies:

a. Climate chamber studies: The aim of these studies is to determine steady-state thermal comfort models. The research is conducted in an environmental test chamber that can vary different climatic parameters. The personal variables (clothing insulation and metabolic rate) are determined by the task, and are normally assumed to be fixed. The most important reason to use such a steady-state situation is the ability to produce the desired environmental conditions (air temperature, radiant temperature, air velocity, humidity) while controlling unwanted variables, which might influence the results. This method has also led to transient body temperature tests which examine body core and skin temperature to estimate comfort perceptions [11].
b. Field studies: The aim of these studies is to study thermal comfort in the real world. Research is conducted as subjects go about normally with their work; there is no attempt to control the environment that may have varied from just the air temperature to all factors. In many surveys clothing value and metabolic rate are recorded. Furthermore, a field study will be influenced by other indirect factors, such as cultural and psychological factors. The first aim is to discover what combination of environmental variables best describes the subjective responses of the subjects. The underlying assumption of the field survey is that people are able to control their environment in such a way that they try to reach comfort. Therefore, also the behaviour of the building plays an important role [3].

§ 3.2.1 Steady-state studies

From a physiological point of view, the very early endeavour to understand the regulatory system of the human body temperature dates back to Blagden [12] with his use of a thermometer in a heated room. His experiments were about human ability to endure high temperatures. In 1885, Richet found the ideas of brain regulations in temperature understanding. In the 1930s, Gagge started working on human heat exchange processes [13-16] and he predicted thermal comfort for ASHRAE in 1969 based on a thermal equilibrium approach [17].

In engineering, the first idea of body heat transfer was introduced by Sir Leonard Hill, Barnard [18]. In 1914 he made a big thermometer which integrated the influence of mean radiant temperature, air temperature and air velocity. Furthermore, Dufton [19] defined the equivalent temperature (Teq) in 1929. This equivalent temperature, however, was no longer applied because environmental variables were not covered in the algorithms [20, 21]. In addition, ASHRAE proposed and used the effective temperature, ET, from 1919 till 1967 [22]. In 1971, Gagge introduced ET* which was more accurate than ET because it covers simultaneously radiation, convection and evaporation. Table 1 shows the development of indices related thermal comfort.

Year	Index	Reference
1897	Theory of heat transfer	18
1905	Wet bulb temperature (Tw)	23
1914	Katathermometer	24
1923	Effective temperature (ET)	25
1929	Equivalent temperature (Teq)	19
1932	Corrected effective temperature (CET)	26
1937	Operative temperature (Top)	15
1945	Thermal acceptance ratio (TAR)	27
1947	Predicted 4-h sweat rate (P4SR)	28
1948	Resultant temperature (RT)	29
1955	Heat Stress Index (HSI)	30
1957	Wet bulb globe temperature (WBGT)	31
1957	Oxford Index (WD)	32
1957	Discomfort Index (DI)	33
1958	Thermal Strain Index (TSI)	34
1960	Cumulative Discomfort Index (CumDI)	35
1962	Index of Thermal Stress (ITS)	36

Table 1
Chronological development of indices related to thermal comfort (table after [53])

Year	Index	Reference
1966	Heat Strain Index (corrected) (HSI)	37
1966	Prediction of Heart Rate (HR)	38
1970	Predicted Mean Vote (PMV)	39
1971	New Effective Temperature (ET*)	40
1971	Wet Globe Temperature (WGT)	41
1971	Humid Operative Temperature	42
1972	Predicted Body Core Temperature	43
1972	Skin Wettedness	44
1973	Standard Effective Temperature (SET)	45
1973	Predicted Heart Rate	46
1986	Predicted Mean Vote (modified) (PMV*)	47
1999	Modified Discomfort Index (MDI)	48
1999	Physiological equivalent temperature (PET)	49
2001	Environmental Stress Index (ESI)	50
2001	Universal Thermal Climate Index (UTCI)	51
2005	Wet Bulb Dry Temperature (WBDT)	52

Table 1
Chronological development of indices related to thermal comfort (table after [53])

In parallel, Fanger [39] developed theories of human body heat exchange. Fanger stated that the human body strives towards thermal equilibrium. He proposed the following formula:

$$S = M \pm W \pm R \pm C \pm K - E - RES \quad (1)$$

Where
S= Heat storage, M= Metabolism, W= External work, R= Heat exchange by radiation, C= Heat exchange by convection, K= heat exchange by conduction, E= Heat loss by evaporation, RES= Heat exchange by respiration (from latent heat and sensible heat). In this system, the thermal responses of subjects are measured by asking their comfort vote for one of the descriptive scales of Table 2:

Vote	ASHRAE	Bedford	HSI	Zone of thermal effect
9			80	Incompensable heat
8	Hot (+3)	Much too hot	40-60	
7	Warm (+2)	Too hot	20	Sweat evaporation

Table 2
The description of comfort vote units based on ASHRAE, Bedford, HSI (Heat Stress Index= the ratio of demand for sweat evaporation to capacity of evaporation (Ereq/Emax), and zone of thermal comfort classification (Table after [53, 54])

Vote	ASHRAE	Bedford	HSI	Zone of thermal effect
6	Slightly warm (+1)	Comfortably warm		Compensable
5	Neutral (0)	Comfortable	0	Vasomotor compensable
4	Slightly cool (-1)	Comfortably cool		Shivering compensable
3	Cool (-2)	Too cool		
2	Cold (-3)	Much too cool		
1				Incompensable cold

Table 2
The description of comfort vote units based on ASHRAE, Bedford, HSI (Heat Stress Index= the ratio of demand for sweat evaporation to capacity of evaporation (Ereq/Emax), and zone of thermal comfort classification (Table after [53, 54])

Furthermore, Fanger introduced 6 parameters which have an effect of thermal comfort are:

a Metabolism refers to all chemical reactions that occur in living organisms. It is also related to the amount of activity. The unit of activity is Watt (W).
b The amount of clothing resistance also affects thermal comfort. This parameter is expressed as clo, and it ranges from 0 (for a nude body) to 3 or 4 (for a heavy clothing suitable for polar regions). In this regard, 1 clo = 0.155 °C/W.
c An ideal relative humidity between 30% to 70%.
d Air velocity has a thermal effect since it can increase heat loss by convection. Moreover, air movement in a cold thermal zone brings draught. The amount of air fluctuations is also important. The unit is normally m/s.
e The air temperature might be one of the most important ones. This is the temperature of the air surrounding a human body (in Celsius or Fahrenheit).
f The other source of heat perception is radiation. Therefore, mean radiant temperature has a great influence for a human body (i.e. how it loses or gains heat from and to the environment).

Later on, Fanger's equation became the basis for ISO 7730-1984 and ASHRAE 55-1992. Table 3 and 4 show examples of temperature bandwidths that resulted from climate chamber (steady- state) studies.

Season	Clothing insulation (clo)	Activity level (met)	Optimum operative temp. (°C)	Operative temp. range (°C)
Winter	1.0	1.2	22	20-24
Summer	0.5	1.2	24.5	23-26

Table 3
Recommended operative temperatures for occupants for sedentary activity based on ISO 7730-1984

Season	Typical clothing	Clothing insulation (clo)	Activity level (met)	Optimum operative temp. (°C)	Operative temp. range (°C)
Winter	Heavy slacks, long sleeve shirt and sweater	0.9	1.2	22	20-23.5
Summer	Light slacks, short sleeve shirt	0.5	1.2	24.5	23-26

Table 4

Recommended operative temperatures for occupants with sedentary activity, 50% relative humidity and mean air speed less than 0.15 m/s based on ASHRAE 55-1992

Advanced thermo-physiological models

In parallel to Fanger's studies, other advanced thermo-physiological models were introduced. The basis of these studies were the requirements of NASA and the US army [55, 56]. "*A thermo-physiological model provides a mathematical description of physiological responses to thermal environments*" [57]. These models, which were developed based on PMV-PPD, could be used to model transient physiological responses (i.e. local skin temperature and body core temperature).

Various studies on thermal stress has concluded to different thermo-physiological models. In these models, the human body is split into several layers. It is considered that the blood circulation system and conduction between the layers cause heat transfer from the body core to the surroundings (Figure 1). This was possible through the simulation of the human body [58]. Gradually, by increased requirements on the prediction of complex thermal environments (transient and non-uniform), thermo-regulatory models were developed from a single homogenous cylinder into multi-layered cylinders of various sizes, together with thermophysical and physiological properties for individual body parts with applied blood circulation [40, 60-67]. In this regard, Figure 2 shows an example of recent advances with computational fluid dynamics aid to predict the thermal sensation of the human body [57]. In this model, which is called ThermoSEM, the human body is subdivided into 18 cylinders and 1 sphere, all of which also containing layers that represent different tissue materials such as: brain, lung viscera, bone, muscle, fat and outer and inner skin [57, 68].

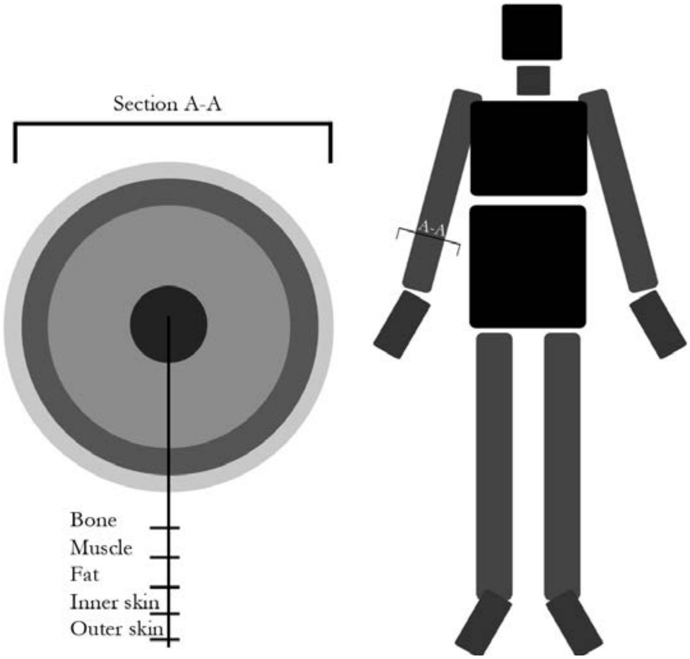


Figure 1
An example of a schematic diagram of the passive system used in simulations [59]

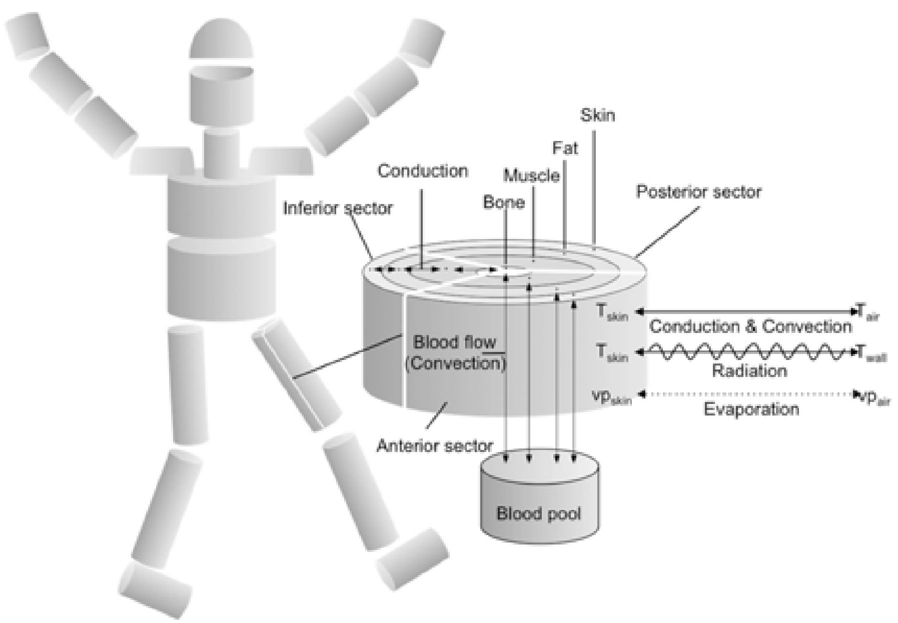


Figure 2
Schematic view of the ThermoSEM model [68]

§ 3.2.2 Field studies

By the increase of using Fanger's equation, four main criticisms were announced:

a The role of clothing resistance,
b Metabolic rate and the activity of subjects,
c The dynamic character of thermal conditions,
d The psychological characteristics of people which can mentally affect the comfort; such as expectation, the ability of acclimatisation and adaptation, etc.

In this regard, Humphreys and Nicol evaluated the validity of comfort theories based on the steady-state endeavours through several field studies [3, 69-71]. Briefly, they stated that the range of comfort temperatures in naturally ventilated buildings is much wider than what PMV-PPD models predict (especially in summer). They stated that there is a discrepancy between the findings from field studies and the comfort predictions based on the heat balance model.

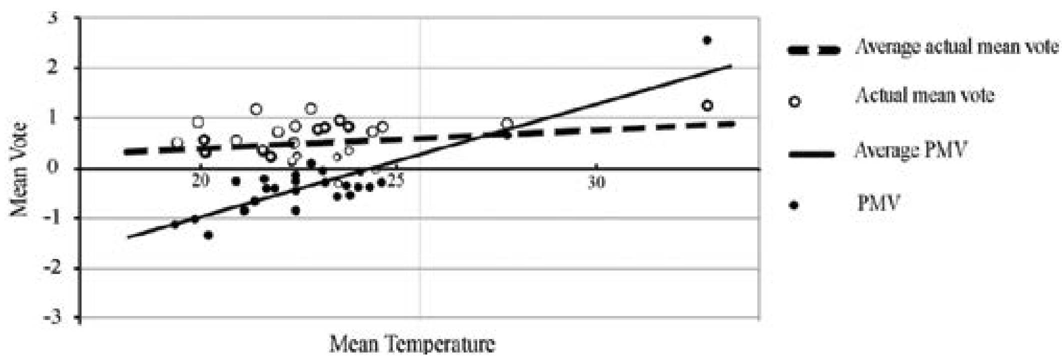


Figure 3
The difference of comfort predictions between the actual mean vote and the PMV in some field surveys (after [69])

Figure 3 shows that people are comfortable in a wider range of indoor climates than would have been expected from the heat exchange models. When Humphreys [69] calculated the PMV using data from some field studies, he noted that the calculated PMV differs from the actual mean vote and the PMV almost always underestimates the actual mean votes. On the other hand, Fanger [72] suggests that the difference in results arises from "poor data input". Here, it is essential that all four environmental factors are properly measured and that a careful estimate is made of the activity and clothing. Malama [73] noted that the difference may arise due to the:

1 difficulty of accurately measuring the parameters of Fanger's equation in the field,
2 difficulty in accounting for short-term fluctuations in those parameters in the field,
3 impact of psychological and cultural factors in the field.

In this regard, based on different studies in several years, Humphreys stated that the application of ISO7730 led to an incorrect evaluation of thermal discomfort because it did not sufficiently reflect a human's capability of thermal adaptation [69, 74-77]. Clearly, with Figure 4 he showed that indoor thermal comfort is a function of outdoor temperature.

Similar analyses of the ASHRAE databases of comfort surveys showed identical results. deDear and Brager [78] collected field survey results from all around the world and divided them into two categories: naturally ventilated buildings and centrally conditioned buildings. de Dear and Brager showed that the PMV prediction fitted 'closely' to conditioned buildings (R2= 53%) (Figure 5a); however, for naturally ventilated buildings, PMV did not predict accurately (R2=70%) (Figure 5b).

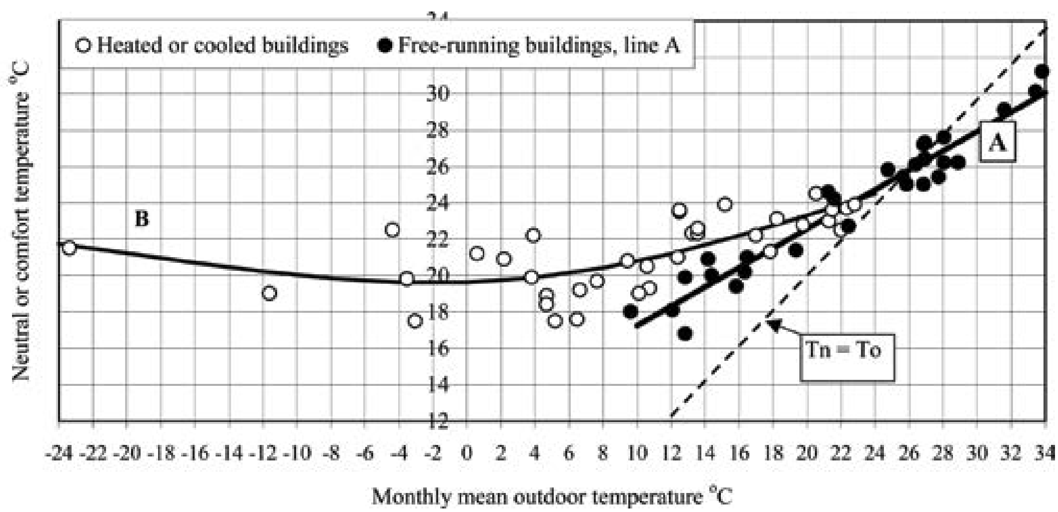
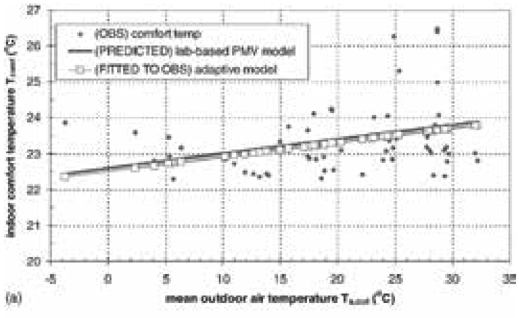


Figure 4
Comfort temperature vs. outside temperature [75]

These attempts to clarify the differences between naturally ventilated and conditioned buildings continued with later studies which are shown in Table 5:



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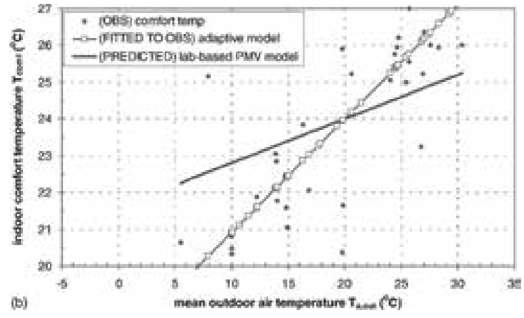

2

Figure 5

Observed (BS) and predicted indoor comfort temperature from ASHRAE database for conditioned buildings (top), and naturally ventilated buildings (below) [78].

Reference	Location	Time of year	Subjects	Results
[79]	Brisbane and Melbourne, Australia	Summer	Occupants of air-conditioned and free-running office buildings (n= 2242)	Differences in neutral temperatures were 1.7 K and -1.3 K between AC and NV buildings in Brisbane and Melbourne in summer.
[80]	San Francisco Bay Area, USA	Winter and summer 1987	304 subjects (187 females, 117 males) in 10 office buildings (2342 visits)	In winter, the measured neutral temperature (ET*) was 22.0 °C, vs. 24.4 °C predicted by PMV. In summer, the measured neutral temperature (ET*) was 22.6 °C, vs. 25.0 °C predicted by PMV. In both seasons, there was a 2.4 K difference between measurements and predictions.
[81, 82]	Bangkok, Thai-land	Hot season and wet season 1988	Over 1,100 Thai office workers in AC and NV buildings	For both seasons, temperatures at which people expressed optimal comfort had a slightly broader bandwidth in NV office buildings compared to AC buildings. In NV buildings, the PMV model unde-restimated neutral temperatures by 3.5 K, while in AC building it overestimated by 0.5 K. The upper limits for thermal comfort in both types of office buildings were higher than stated in standards.
[83]	Wuxi, China	All year round	10 students (5 males, 5 females), in residential buildings and a school	People prefer different thermal conditions during long-term exposure without space heating or cooling than based on thermal comfort standards. Local young people accepted operative temperatu-res of 10–12 °C in winter.
[84]	UK	Winter and summer	Winter: (n = 935 questionnaires) + 6,050 half-day ques-tionnaires. Summer: (n = 5,037 question-naires), in 4 NV and 4 AC buildings	In NV offices, the neutral temperature was 1.3 to 2.2 K (winter-summer) lower than in AC buildings. At the same time, there were only minor differences between dress code and activity levels. Discrepan-cies of up to 4 K were found between the observed neutral temperatures in NV buildings and those predicted by the PMV model.

Table 5

Overview of studies showing differences of comfort temperature between naturally ventilated and conditioned buildings [92]

Reference	Location	Time of year	Subjects	Results
[85]	Ghadames, Libya	Summer 1997–1998	Residents (n = 60) of NV (50%) and mechanically (50%) ventilated dwellings	Occupants were comfortable at temperatures to 35.6°C in traditional buildings compared to 30.0°C in AC buildings. The PMV model failed to predict comfort temperatures adequately.
[86]	Karachi, Multan, Quetta, Islamabad, Peshawar, and Saidu Sharif, Pakistan	(1) Longitudinal in summer and winter, and (2) transverse with monthly surveys over a year	Both residential and commercial buildings. (n = 36 subjects, n = 4927 questionnaires). Study 2: (n = 846 subjects, n = 7,112 data sets)	PMV tended to overestimate the impact of high indoor temperatures especially in summertime conditions, overemphasizing the need for air-conditioning. There was generally little discomfort at indoor globe temperatures between 20 and 30°C.
[87]	the Netherlands	Summer (≤1990)	Samples from 29 AC buildings, 32 with individual temperature control, of which 21 with natural and 11 mechanical ventilation. Number of subjects not mentioned	Occupants of NV and mechanically ventilated buildings experienced the indoor climate as being warmer than in AC buildings, even though the percentage of dissatisfied (PD) is lower in the first two buildings (PD 25%, AMV 0.5/PD 41%, AMV 1.0) than in air-conditioned buildings (PD 42%, AMV 0.5/PD 49%, AMV 1.0).
[88]	Ilam, Iran	Hot summer and cold winter 1998, and whole year 1999	Occupants of NV buildings. Hot summer (n = 513), Cold winter (n= 378), whole year (n= 30 people, n= 3819 questionnaires)	The neutral temperature during the hot summer in the short-term study was 28.4°C, and 26.7°C for the long-term study. The neutral temperature during the cold winter in the short-term study was 20.8°C, and 21.2°C for the long-term study. People in NV buildings were comfortable at indoor higher temperatures than recommended by standards.
[89]	Samples from Singapore and Indonesia	Rainy and dry seasons (2000–2002)	Singapore (n= 538), Indonesia (n= 525)	PMV model has discrepancies for NV buildings in the tropics in terms of tolerance and perception of thermal comfort, which is due to lexical uncertainty of the ASHRAE 7-point scale of thermal sensation. People in the tropics may have another perception of the meaning of the word 'warm' than people from temperate maritime climates. In tropical conditions it fails to give accurate information about the temperatures people find comfortable.
[90]	Bari, Italy	Summer (1995, 1999), and winter (1996, 2000)	University students. Sample size: 423 in 1995, 1034 in 1996, 250 in 1999, and 133 in 2000. Building type (two modes): AC in winter, NV in summer	Neutral temperatures were 24.4°C in summer 1995, 26.3°C in summer 1999, 20.7°C in winter 1996, and 20.6°C in winter 2000. Occupants of NV buildings (summer) regarded a 3.3 K and 2.1 K bandwidth to be acceptable compared to 3.6 K in AC buildings (winter).

Table 5
Overview of studies showing differences of comfort temperature between naturally ventilated and conditioned buildings [92]

Reference	Location	Time of year	Subjects	Results
[91]	Thailand (Chiang Mai, Bangkok & Mahasarakham, Prachuabkirik-han)	August 2001	Users of AC buildings in private and public sectors (n = 1520)	The neutral temperature of people with a post-graduate education level was the lowest around 25.3°C, while that of the other groups (graduate and scholar) was higher at 26.0°C. For people with air-conditioning home, the difference between neutral temperature of every education level is rather small (0.3 K). However, for the other group (no air-conditioning), the difference of 0.9 K is larger. People with higher educational degrees are found to prefer lower indoor temperature compared to the less-educated.

Table 5
Overview of studies showing differences of comfort temperature between naturally ventilated and conditioned buildings [92]

§ 3.3 Adaptive thermal comfort standards

The results of Figures 4 and 5 showed a clear division between people in buildings which were free-running and in buildings that were heated or cooled. The relationship for the free-running buildings was closely linear. However, for heated and cooled buildings the relationship is more complex since the expectations of people in those buildings are different. deDear and Brager discussed the role of expectation explaining the difference between these two building types [93].

Figure 6 shows how the comfort temperatures change with outdoor temperature in buildings which are free-running or conditioned from Humphreys [75] from the 1970s and from the ASHRAE database [94] from the 1990s.

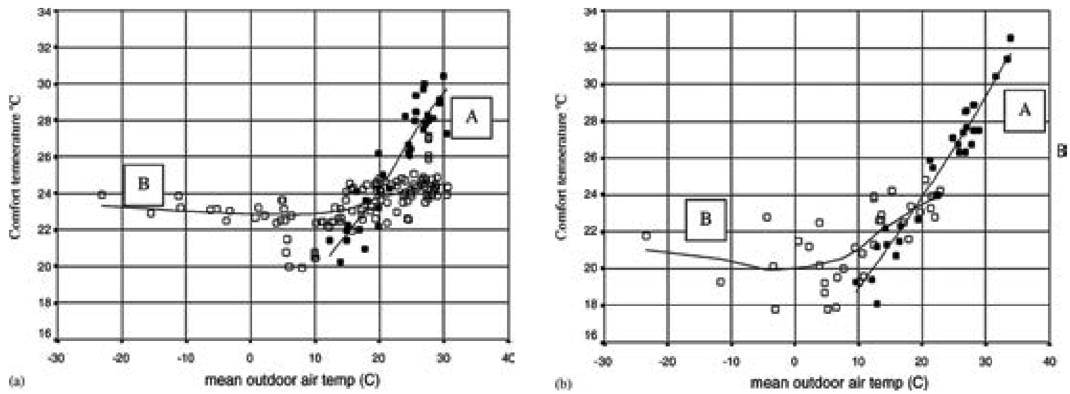

Figure 6
Comfort temperature as a function of outdoor temperature in free-running buildings (A) and conditioned buildings (B): (left) from the ASHRAE data base from the 1990s [93]; (right) from Humphreys surveys from the 1970s [75].

Referring to the linear relationship between comfort temperature and outdoor temperature in naturally ventilated buildings, Humphreys suggested that the desired comfort temperature could be determined by a linear equation:

$$T_{CO} = a * T_{out} + b \quad (2)$$

Where

T_{CO} = comfort temperature (°C),
T_{out} = outdoor temperature (°C),
a, b = constants.

In 1978, Humphreys suggested to use the monthly mean outdoor temperature (T_{rm}) as the outdoor temperature in formula (2). Afterwards, Nicol, Humphreys and McCartney [95, 96] showed that an exponentially weighted running mean outdoor temperature gave a more accurate prediction:

$$\theta = (1-\alpha).(\theta_{ed-1} + \alpha.\theta_{ed-2} + \alpha^2.\theta_{ed-3} \cdots) \quad (3)$$

This equation could be simplified to:

$$\theta_{rm} = (1-\alpha).\theta_{ed-1} + \alpha.\theta_{rm-1} \quad (4)$$

Where

α is a reference constant value, ranging between 0 and 1, and

θ_{rm}	running mean temperature of today,
θ_{rm-1}	running mean temperature of the previous day,
θ_{ed-1}	the daily mean outdoor temperature of the previous day,
θ_{ed-2}	the daily mean outdoor temperature of the day before and so on.

In this regard, all these endeavours led to the theory of adaptive comfort. Briefly, this theory states:

If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort [77]. In the next subsections, three basic adaptive thermal comfort standards and guidelines will be described.

§ 3.3.1 ASHRAE 55-2010

The main purpose of the ASHRAE-55 standard is to specify the combinations of indoor thermal environmental parameters (temperature, thermal radiation, humidity, and air speed) and personal parameters (clothing insulation and metabolism rate) that will produce thermal environmental conditions acceptable to a majority of the occupants. This standard was similar to ISO 7730 in the beginning (which was not adaptive).

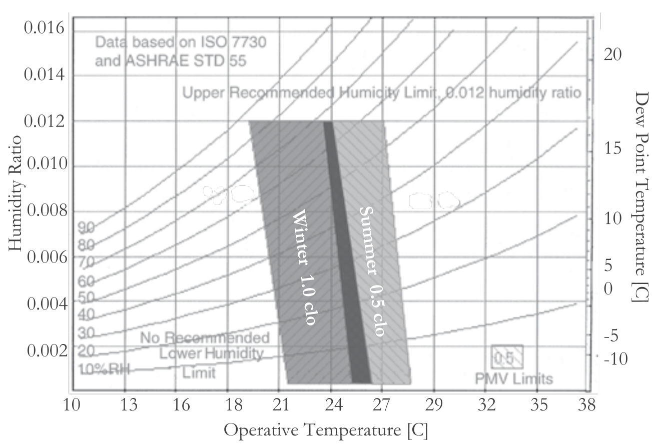

Figure 7

The Graphic Comfort Zone Method: Acceptable range of operative temperature and humidity for 80% of occupants acceptability (10% of dissatisfied based on PMV-PPD index) for 1.1 met and, 0.5 and 1 clo [97]. 0.5 clo normally refers to summer, and 1 to winter.

In the 1990s, ASHRAE appointed deDear and Brager [98] to conduct a specific research project to collect information from a lot of different field studies performed in several countries: Thailand, Indonesia, Singapore, Pakistan, Greece, UK, USA, Canada and Australia (Figure 8).

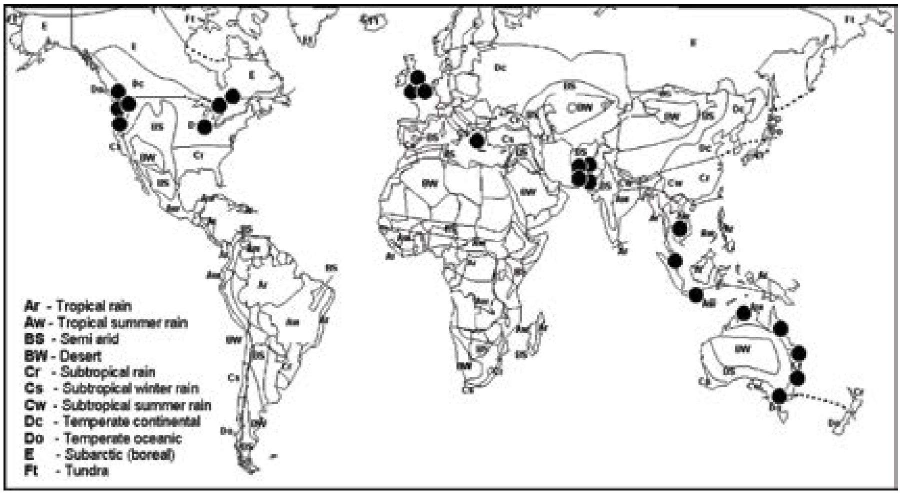

Figure 8
The geographic distribution of building studies that formed the basis of the adaptive model and adaptive comfort standard of ASHRAE [78].

This study showed that occupants' thermal responses in free-running spaces depend largely on the outdoor temperature (and may differ from thermal responses in HVAC buildings). This is due to the different thermal experiences, changes in clothing, availability of control, and shifts in occupant expectations. Therefore, ASHRAE proposed an optional method for determining acceptable thermal conditions in naturally conditioned spaces. These spaces must be equipped with operable windows and have no mechanical cooling system. This method introduces the following equation, which resulted from more than 21,000 measurements taken around the world, primarily in office buildings:

$$T_{CO} = 0.31 * T_{ref} + 17.8\ °C \qquad (5)$$

Tref = prevailing mean outdoor air temperature (for a time period between last 7 to 30 days before the day in question) [99].

This equation is used for summer when the outdoor temperatures range from 5°C to 32°C. In the previous version of ASHRAE 55 (2004), the reference temperature was the mean monthly outdoor air temperature. Figure 9 shows the comfort bandwidths based on equation (5). This figure includes 80% and 90% acceptability ranges of occupants. The 80% acceptability limits are for typical applications and the 90% may be used when a higher standard of thermal comfort is desired. Moreover, the activity level is determined as being less than 1.3 met (normally sedentary activities).

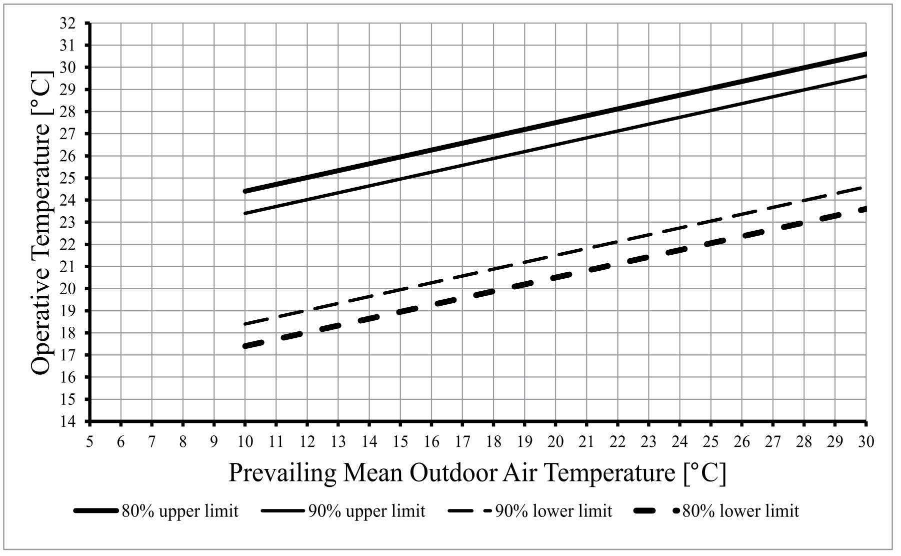

Figure 9
Comfort bandwidths of ASHRAE 55-2010 [99].

§ 3.3.2 EN15251

This standard specifies how to establish environmental input parameters for non-industrial buildings (i.e. single family houses, apartment buildings, offices, educational buildings, etc.) for design and energy performance calculations [100]. The guidelines of thermal comfort from this standard are based on the Smart Control and Thermal Comfort project (SCATs), commissioned by the European Commission. In this project, 26 European buildings in France, Greece, Portugal, Sweden and the UK were surveyed for three years covering free-running, conditioned and mixed-mode buildings [101]. Based on the survey, different adaptive algorithms for each participating country were developed (Table 6).

Country	Adaptive control algorithm	
	Trm≤10°C	Trm>10°C
All	22.88°C	0.302 * Trm+19.39
France	0.049 * Trm+22.85	0.206 * Trm+21.42
Greece	NA	0.205 * Trm+21.69
Portugal	0.381 * Trm+18.12	0.381 * Trm+18.12
Sweden	0.051 * Trm+22.83	0.051 * Trm+22.83
UK	0.104 * Trm+22.85	0.168 * Trm+21.63

Table 6
Adaptive Comfort Algorithms for individual countries [101].

Based on SCATs project, in 2007 the European Committee for Standardisation (CEN) released EN15251:2007 [100] the following equation for naturally ventilated buildings:

$$T_{co} = 0.33 * T_{rm7} + 18.8\ °C \qquad (6)$$

Where

Trm7 = the exponentially weighted running mean of the daily outdoor temperature of the previous seven days based on equation (3).

This standard recommends 0.8 for the constant α in the equation (3) and leads to:

$$T_{rm7}=((T_{(-1)}+0.8T_{(-2)}+0.6T_{(-3)}+0.5T_{(-4)}+0.4T_{(-5)}+0.3T_{(-6)}+0.2T_{(-7)}))/3.8 \qquad (7)$$

In this standard, the accepted deviation of the indoor operative temperature from the comfort temperature is divided into four categories (Table 7).

Category	Explanation	Limit of deviation	Range of acceptability
I	High level of expectation for very sensitive and fragile users (hospitals, ...)	±2°C	90%
II	Normal expectation for new buildings	±3°C	80%
III	Moderate expectation (existing buildings)	±4°C	65%
IV	Values outside the criteria for the above categories (only in a limited period)	±>4°C	<65%

Table 7
Suggested applicability for the categories and their associated acceptable temperature ranges (table after [100]).

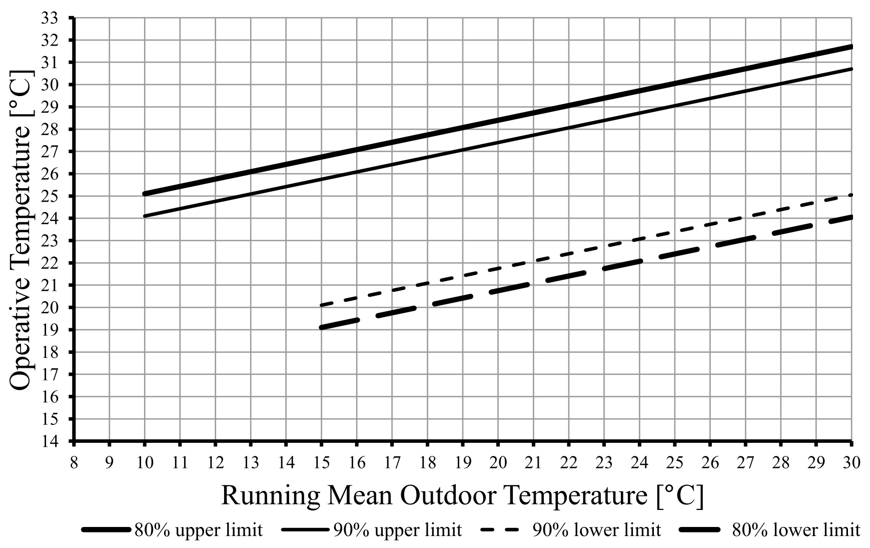

Figure 10
Comfort bandwidths of EN15251 [100].

Furthermore, based on the comfort algorithm and the range permitted for different percentages of acceptability, Figure 10 presents the comfort bandwidths.

§ 3.3.3 ATG

In 2004, the Dutch new guideline for thermal comfort was introduced prior to the European EN15251:2007. This Adaptive Temperature Limits guideline (ATG) was developed as an alternative to the former guideline (in 1970s), the Weighted Temperature Exceeding Hours method (GTO) which was based on Fanger's model

[102]. This new standard was established because the former standard did not have the flexibility to predict various types of buildings. In this regard, the new method divides buildings into two types: alpha and beta buildings. The first are naturally ventilated buildings, and the latter mechanically conditioned buildings with sealed facades (Figure 11).

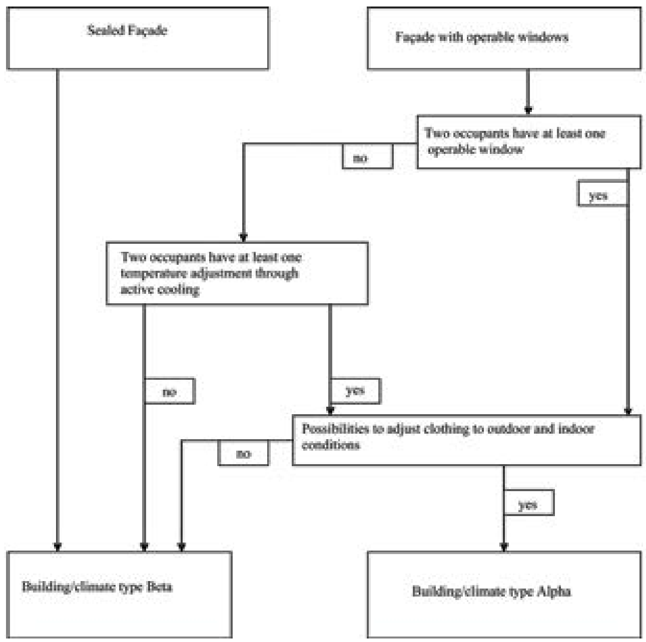

Figure 11
Diagram for determining the type of building/climate: alpha or beta [103].

In Table 8, the equations related to the type alpha are described:

Acceptance	Condition	Algorithm
A-90%	Tref>12 °C	Tco = 20.3 + 0.31 * Tref
	Tref<12 °C	Tco = 22.7 + 0.11 * Tref
B-80%	Tref>11 °C	Tco = 21.3 + 0.31*Tref
	Tref<11 °C	Tco = 23.45 + 0.11 * Tref

Table 8
ATG Comfort bandwidths for the alpha type (table after [104]).

Acceptance	Condition	Algorithm
C-65%	Tref>10 °C	Tco = 22.0 + 0.31 * Tref
	Tref<10 °C	Tco = 23.95 + 0.11 * Tref

Table 8
ATG Comfort bandwidths for the alpha type (table after [104]).

In this case, the outdoor reference temperature is determined by the running mean outdoor temperature, based on equation (3) as:

$$T_{rm}=(T_i+0.8 * T_{(i-1)}+0.4 * T_{(i-2)}+0.2 * T_{(i-3)})/2.4 \quad (8)$$

Where

T_{rm} = running mean outdoor temperature
T_i = average outdoor temperature of the day in question
$T_{(i-1)}$ = average outdoor temperature of one day before (and so on ...)

This equation is based on a time interval of 4 days back in time starting from the current one.

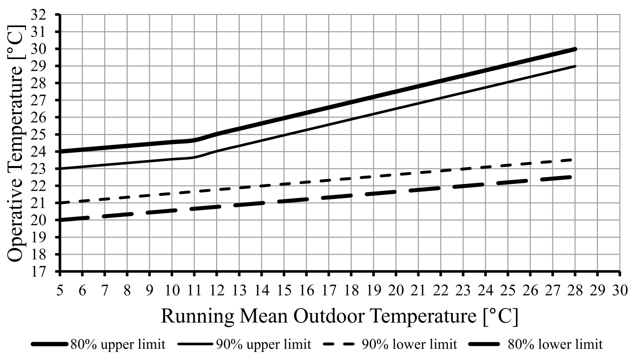

Figure 12
Adaptive comfort bandwidths (for naturally ventilated buildings) according to ATG [103].

Later on, Peeters, deDear [105] developed an adaptive thermal comfort guideline for residential buildings with different activities. They divided a home into three zones: bathroom, bedroom and other rooms (kitchen, study room and living room). In their classification, each zone has its own comfort algorithms since the metabolic rate, clothing and the other variables in human thermal perception are different in each of these zones. Table 9 summarises the equations based on 80% of acceptability in the different zones:

Zone	Condition	Algorithm
Bathroom	Tref ≥11 °C	Tco = 20.32 + 0.306 * Tref
	Tref <11 °C	Tco = 22.65 + 0.112 * Tref
Bedroom	Tref ≥21.8 °C	Tco = 26 °C
	12.6 °C ≤ Tref <21.8 °C	Tco = 9.18 + 0.77 * Tref
	0 °C ≤ Tref <12.6 °C	Tco = 16 + 0.23 * Tref
	Tref <0 °C	Tco = 16 °C
Other room	Tref ≥12.5 °C	Tco = 16.63 + 0.36* Tref
	Tref <12.5 °C	Tco = 20.4 + 0.06 * Tref

Table 9
specified comfort temperature bandwidths for dwellings based on [105].

§ 3.4 Comparison and discussion

One of the common ways to show the differences between thermal comfort standards is to apply them to estimate comfort temperatures of a city or climate [106-112]. In this section, the mentioned American, European and Dutch standards are used to estimate the indoor comfort temperature of the town of De Bilt in the Netherlands. The climate of De Bilt (52°N, 4°E), representing the climate of the Netherlands, is known as a temperate climate based on the climatic classification of Köppen-Geiger [113]. The prevailing wind is South-West. The mean annual dry bulb temperature is 10.5 °C (Figure 13). In this chapter, the reference weather data of De Bilt is used according to Dutch standard NEN5060. According to this standard, every month belongs to a specific year which is representative of the period of 1986 till 2005. The selection is presented in Table 10.

Furthermore, based on the comfort algorithm and the range permitted for 80% of acceptability, Figure 14 presents the indoor operative comfort temperatures during the free running mode period in De Bilt. The duration of this period is based on the former Dutch energy performance standard for residential buildings [114]. This standard states that the free running mode typically occurs from 1st of May till 30th of September in the Netherlands.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Year	2003	2004	1992	2002	1986	2000	2002	2000	1992	2004	2001	2003

Table 10
Representative weather data of De Bilt as used in the calculations.

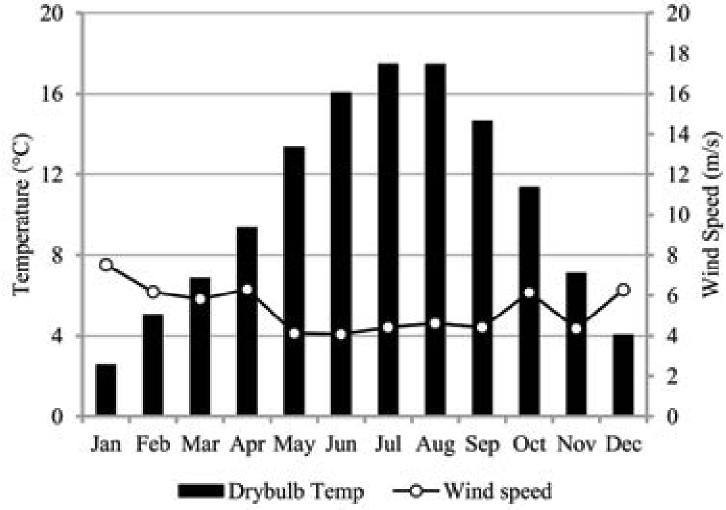

Figure 13
Representative mean dry bulb outdoor temperature and mean wind speed of De Bilt.

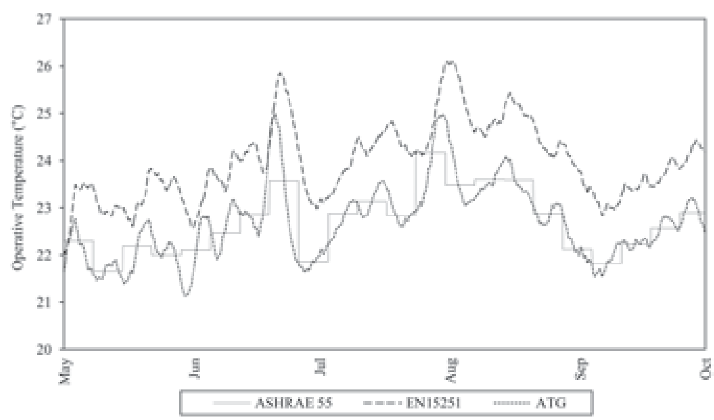

Figure 14
Indoor operative thermal comfort temperature estimated by the standards for De Bilt.

Based on the different estimations for the period of 5 months, the average comfort temperature of ASHRAE is 22.7 °C, EN15251 is 24.0 °C and for ATG is 22.7°C. Moreover, Figure 14 depicts clearly that the comfort temperatures have rhythmic differences. The differences are mainly due to:

a The intercepts are different (Figure 15). As an illustration, ASHRAE has the lowest estimated comfort temperatures because its intercept is the lowest (17.8 °C referring equation 5).

b Calculation of the reference temperatures is different in the standards. ASHRAE 55 in its 2004 edition uses monthly outdoor dry bulb temperature. This wide period of time reduces the accuracy of the reference temperature because there might be lots of fluctuations in the weather. Therefore, this period is allowed to be limited from 30 days to at least 7 days in ASHRAE 55-2010 edition. EN15251 uses the exponentially weighted running mean of the daily outdoor temperature of seven days before the day in question.

c The lower bandwidths have different slopes. The slopes in the upper limit are more or less identical (0.31 for both ASHRAE and ATG, and 0.33 for EN15251). However; the Dutch standard uses a slope of only 0.11 for the lower limit. This is shown with a grey hatched triangle in Figure 15.

d The acceptable variations from the optimum temperature (most comfortable temperature) are different. ASHRAE and ATG allow ±3.5 °C and EN15251 uses ±3 °C. This 1 °C difference (in total upper and lower limit) can cause differences in calculations.

e Last but not least, the databases of field studies led to the equations of the standards are different in location and size. ASHRAE used 21,000 measurements from many countries (excluding countries in Africa and South America). The European standard has tried to use data from different climates in Europe (such as France, Sweden, Portugal, Greece and the UK). Finally, ATG used a Dutch database from 2004.

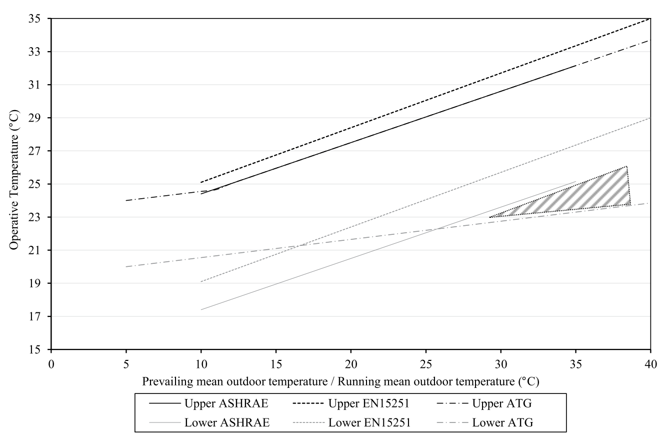

Figure 15
The upper and lower limits of the thermal comfort standards for 80% of acceptability.

Standard	Database	applicability	Range of acceptance	Reference temp	Equation
ASHRAE 55-2010	21,000 measurements taken primarily in office buildings	Office buildings	±3.5 °C	prevailing mean outdoor air temperature	17.8°C + 0.31 × Tref
EN15251	SCATs Project; office buildings	Offices; comparable buildings with sedentary activities	±3 °C	Trm7 = (T-1 + 0.8T-2 + 0.6T-3 + 0.5T-4 + 0.4T-5 + 0.3T-6 + 0.2T-7)/3.8	18.8°C + 0.33 × Trm7
ATG	ASHRAE55-2004;	Office spaces and comparable spaces	±3.5 °C	Trm4= (T0 + 0.8T-2 + 0.4T-3 + 0.2T-4)/2.4	17.8°C + 0.31 ×Trm4

Table 11
Comparison of the comfort standards for summer time.

§ 3.5 Conclusions

This chapter reviewed the development of the idea of human thermal comfort. Steady-state and field studies were described chronologically. As the main result of the field studies, three internationally well-known thermal comfort standards: ASHRAE 55-2010, EN15251:2007 and ATG were comprehensively presented. In each standard, database, basic equations, upper and lower boundaries and reference temperatures were discussed comprehensively. In this chapter, the standards were elaborated in a way to be applicable for naturally ventilated buildings. Through a case study from the Netherlands, the standards were compared. The results obtained from the estimation of thermal comfort for the city of De Bilt showed excellent agreement with the corresponding literature reviewed. The main differences between the standards were related to the equations for the upper and lower limits, reference temperatures, acceptable temperature ranges and databases.

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References

1 IPCC, Climate Change 2007, in The physical science basis. Contribution of the working group I to the fourth assessment report of the intergovernmental panel on climate change, S. Solomon, et al., Editors. 2007: Cambridge.

2 ISO, International Standard 7730. 1984, ISO Geneva, revised 1990.

3 Nicol, J.F., Thermal Comfort- A Handbook for Field Studies toward an Adaptive Model. 1993, London: University of East London.

4 Sayigh, A. and A.H. Marafia, Chapter 1—Thermal comfort and the development of bioclimatic concept in building design. Renewable and Sustainable Energy Reviews, 1998. 2(1–2): p. 3-24.

5 Omer, A.M., Renewable building energy systems and passive human comfort solutions. Renewable and Sustainable Energy Reviews, 2008. 12(6): p. 1562-1587.

6 Raw, G.J. and N.A. Oseland, Why another thermal comfort conference?, in Thermal Comfort: Past, Present and Future. . 1994, The Building Research Establishment: Garston. p. 1-10.

7 Khodakarami, J. and N. Nasrollahi, Thermal comfort in hospitals – A literature review. Renewable and Sustainable Energy Reviews, 2012. 16(6): p. 4071-4077.

8 Ormandy, D. and V. Ezratty, Health and thermal comfort: From WHO guidance to housing strategies. Energy Policy, 2012. 49(0): p. 116-121.

9 Chen, A. and V.W.C. Chang, Human health and thermal comfort of office workers in Singapore. Building and Environment, 2012. 58(0): p. 172-178.

10 Leyten, J.L., S.R. Kurvers, and A.K. Raue, Temperature, thermal sensation and workers' performance in air-conditioned and free-running environments. Architectural Science Review, 2012: p. 1-8.

11 Heidari, S., Thermal Comfort in Iranian Courtyard Housing. 2000, PhD Thesis. The University of Sheffield.

12 Blagden, C., Experiments and observations in a heated room. Philosophical Transactions of the Royal Society, 1775. 65: p. 111-123.

13 Gagge, A.P., A new physiological variable associated with sensible and insensible perspiration. American Journal of Physiology, 1937. 120: p. 277-287.

14 Winslow, C.A., L.P. Herrington, and A.P. Gagge, A new method of partitional calorimetry. american Journal of Physiology, 1936. 116: p. 641-655.

15 Winslow, C.A., L.P. Herrington, and A.P. Gagge, Physiological reaction of the human body to varying environmental temperature. American Journal of Physiology 1937. 120: p. 1-22.

16 Gagge, A.P., A.C. Burton, and H.C. Bazett, A practical system of units for the description of the heat exchange of man with his environment. Science, 1941. 94(2445): p. 428-430.

17 Gagge, A.P., J.A.J. Stolwijk, and Y. Nishi, The prediction of thermal comfort when thermal equilibrium is maintained by sweating. ASHRAE Transaction, 1969. 75: p. 108-125.

18 18Hill, L., H. Barnard, and J.H. Sequeira, The Effect of Venous Pressure on the Pulse. The Journal of Physiology, 1897. 17(21): p. 147-159.

19 Dufton, A.F., The eupatheostat. Scientific Instruments, 1929. 6: p. 249-251.

20 Yongping, J. and M. Jiuxian, Evolution and evaluation of research on the relation between room airflow and human thermal comfort. Journal of Heating Ventilating & Air Conditioning, 1999. 29(4): p. 27-30.

21 Ouzi, L., H. Yuli, and L. Xunqian, Study of thermal comfort of occupants and indoor air quality—historical review, present status and prospects. Building Energy & Environment, 2001. 21(2): p. 26-28.

22 Hanqing, W., et al., Dynamic evaluation of thermal comfort environment of air-conditioned buildings. Building and Environment, 2006. 41(11): p. 1522-1529.
23 Haldane, J.S., The influence of high air temperature. Hygiene, 1905. 5(4): p. 494-513.
24 Hill, L., O.W. Griffith, and M. Flack, The Measurement of the Rate of Heat-Loss at Body Temperature by Convection, Radiation, and Evaporation. Philosophical Transactions Research Society London B, 1916. 207: p. 183-220.
25 Houghton, F.C. and C.P. Yaglou, Determining equal comfort lines. American Society of Heating Ventilation Engineers, 1923. 29: p. 165-176.
26 Vernon, H.M. and C.G. Warner, The influence of the humidity of the air on capacity for work at high temperature. Hygiene, 1932. 32(3): p. 431-463.
27 Robbinson, S., E.S. Turrell, and S.D. Gerking, Physiologically equivalent conditions of air temperature and humidity. American Journal of Physiology, 1945. 143: p. 21-32.
28 McArdle, B., et al., The prediction of the physiological effects of warm and hot environments, in Medical Research Council. 1947, London RNP Report 47/391: London.
29 Missenard, A., A thermique des ambiences: équivalences de passage, équivalences de séjours. Chaleur Industry, 1948. 276(159-172 (in French)).
30 Belding, H.S. and T.F. Hatch, Index for evaluating heat stress in terms of resulting physiological strain. Heating, piping, and air conditioning, 1955. 27: p. 129-136.
31 Yaglou, C.P. and D. Minard, Control of heat casualties at military training centers. AMA Arch.Industr.Health, 1957. 16: p. 302-316.
32 Lind, A.R. and R.F. Hallon, Assessment of physiologic severity of hot climate. Applied Physiology, 1957. 11: p. 35-40.
33 Thom, E.C., The Discomfort Index. Weatherwise, 1959. 12(2): p. 57-61.
34 Lee, D.H.K., Proprioclimates of man and domestic animals, in Climatology, Arid zone research. 1958: UNESCO, Paris. p. 102-125.
35 Tennenbaum, J., et al., The physiological significance of the cumulative discomfort index (CumDI). Harefuah, 1961. 60: p. 315-319.
36 Givoni, B., The influence of work and environmental conditions on the physiological responses and thermal equilibrium of man., in f UNESCO Symposium on Environmental Physiology and Psychology in Arid Conditions. 1962: Lucknow. p. 199-204.
37 McKarns, J.S. and R.S. Brief, Nomographs give refined estimate of heat stress index. Heating, piping, and air conditioning, 1966. 38: p. 113-116.
38 Fuller, F.H. and L. Brouha, New engineering methods for evaluating the job environment. ASHRAE, 1966. 8: p. 39-52.
39 Fanger, P., Thermal Comfort: Analysis and Applications in Environmental Engineering. 1970, Copenhagen Danish Technical Press.
40 Gagge, A.P., J.A.J. Stolwijk, and Y. Nishi, Effective temperature scale, based on a simple model of human physiological regulatory response. ASHRAE, 1971. 13(1).
41 Botsford, J.H., A Wet Globe Thermometer for Environmental Heat Measurement. American Industrial Hygiene Association Journal, 1971. 32(1): p. 1-10.
42 Nishi, Y. and A.P. Gagge, Humid operative temperature. Physiology- Paris, 1971. 63: p. 365-368.
43 Givoni, B. and R.F. Goldman, Predicting rectal temperature response to work, environment and clothing. Applied Physiology, 1972. 32: p. 812-822.
44 Kerslake, D.M., The stress of hot environment. 1972, Cambridge: Cambridge University Press.

45 Gonzalez, R.R., Y. Nishi, and A.P. Gagge, Experimental evaluation of standard effective temperature a new biometeorological index of man's thermal discomfort. International Journal of Biometeorology, 1974. 18(1): p. 1-15.

46 Givoni, B. and R.F. Goldman, Predicting heart rate response to work, environment, and clothing. Applied Physiology, 1973. 34: p. 201-204.

47 Gagge, A.P., A.P. Fobelets, and L.G. Berglund, A standard predictive index of human response to the thermal environment., in ASHRAE Transaction 92. 1986. p. 709-731.

48 Morans, D.S., et al., A modified discomfort index (MDI) as an alternative to the wet bulb globe temperature (WBGT). in Environmental Ergonomics VIII, Hodgdon JA, Heaney JH, and B. MJ, Editors. 1998: San Diego. p. 77-80.

49 Höppe, P., The physiological equivalent temperature – a universal index for the biometeorological assessment of the thermal environment. International Journal of Biometeorology, 1999. 43(2): p. 71-75.

50 Moran, D.S., et al., An environmental stress index (ESI) as a substitute for the wet bulb globe temperature (WBGT). Journal of Thermal Biology, 2001. 26(4–5): p. 427-431.

51 Jendritzky, G., A. Maarouf, and S. Henning, Looking for a Universal Thermal Climate Index UTCI for Outdoor Applications, in Windsor Conference on Thermal Standards. 2001, Network for Comfort and Energy Use in Buildings: Windsor, UK.

52 Wallace, R.F., et al., The Effects of Continuous Hot Weather Training on Risk of Exertional Heat Illness. Medicine & Science in Sports & Exercise, 2005. 37(1): p. 84-90.

53 Epstein, Y. and D.S. Moran, Thermal comfort and the heat stress indices. Industrial Health, 2006. 44: p. 388-398.

54 Nicol, F.J., Thermal Comfort, in Solar Thermal Technologies for Buildings: The State of the Art, M. Santamouris, Editor. 2003, James & James (Science Publishers) Limited.

55 Stolwijk, J.A.J., A mathematical model of physiological temperature regulation in man. 1971: Washington DC: National Aeronautics and Space Administration.

56 Parsons, K.C., Human thermal environments: the ffect of hot, moderate, and cold environments on human health, comfort and performance. 2003: Taylor & Francis.

57 Schellen, L., et al., The use of a thermophysiological model in the built environment to predict thermal sensation: Coupling with the indoor environment and thermal sensation. Building and Environment, 2012(0).

58 Psikuta, A., et al., Validation of the Fiala multi-node thermophysiological model for UTCI application. International Journal of Biometeorology, 2012. 56(3): p. 443-460.

59 Fiala, D., K. Lomas, and M. Stohrer, A computer model of human thermoregulation for a wide range of environmental conditions: the passive system. Journal of Applied Physiology, 1999. 87(5): p. 1957-1972.

60 Wissler, E.H., Mathematical simulation of human thermal behaviour using whole body models, in Heat transfer in medicine and biology, S. A. and E. R.C., Editors. 1985, Plenum Press: New York. p. 325-373.

61 Huizenga, C., Z. Hui, and E. Arens, A model of human physiology and comfort for assessing complex thermal environments. Building and Environment, 2001. 36(6): p. 691-699.

62 Fiala, D., et al., UTCI-Fiala multi-node model of human heat transfer and temperature regulation. International Journal of Biometeorology, 2012. 56(3): p. 429-441.

63 van Marken Lichtenbelt, W.D., et al., Effect of individual characteristics on a mathematical model of human thermoregulation. Journal of Thermal Biology, 2004. 29(7–8): p. 577-581.

64 van Marken Lichtenbelt, W., et al., Validation of an individualised model of human thermoregulation for predicting responses to cold air. International Journal of Biometeorology, 2007. 51(3): p. 169-179.

65 Osczevski, R., The basis of wind chill. Arctic, 1995. 48(4): p. 372-382.

66 Stolwijk, J.A.J., et al., Development and application of a mathermatical model of human thermoregulation. Archives des sciences physiologiques, 1973. 27(3): p. A303- A310.
67 Tanabe, S.-i., et al., Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). Energy and Buildings, 2002. 34(6): p. 637-646.
68 Kingma, B., Human thermoregulation- a synergy between physiology and mathematical modelling. 2012, Maastricht University: Maastricht.
69 Humphreys, M., Thermal Comfort Requirements, Climate and Energy, in the 2nd World Renewable Energy Congress, A.A.M. Sayigh, Editor. 1992, Pergamon.
70 Humphreys, M.A. and J.F. Nicol, Understanding the adaptive approach to thermal comfort, field studies of thermal comfort and adaptation. ASHRAE Technical Data Bulletin, 1998. 14(1): p. 1-14.
71 Humphreys, M.A. and F.J. Nicol, The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. Energy and Buildings, 2002. 34(6): p. 667-684.
72 Fanger, P.O., How to apply models predicting theral sensation and discomfort in practice, in Thermal Comfort: Pas, Present and Future. 1994, The Building Research Establishment: Garston. p. 11-16.
73 Malama, A., Thermal Comfort and Thermal Performance of Traditional and Contemporary Housing in Zambia. 1997, PhD thesis, University of Sheffield.
74 Humphreys, M.A., Field studies of thermal comfort compared and applied Journal of the Institute of Heating and Ventilating Engineers, 1976. 44: p. 5-27.
75 Humphreys, M.A., Outdoor temperatures and comfort indoors. Building Research and Practice (Journal of CIB), 1978. 6(2): p. 92-105.
76 Humphreys, M.A., Field studies and climate chamber experiments in thermal comfort research, in Thermal comfort: past, present, and future, N.A. Oseland and M.A. Humphreys, Editors. 1994, Building Research Establishment Report: Watford.
77 Humphreys, M.A., An adaptive approach to thermal comfort criteria, in Naturally ventilated buildings: buildings for the senses, the economy and society, D. Clements-Croome, Editor. 1997, E&FN Spon: London.
78 deDear, R.J. and G.S. Brager, Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and Buildings, 2002. 34(6): p. 549-561.
79 de Dear, R.J. and A. Auliciems, Validation of the predicted mean vote model of thermal comfort in six Australian field studies. ASHRAE Transaction, 1985. 91: p. 452-468.
80 Schiller, G.E., A comparison of measured and predicted comfort in office buildings. ASHRAE Transaction, 1990. 96: p. 609-622.
81 Busch, J.F., Thermal responses to the Thai office environment. ASHRAE Transaction, 1990. 96: p. 859-872.
82 Busch, J.F., A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. Energy and Buildings, 1992. 18(3–4): p. 235-249.
83 Fan, Y., S. Lang, and W. Xu, Field study on acceptable thermal conditions for residential buildings in transition zone of China in Indoor Air 93, J.J.K. Jaakkola, R. Ilmarinen, and O. Seppanen, Editors. 1993: Helsinki. p. 109-114.
84 Oseland, N.A., Thermal comfort in naturally ventilated versus air-conditioned offices, in Indoor Air 96, S. Yoshizawa, et al., Editors. 1996: Tokyo. p. 215-220.
85 Ealiwa, M.A., et al., Field investigation of thermal comfort in both naturally and mechanically ventilated buildings in Ghadames, Libya, in Indoor Air 99, G. Raw, C. Aizlewood, and P. Warren, Editors. 1999: Edinburgh. p. 166-171.
86 Nicol, J.F., et al., Climatic variations in comfortable temperatures: the Pakistan projects. Energy and Buildings, 1999. 30(3): p. 261-279.

87 van der Linden, K., et al., Thermal indoor climate building performance characterized by human comfort response. Energy and Buildings, 2002. 34(7): p. 737-744.
88 Heidari, S. and S. Sharples, A comparative analysis of short-term and long-term thermal comfort surveys in Iran. Energy and Buildings, 2002. 34(6): p. 607-614.
89 Feriadi, H. and W.N. Hien, Modelling thermal comfort for tropics using fuzzy logic, in Building Simulation 2003, J.L.M. Hensen and G. Augenbroe, Editors. 2003: Eindhoven. p. 323-330.
90 Fato, I., F. Martellotta, and C. Chiancarella, Thermal comfort in the climatic conditions of Southern Italy. ASHRAE Transaction, 2004. 110: p. 578-593.
91 Yamtraipat, N., J. Khedari, and J. Hirunlabh, Thermal comfort standards for air conditioned buildings in hot and humid Thailand considering additional factors of acclimatization and education level. Solar Energy, 2005. 78(4): p. 504-517.
92 Van Hoof, J., Forty years of Fanger's model of thermal comfort: comfort for all? Indoor Air, 2008. 18(3): p. 182-201.
93 deDear, R. and G. Brager, Developing and adaptive model of thermal comfort and preference. ASHRAE Transaction, 1998. 104(1): p. 145-167.
94 deDear, R., A global database of thermal comfort field experiments. ASHRAE Transaction, 1998. 104(1): p. 1141-1152.
95 Nicol, J.F. and M.A. Humphreys, Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings, 2002. 34(6): p. 563-572.
96 McCartney, K.J. and J. Fergus Nicol, Developing an adaptive control algorithm for Europe. Energy and Buildings, 2002. 34(6): p. 623-635.
97 ASHRAE, ASHRAE Standard 55–2004, in Thermal Environmental Conditions for Human Occupancy. 2004, ASHRAE Atlanta, GA.
98 deDear, R.J. and G.S. Brager, ASHRAE RP-884 Final Report: developing an adaptive model of thermal comfort and preference, R.a.A.-C.E. American Society of Heating, Editor. 1997: Atlanta.
99 ASHRAE, ASHRAE Standard 55–2010 in Thermal Environmental Conditions for Human Occupancy. 2010, ASHRAE Atlanta, GA.
100 CEN, C.E.e.d.N., CEN Standard EN 15251, in Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. 2007, CEN: Brussels.
101 McCartney, K.J. and F.J. Nicol, Developing an adaptive control algorithm for Europe. Energy and Buildings, 2002. 34(6): p. 623-635.
102 Kurvers, S., et al., Adaptive Thermal Comfort set to practice: Considerations and experiences with the New Dutch Guideline, in Healthy Buildings 2006. 2006: Lisbon, Portugal.
103 van der Linden, A.C., et al., Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate. Energy and Buildings, 2006. 38(1): p. 8-17.
104 Thermische-Behaaglijkheid, eisen voor de binnentemperatuur in gebouwen, in Publication 74, ISSO. 2004: Rotterdam.
105 Peeters, L., et al., Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. Applied Energy, 2009. 86(5): p. 772-780.
106 van Hoof, J. and J.L.M. Hensen, Quantifying the relevance of adaptive thermal comfort models in moderate thermal climate zones. Building and Environment, 2007. 42(1): p. 156-170.

107 Moujalled, B., R. Cantin, and G. Guarracino, Comparison of thermal comfort algorithms in naturally ventilated office buildings. Energy and Buildings, 2008. 40(12): p. 2215-2223.

108 Sourbron, M. and L. Helsen, Evaluation of adaptive thermal comfort models in moderate climates and their impact on energy use in office buildings. Energy and Buildings, 2011. 43(2–3): p. 423-432.

109 Borgeson, S. and G. Brager, Comfort standards and variations in exceedance for mixed-mode buildings. Building Research & Information, 2011. 39(2): p. 118-133.

110 Ferrari, S. and V. Zanotto, Adaptive comfort: Analysis and application of the main indices. Building and Environment, 2012. 49(0): p. 25-32.

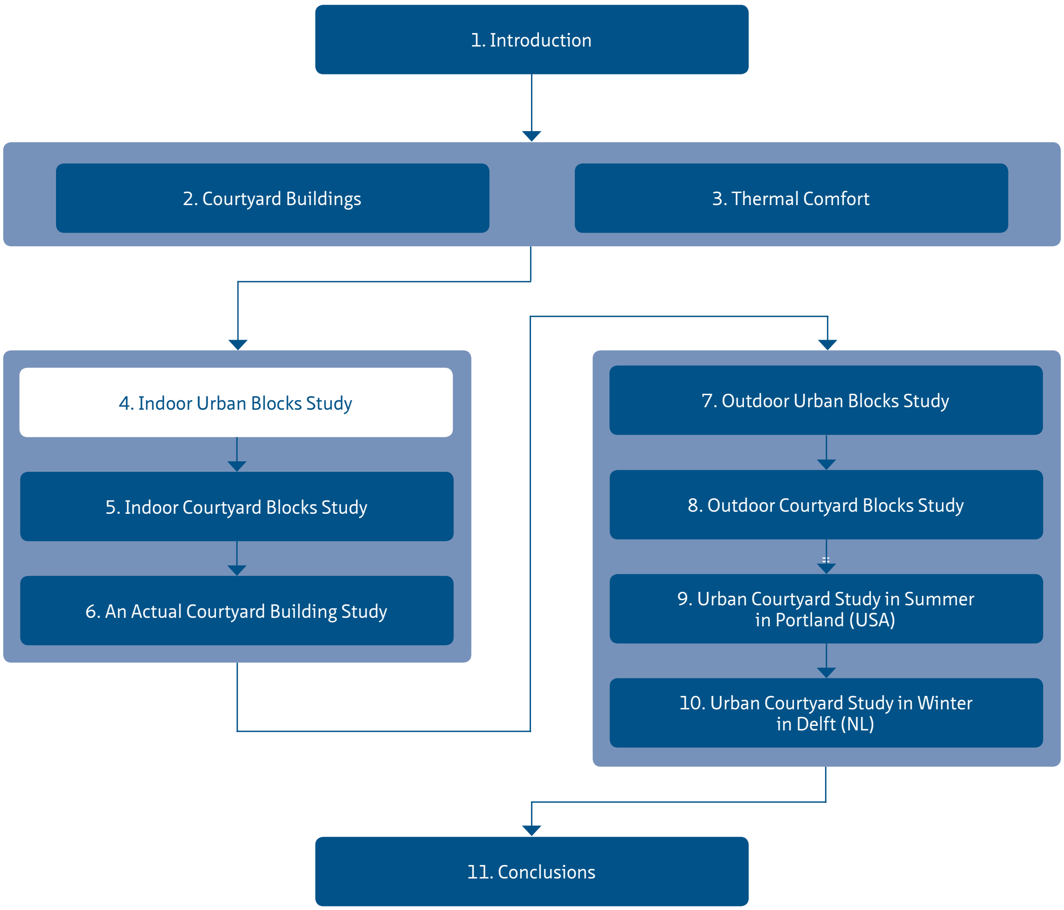
111 Lomas, K.J. and R. Giridharan, Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards. Building and Environment, 2012. 55(0): p. 57-72.

112 Filippín, C. and S. Flores Larsen, Summer thermal behaviour of compact single family housing in a temperate climate in Argentina. Renewable and Sustainable Energy Reviews, 2012. 16(5): p. 3439-3455.

113 Kottek, M., et al., World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, 2006. 15(3).

114 NEN-5128, Energieprestatie van woonfuncties en woongebouwen - Bepalingsmethode. 2004.

PART 2 Indoor study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