EXAMINATION OF ADAPTIVE THERMAL MODELS FOR APPROPRIATE ASSESSMENT OF THERMAL COMFORT IN TRANSITORY AND SEMI-EXTERNAL SPACES

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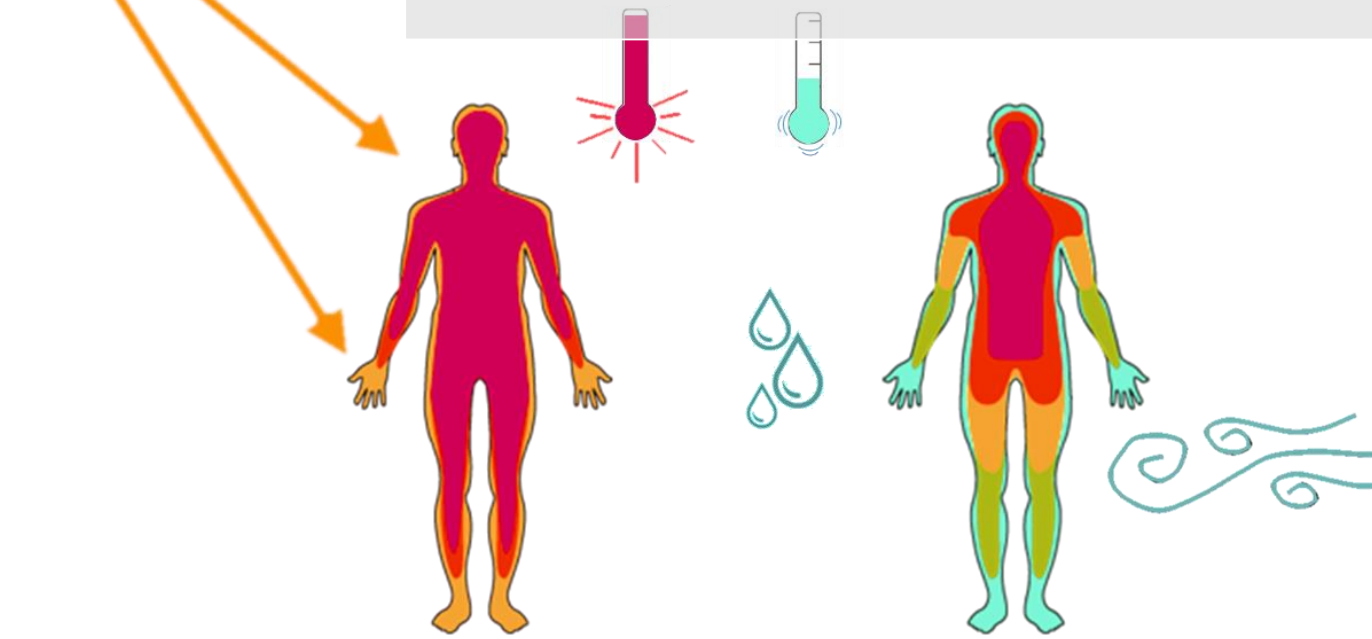

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Keywords:

Thermal comfort, PMV, adaptive comfort model, UTCI, transitory spaces, semi-external spaces

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Abstract

Thermal comfort is a topic that for the last century has interested designers and researchers. European and International standards have given guidelines for assessment of thermal comfort in typical indoor environments for long occupancy, however the transitory spaces and semi-external spaces have not been addressed.

Available literature was reviewed and summarize to find appropriate methods for assessment of thermal comfort in transitory and semi-external spaces. A methodology was developed that uses Predicted Mean Vote, Adaptive Model and Universal Thermal Climate Index for assessment of thermal comfort and informs designers on the comfort limits for different environmental parameters. The method uses Predicted Mean Vote and adaptive comfort models for defining comfort boundaries for indoor spaces with specified activity and clothing levels. Standard recommended comfort models (EN 15251; ISO 7730) are used, as well as an extended adaptive model for transitory spaces. For semi-external spaces the Universal Thermal Climate Index was used.

Through a case study it was demonstrated that the method is valuable for building designers in understanding thermal comfort and the effect of different environmental parameters as air temperature, mean radiant temperature, air velocity and relative humidity. The method can help designers in finding appropriate measures for avoiding thermal discomfort.

Further development is necessary to include standard recommendations for local discomfort in the assessment of design solutions.

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Contents

Nomenclature

T_a – air temperature (°C)
T_{mrt} – mean radiant temperature (K)
MRT – mean radiant temperature (°C)
MRT_corrected – mean radiant temperature including the effect of short-wave radiation (°C)
T_{op} – operative temperature (°C)
RH – relative humidity (%)
V_p – vapor pressure (Pa)
v_a –velocity of air (m/s)
I_{cl} – insulation of clothing (clo)
T_{rm} – running mean outdoor temperature (°C)
$T_{ed\text{-}1}$ – the daily mean outdoor temperature one day before (°C)
T_{comf} – the comfortable operative temperature
M – the metabolic rate
W – external mechanical work
E – heat transfer through evaporation
R – heat transfer through radiation
C – heat transfer through convection
K – heat transfer through conduction
S – heat storage
H - metabolic heat production
Edif – heat loss by vapor diffusion from skin
Esw – heat loss by evaporation of sweat
Eres – latent respiration heat loss
Cres – dry respiration heat loss
R – heat loss through radiation
C – heat loss through convection.
ADu – Du Bois area: surface area of the human body
η - external mechanical efficiency of the body
,f_{cl} –clothing area factor
h_c – convective heat transfer coefficient
t_{cl} – mean temperature of outer surface of clothed body
p_a – partial pressure of water vapor in ambient air
T_{mrt} – mean radiant temperature (K)
T_n – surface temperature (K)
F_n – the view factor to surface
PMV – predicted mean vote
PPD – predicted percentage dissatisfied
SET – standard effective temperature
UTCI – Universal thermal climate index
PET – Physiological equivalent temperature

AM - Adaptive comfort model
VBA – Visual Basic for Applications

1 Introduction

1.1 Motivation

The main purpose of a building is to provide shelter and good conditions for carrying out the processes for which it is designed. However, in recent years attention has been focused on energy efficiency in buildings and this is often in conflict with the comfort conditions if appropriate design is not considered from the begging. Defining the comfortable conditions in early stages of the building planning is essential for achieving good indoor environment as well as energy efficiency. It could help for making appropriate design decisions, which will lead to robust design requiring minimum energy to fulfil the buildings occupant's demands for comfort.

The deterministic approach to thermal comfort used in the European and US standards is developed on the basis of laboratory research, which may not reflect the real feelings of the occupants in their daily routines. It also does not include the possibility of people adapting to thermal conditions, accept for wearing different clothes during the seasons.

The adaptive method is based on field studies and is finding a relation between outdoor temperature and optimal indoor temperature. It is based on the assumption that people given the opportunity will adapt to the thermal conditions by different means. However, the adaptation also has its boundaries and thus a span of tolerable temperatures needs to be found in relation with the outdoor temperature. The adaptive approach is also included in latest standards covering non-conditioned buildings or parts of the year when air conditioning is not necessary.

When dealing with thermal comfort European and US standards refer to the above mentioned model regarding spaces with what is stated as long occupancy or longer than 15 minutes. For transitory spaces such as corridors, atriums, entrance areas, waiting areas in different types of buildings that could be both internal and semi-external, there is no clear guidelines. Focusing on such spaces can help find appropriate way of assessing thermal climate and can also help bring the consideration of thermal comfort into urban planning.

1.2 Goals and objectives

omfort

In order to develop this method the following topics should be researched: What is considered to be comfortable thermal environment in such spaces? Which are the AMs (Adaptive comfort Model) developed for semi-external and transitory spaces in colder climates? How can the models be used to specify comfort boundaries? How these boundaries can be used to assess different design solutions?

1.3 Limitations

The following limitations were set for this thesis:

- This work does not examine the implications of comfort requirements to energy demand.
- The psychological factors affecting thermal comfort are not considered in this work. They might be accounted for within the AMs as it is based on surveys, reflecting the real feeling of occupants in their everyday environment. However, there is not enough research for this subject and therefore it is not a focus for this thesis.
- Thermal memory and previous experience can be an important factor in the perception thermal conditions in transitory spaces, however due to limited knowledge of the author and lack of models that can quantify the effect of this factor it is not included in the recommendations for comfort limits. By using the AM for assessing transitory space the effect of outdoor conditions to the thermal perception is partially accounted for, however the full effect of the thermal conditions experienced before entering the space could not be assessed.
- For calculation of comfort limits for the environmental parameters, air temperature, *MRT*, air velocity and *RH*, limitations suggested in ISO 7730 for calculation of PMV (predicted mean vote) were used. Only when the comfort limits were calculated using *UTCI* (Universal Thermal Comfort Index) the limitations were extended considering the specifics of the semi-external environment.
- The effect of the local discomfort from factors, such as radiant asymmetry and draughts, is not considered in the method developed within this thesis.

2 Background theory

2.1 Human thermal sensation

Human thermal sensation is dependent on the need to maintain stable core temperature of 37 °C. Conditions leading to deviation from this temperature provoke feeling of cold or hot i.e. thermal sensations. The bodies mechanisms for thermal regulation, as shivering when it is too cold and sweating when it is too warm, are triggered by those thermal sensations. In other words the body is always trying to return to thermal neutrality, where the produced heat is equal to the heat lost to the environment at core body temperature of 37 °C. This process is governed by the heat balance equation for human body, equation 1 (Parsons, 2003).

$$M - W = E + R + C + K + S \qquad (1)$$

M is the metabolic rate, *W* is external mechanical work, *E* is heat transfer through evaporation, *R* is heat transfer through radiation, *C* is heat transfer through convection, *K* is heat transfer through conduction, and *S* is heat storage.

When thermal balance is reached $S = 0$. For human body, heat transfer through conduction is considered negligible thus is also equal to zero. Fanger (1970) has presented a classical formula for human thermal balance which is as follows:

$$H - E_{dif} - E_{sw} - E_{res} - C_{res} = R + C \qquad (2)$$

H is metabolic heat production, E_{dif} is heat loss by vapor diffusion from skin, E_{sw} is heat loss by evaporation of sweat, E_{res} is latent respiration heat loss, *Cres* is dry respiration heat loss, *R* is heat loss through radiation, *and C* is heat loss through convection.

Human thermal sensation, however, is very complex and can be affected by factors not included in the heat balance formula. Nicol, et al., 2012 argues that age and gender can affect thermal sensation. However Parsons, 2003 summarizes studies from several sources, showing that the differences observed between young and elderly are due to different life styles – lower metabolic rate and different clothing. No significant difference in thermal sensation between genders was found and differences, based on geographical location, are also attributed to traditional clothing and activity habits.

Even though thermal sensation is governed by the heat balance formula, it is a psychological response and is dependent on the previous experience of the body as well as area, position and duration of the thermal stimuli; temperature intensity and rate of change in temperature. Previous thermal experience will affect the sensation in such a way that if the body is too hot or too cold any conditions that would help returning to balance will feel pleasant (Parsons, 2003). This is also confirmed by (Nicol, et al., 2012).

Psychological factors as personality, expectations and adaptation possibility are also influencing the thermal sensation, however they are not very well studied (Nicol, et al., 2012). In a study of thermal comfort in transitory spaces as atria, entrances and corridors, it was found that social and psycho-social factors as company, space design etc. can also affect people's tolerance to thermal conditions (Pitts, 2010). As mentioned before those factors are not considered in this work, due to lack of model quantifying their effect on thermal comfort.

2.1.1 Human responses to thermal environment

Responses of the body to the thermal environment can be several. When the conditions are too hot the body triggers the process of vasodilation - increasing blood flow, and sweating -losses heat through evaporation of the secreted sweat. In cold conditions the body try to restrict the heat loss by vasoconstriction - reducing blood flow, and piloerection -hairs standing on end – creating a layer of still air around the body, moreover to increase the heat production shivering is triggered (Parsons; 2003).

The behavior responses are a significant part of the human thermoregulation. Behavioral acclimatization can be reached after long-term exposure to certain thermal conditions. Those responses can become automatic and difficult to resist if the thermal stimuli is strong. Possible behavior responses are changing posture, changing clothes, looking for shelter, moving to different location. The behavior is recognized as the most effective form of thermal regulation (Parsons; 2003)

2.1.2 Adaptation and acclimatization

Experience has shown that varying thermal conditions throughout the seasons can be considered acceptable and even desirable, due to adaptation practices and expectations of the occupants. Important factor for people satisfaction is their ability to control the thermal environment, by changing clothing, opening windows, regulating the heating or cooling etc. (Nicol, et al., 2012).

Parsons (2003) also states that expectations and the opportunities for adaptation can strongly influence human perception of the thermal environment. Environments that can be considered acceptable might be perceived as uncomfortable if there is no possibility of adaptation and control over the environment.

Acclimatization is defined by Parsons as the change in physiological responses to heat after humans have been exposed to high temperatures for longer periods of time. Summarizing the results from several studies he concludes that acclimatization affects more active individuals. For light activities it does not show significant effect on comfort preferences (Parsons, 2003).

2.1.3 Computer models for predicting thermal sensation

On the basis of heat balance theory and equations several computer models for predicting human response to the thermal environment have been developed. Examples of these are the Stowijk and Hardy 25-node model and the Nishi and Gagge 2-node model. They use dynamic simulations of the human body and its response to the thermal environment.

Nishi and Gagge 2-node model differentiates between passive and active systems of human thermal regulation, representing the human body (passive system) as 2 layered cylinder: a body core surrounded by a skin shell. The controlling system reacts to deviations of the body core temperature from a reference temperature. The model incorporates vasomotor – constriction or dilation of blood vessels, shivering and sweating responses (Haslam, 1989).

Stowijk and Hardy is 25-node model that considers the human body as five cylinders representing the trunk and the limbs, and a sphere representing the head. Each of the elements have four layers. The 25th node represents the blood. This model also incorporates vasomotor, shivering and sweating responses and predicts temperature changes in each layer (Stolwijk, 1971). The model provides evaluation of the thermal comfort of each body part, as often the thermal conditions throughout the body can vary (Haslam, 1989).

2.2 Thermal comfort models

2.2.1 What is comfort?

ASHRAE standard 55 gives the following definition of comfort:

"*That condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation*."

As mentioned before the perception of thermal comfort for human begins is connected to the need of maintaining relatively constant core temperature of 37 °C (Nicol et al. 2014, Parsons 2003). This need is fulfilled by (physiological and behavioral responses to the thermal environment) mechanisms of thermal regulation that are established in human bodies, which ensure that appropriate actions will be taken in certain situations. By feeling too hot or too cold, human thermoregulatory system receives signals and triggers physiological mechanisms -described in chapter 2.1. Disturbance in the thermal environment may also result in change of clothing, activity level, posture or environment which are categorized as behavioral responses and have significant effect on thermal regulation (Parsons, 2003). Stating that thermal balance is not sufficient to provide comfort, Fanger (1970) suggests that thermal comfort is reached if the skin temperature and the sweat secretion are within certain comfortable limits, which are specific for individual person in a certain activity level.

Six physiological factors that affect thermal comfort are recognized by the standards concerning thermal comfort: air temperature T_a, mean radiant temperature *MRT*, air velocity v_a, relative humidity *RH*, clothing and activity ((EN 15251, 2007); (ASHRAE, 2004); (CIBSE Guide A, 2006)). The effect of *MRT* on the thermal sensation is important for designers. It is calculated that at lower temperatures a drop of 0.6 °C can be compensated with 0.48 °C increase in the *MRT*. It is also calculated that 15 W/m^2 of sun radiation can compensate for 2.3 °C lower dry-bulb temperature (Olgyay, 1992).The effect of air velocity, v_a is due to increased heat loss from convection and evaporation. With higher velocities the temperature limit can increase, this effect is smaller with higher temperatures (Olgyay, 1992). Researchers have argued that *RH* has limited effect on thermal comfort and is only important at very high temperatures (Nicol, et al., 2012). Air quality is also mentioned as a factor affecting the thermal comfort but is considered as a separate issue, concerning design requirements.

Psychological factors as expectation, design of the surroundings or even color have also been considered to have an effect to the thermal comfort. However these factors and their possible effects are not well studied (Parsons, 2003). Therefore they are not a subject of this thesis.

In the last century efforts have been made to predict the environments providing comfort conditions. The following sections will discuss the models and indices developed for predicting thermal comfort of humans in different environments.

2.2.2 *PMV* model

Using the theory of heat balance a formula for predicted mean vote (*PMV*) is elaborated, taking into account six factors (Fanger, 1970).The formula is developed by using research results from a climate chamber. The *PMV* index is expressed in 7 step scale from -3 to +3 where -3 represents sensation of too cold, 0 stands for neutral thermal sensation and +3 is for too hot and is calculated using equations 3,4 and 5. Another index *PPD* (Percentage of People Dissatisfied) is developed based on the *PMV* index. The *PPD* is calculated with equation 6.

$$PMV = \left(0.352 \cdot e^{-020.042 \cdot \left(\frac{M}{A_{Dui}}\right)} + 0.032\right) \cdot \left\{\frac{M}{A_{Dui}}(1-\eta) - 0.35\left[43 - 0.061\frac{M}{A_{Dui}}(1-\eta) - p_a\right] - 0.42\left[\frac{M}{A_{Dui}}(1-\eta) - 50\right] - 0.0023\frac{M}{A_{Dui}}(44 - p_a) - 0.0014\frac{M}{A_{Dui}0}(34 - T_a) - 3.4 \cdot 10^{-8} f_{cl}[(t_{cl} + 273)^4 - (MRT + 273)^4] + f_{cl}h_{cl}(t_{cl} - T_a)\right\} \tag{3}$$

Where:

$$t_{cl} = 35.7 - 0.039\frac{M}{A_{Dui}}(1-\eta) - 0.18 I_{cl}\{3.4 \cdot 10^{-8} f_{lc}[(t_{cl}+273)^4 - (MRT+273)^4] + f_{cl} h_c (t_{cl} - T_a)\} \quad (4)$$

and:

$$h_c = \begin{cases} 2.05(t_{cl}-t_a)^{0.25} & for\ 2.05(t_{cl}-t_a)^{0.25} > 1.04\sqrt{v} \\ 10.4\sqrt{v} & for\ 2.05(t_{cl}-t_a)^{0.25} < 1.04\sqrt{v} \end{cases} \quad (5)$$

M is metabolic rate, *ADu* is Du Bois area: surface area of the human body, η is external mechanical efficiency of the body, p_a is partial pressure of water vapour in ambient air, T_a = air temperature, *MRT* is mean radiant temperature in °C, f_{cl} is ratio of the surface area of the clothed body to the surface area of the nude body (clothing area factor), h_c is convective heat transfer coefficient, t_{cl} is mean temperature of outer surface of clothed body *and* v_a is relative air velocity.

$$PPD = 100 - 95 \cdot e^{(-0.33353.PMV^4 - 0.272.PMV^2)} \quad (6)$$

The formula includes four environmental factors that affect thermal comfort: air temperature, mean radiant temperature, humidity and air velocity. Clothing and activity level are also included as factors.

This model evaluates a steady state thermal environment, which is rarely the case in building environment. However the standards suggest methods of assessing thermal environment for a period of time using the model ((EN ISO 7730, 2005) (EN 15251, 2007), (ASHRAE, 2004), (CIBSE Guide A, 2006)).

Concerns of the accuracy of this model in predicting the thermal sensation of people are due to the fact that it does not consider the adaptation abilities that people have, nor the expectations of the occupants. It is also questionable if the votes of people in a climate chamber are a good representation of the thermal experience of people in their daily routines.

The model can be used in environments where people have very little control over the thermal conditions and are also limited from options of personal adaptation, like changing clothes and activity or relocating.

Addressing the critiques of the *PMV* model – that it does not consider the expectation of the occupants and also does not give accurate predictions for neutral temperatures in naturally ventilated buildings, Fanger & Toftum (2002) have developed an expectancy factor that can be used to adjust the *PMV* index. It is multiplied with the *PMV* to result in more accurate prediction. The expectancy factor varies between 0.5 and 1. It is used depending on the duration of warm weather experienced in the area of the building and the type of the surrounding buildings (if they are air conditioned or not (Fanger & Toftum, 2002).Table 1 shows how to attribute the expectancy factor to different environments.

Table 1. Expectancy factors and the corresponding conditions

Expectancy factor	**Conditions**
0.9-1	For sites where air-conditioned buildings are common and warm weather appears for short period of time.
0.7-0.9	For sites where there are air-conditioned buildings and a warm summer is normal
0.5-0.7	Where there are few air-conditioned buildings and warm weather is common throughout the whole year.

Fanger & Toftum (2002) have demonstrated with several cases that by using this factor the predictions of thermal sensation are reasonably accurate. When the expectations of an office workers are considered, however, it is most likely that the occupant will adjust his or her expectations according to what was his or her experience in the building in question and not according to the surrounding buildings as it is suggested in the above mentioned study. Other researchers have also expressed concerns about the validity of the expectancy factor (Halawa & van Hoof, 2012).The expectancy factor is not introduced in any of the standards studied within this work and is not implemented in the method developed.

2.2.3 Adaptive comfort models

The adaptive theory of thermal comfort is based on the assumption that people can adapt to the thermal conditions to which they are exposed if given the time and means of doing so. It also take consideration of the acclimatization and expectation of occupants. It is assumes that people from one climate would accept conditions closer to the climate they inhabit and also that expectations of the occupants would affect their evaluation of the thermal conditions (Nicol, et al., 2012).

By analyzing results from building surveys researchers have found that the neutral or comfort temperature for the occupants is similar to the actual operative temperature of the building. Further relation between outdoor prevailing mean temperature and the comfort temperature was found that was different for free running and air conditioned buildings. Formulas describing these relations can be derived thus allowing for prediction of comfort temperatures based on outdoor temperatures

(Nicol, et al., 2012) .These formulas need to be derived from field studies specific for the climate and type of building.

Nicol et al have derived such formulas in their book Adaptive thermal comfort: Principles and Practice. The formulas for free running and conditioned are as follows:

$$T_{comf} = 0.33 \cdot T_{rm} + 18.8 \qquad \textit{for free running} \qquad (7)$$

$$T_{comf} = 0.09 \cdot T_{rm} + 22.6 \qquad \textit{for heated or cooled} \qquad (8)$$

T_{comf} is the comfortable operative temperature and T_{rm} is the outdoor mean running temperature.

The formulas are suited for European office buildings. The authors consider that temperature deviation of 2 °C can still be experienced as comfortable and thus upper and lower margin for the comfort temperatures can be set by adding and subtracting 2 °C to the comfort temperature. The comfort temperature in this model corresponds to the operative temperature which combines the effect of air temperature and mean radiant temperature.

It is not clear though why the authors have considered it appropriate to express the relation between comfort temperatures for heated and cooled buildings with a linear formula, when the field survey results have shown more complex behavior. However, standards have adopted this method only for free running buildings.

It is acknowledged that air movement can elevate the comfort temperature by 2 °C, but the effect is not incorporated into the model (Nicol, et al., 2012). However, it is not documented if in the field surveys, where high temperatures are recorded, the occupants have already increased the air velocity by opening windows or using portable fans.

Activity level and clothing are the main means of adaptation considered in the theory, together with possibility of controlling operable windows. In some work environments it is not possible to change activity level in order to adapt to thermal environment. Dress codes at the work place can further reduce the means of adaptation. It is also not mentioned how these adaptation practices would affect the productivity of the occupant.

This method can be used for environments where the main factors influencing the thermal comfort are T_a and *MRT*. The effects of increased air speed and humidity level are not considered in the model. Separate models need to be developed for different types of spaces (offices, shopping areas, transitory), this can be achieved by analyzing information from already carried surveys in building types and climates fitting the project in question or by conducting a new field study. Such model has been developed for office buildings in hot humid climates (Toe & Kubota, 2013).

2.2.4 Bioclimatic approach

Based on several researches of comfortable thermal conditions for humans Olgyay (1992) has outlined a comfort zone where the conditions are supposed to be experienced as comfortable. A zone of thermal neutrality can be set, where no feeling of discomfort occurs. This zone is strongly dependent on the individual. In reality the comfort zone does not have concrete boundaries as the feeling of comfort would gradually convert to slight degree of stress when approaching the zones boundaries (Olgyay, 1992).

The comfort zone is plotted on a chart, where the *x*-axis represents the relative humidity and the *y*-axis represents the dry-bulb temperature. The lower boundary is extended to create winter comfort zone. For conditions outside the comfort zone actions can be taken to restore the feeling of comfort: increasing air movement, adjusting the mean radiant temperature, adding moisture for evaporative cooling or receiving solar radiation. These components and the necessary amounts for restoring the comfort feeling for each point on the chart are also plotted as well as limit lines, where the conditions will be unbearable (Olgyay, 1992).

This method is suitable for early design stage of the project, because of its simplicity of presenting the comfort limits. It is good to evaluate the climate specifications of the location and consider passive measures for achieving thermal comfort. Concerns have been raised that the bioclimatic chart is created for evaluation of outdoor conditions and cannot be used to assess thermal comfort in buildings if the indoor conditions are much different than the outdoor. This could be the case in buildings with high thermal mass, located in hot climate areas (Givoni, 1992).

2.2.5 Givoni's Building Bioclimatic Chart

Givoni has developed Building Bioclimatic Chart (BBCC) that builds on Olgyays chart but considers the effect of the building itself. In this chart comfort zone is plotted on a normal psychometric chart together with areas including conditions that can be comfortable if certain measures, like adding thermal mass, ventilation, humidification and internal heat gain, are considered (Steinfeld, et al., 2010). It is however noted by Steinfeld et al, 2010 that to assess the effect of each measures a set of assumptions needs to be made, which might not present the reality in the future building. This chart was not used within this method.

2.2.6 Other indices for predicting thermal comfort

Throughout the last century several indices have been developed in order to predict the thermal sensation of humans using a standardized reference environment in order to evaluate the actual conditions. Four of them are presented in the following section. Table 2 summarizes the settings for reference environment used to calculate different thermal indices. In Table 3 the assessment scales are presented for the described thermal indices. The *UTCI* is chosen for further use in the development of a method for assessing thermal comfort in semi-external spaces.

2.2.6.1 *SET* – Standard Effective Temperature

SET is based on a 2-node model of human response to the thermal environments. It is defined as the equivalent air temperature of an isothermal environment in which a subject, while wearing clothing standardized for the activity concerned, has the same thermal sensation as in the actual environment. The isothermal environment is characterized with mean radiant temperature equal to air temperature, *RH* of 50% and still air. Increase in air velocity due to higher activity is accounted for. The standard clothing and the velocity of air are estimated as a functions of the given activity (Gagge, et al., 1986). Table 2 presents the conditions assumed for the reference environment of *SET*.

2.2.6.2 OUT_SET

The index *OUT_SET* is developed specially for evaluation of external environments. It uses the same settings for the reference environment as are used in SET. In order to be fitted for evaluation of outdoor conditions this index includes the effect of short-wave and long-wave radiation by incorporating it into the calculation of *MRT* (Pickup & de Dear, 2000). It is noted by the developers that the current model is suited for open areas and it might underestimate the effect of long-wave radiation and air velocity within an urban setting (Pickup & de Dear, 2000). The same assessment scale is applicable as the one presented in for *SET*.

2.2.6.3 PET - Physiological Equivalent Temperature

PET is defined as the air temperature of an isothermal reference environment, which results in the same core and skin temperature as those under the conditions being assessed (Mayer & Höppe, 1986). The conditions for the reference environment are presented in Table 2.

For the prediction of the physiological responses, the model called MEMI (Munich Energy-balance Model for Individuals) is used. It is a steady state two node model (Höppe, 1993).

The limits for this index are derived, by calculating *PMV* with the same values as assumed for the PET reference environment and are presented in Table 3.

2.2.6.4 UTCI

The Universal Thermal Climate Index (*UTCI*) is based on the Fiala multi-node model of human reaction to thermal environment ((Fiala, et al., 1999) and (Fiala, et al., 2001)). The index is an equivalent of the air temperature in Celsius of a reference environment that is providing the same thermal sensation as the actual environment (Blazejczyk, et al., 2010). The meteorological and non-meteorological parameters of the reference environment are presented in Table 2.

The formula for determening the clothing level is derived from observations through a wide range of meteorological conditions (Havenith, et al., 2012).

The *UTCI* index is used in the method developed within this work for assessment of semi-external spaces. It was chosen among other indices as it is valid for wide range of conditions and also includes partly the actions of adaptation by calculating the clothing level according to the outdoor temperature.

Table 2. Thermal indices and assumptions for the reference environment

Parameters	**Indices**		
	SET [1)]	*PET* [3)]	*UTCI* [4)]
T_a	Equal to *MRT*	Equal to *MRT*	Equal to *MRT*
MRT	Equal to T_a	Equal to T_a	Equal to T_a
Va	Still air [2)]	0.1 m/s	0.5 m/s at 10m above ground
RH	50 %		For T_a<29 – *RH*=50%
v_p – vapor pessure		12 hPa	For T_a>29 v_p= 20 hPa
Clothing	Function of the activity	0.9 clo	Function of Ta
Activity	Actual activity	Typical indoor (work metabolism – 80W)	2.3 met
[1)] (Gagge, et al., 1986) [2)] (McIntyre, 1980) [3)] (Mayer & Höppe, 1986) [4)] (Blazejczyk, et al., 2010)			

Table 3. Assessment scale for *SET*, *PET* and *UTCI* in °C

Sensation	**Indices**		
	SET[1)]	*PET*[2)]	*UTCI*[3)]
extreme heat stress			above +46
very strong heat stress	above +37.5	Above +41	+38 to +46
strong heat stress	+34.5 to +37.5	+35 to +41	+32 to +38
moderate heat stress	+30.0 to +34.5	+23 to +35	+26 to +32
slight heat stress	+25.6 to +30.0		
Comfort	+22.2 to +25.6	+18 to +23	+18 to +26
no thermal stress			+9 to +26
slight cold stress	+17.5 to +22.2		+9 to 0
moderate cold stress	+14.5 to +17.5	+8 to +18	0 to -13
strong cold stress	+10.0 to + 14.5	+4 to +8	-13 to -27
very strong cold stress		Below +4	-27 to -40
extreme cold stress			below -40
[1)] (McIntyre, 1980) [2)] (Blazejczyk, et al., 2012) [3)] (Bröde, et al., 2012)			

2.3 Standards and guidelines regarding thermal comfort

In this section international and European standards dealing with thermal comfort will be discussed. The European standard for defining thermal comfort limits is EN15251 which refers to ISO 7730 concerning definition of thermal comfort using *PMV* method. The British CIBSE guide A also covers thermal comfort in buildings as well as the US standard ASHRAE standard 55. All of the above mentioned standards are focused on spaces with low (sedentary) activity and typical indoor clothing (office environment), they refer to the *PMV* method for assessing thermal comfort in air conditioned spaces. They include the adaptive method, when the assessed spaces are non-conditioned. Table 6 summarizes the information within the different standards.

2.3.1 EN 15251 – ISO 7730 (*PMV*)

The standard recognizes six factors affecting thermal comfort – T_a, *MRT*, v_a, *RH*, clothing and activity level. It uses three building categories for assessment of different type of buildings. The requirements for the thermal climate of the three categories are presented in Table 4 EN15251 recommends *PMV* as method for assessment of thermal comfort in air conditioned buildings. For free running buildings an AM is recommended for defining lower and upper limit for operative temperature, depending on the outdoor running mean temperature, by using equation 3.

For assessment of local discomfort due to draft or radiant asymmetry the standard refers to ISO 7730 where formulas for *PPD* are presented.

The standard suggests three methods for long term assessment of the thermal climate. A method assessing the percentage of hours outside the comfort limits is used in this work. The standard suggests that for a space to be within a specific category, the conditions in 95% of the time should be within the limits of that category.

Table 4. Deviation from neutrality for different building categories according to EN 15251 for *PMV* and AM.

Category	PMV	AM
1	±0.2	±2 ºC
2	±0.5	±3 ºC
3	±0.7	±4 ºC

2.3.2 ISO 7730

This standard gives recommendation on using the *PMV* and *PPD* indices developed by Fanger, 1970, when assessing thermal comfort. It specifies the limits for the environmental and personal parameters for which the *PMV* model is valid, the limits are presented in Table 5. Examples are given of operative temperature - T_{op} limits for different types of spaces with standard activity and clothing according to the season, *RH* set to 60% for summer and 40% for winter. However, in examples of *PMV* for different combinations of T_{op}, v_a, clothing and activity *RH* is 50%. It is noted that the humidity has limited impact to the thermal sensation and an increase of 10% in *RH* is equal to 0.3 ºC increase in T_{op}.

ISO 7730 suggests three space categories corresponding to the three categories used in EN 15251. Local discomfort is addressed by providing formulas for *PPD* depending on different local factors, namely draughts, vertical temperature difference, warm and cool floors, and radiant asymmetry. The *PPD* of local discomfort is not to be added to the *PPD* acquired from *PMV* calculations. This means that they are assessed separately and neither of them should exceed the recommended limits.

Table 5. Limitation for environmental and personal parameters when calculating *PMV* according to ISO 7730

Parameter	Limits
T_a	10 ºC to 30 ºC
MRT	10 ºC to 40 ºC
v_a	0 m/s to 1 m/s
p_a	0 Pa to 2700 Pa
Clothing	0 clo to 2 clo
activity	0.8 met to 4 met

2.3.3 ASHRAE standard 55

Similarly to the EN15251, ASHRAE standard 55 also considers the same six factors affecting thermal comfort. It is noted that the recommendations in this standard refer to indoor spaces for human occupancy with duration no less than 15 min.

The standard has two building categories according to the thermal climate, the first has 90% acceptancy on maximum of 10 % *PPD* and the second has 80 % acceptancy. For the second category the *PPD* from calculations of *PMV* should not be higher than 10 %, the additional 10 % are considered for local discomfort.

When the AM is to be applied the standard gives two limits one for 80 % acceptancy and another for 90 %. The AM is recommended only for non-conditioned spaces, the formula of the AM in ASHRAE is presented in Table 6. For 80% acceptancy the deviation is ±3.5 ºC and ±2.5 ºC for 90 %.

Long term evaluation of thermal conditions is suggested to be carried out by calculating hours with thermal conditions outside the comfort limits. However, no limits for these hours are implemented. Four other methods are suggested, it is noted though that they are not required from the standard and no recommendations for limits are implemented.

2.3.4 CIBSE Guide A

The standard recognizes six factors affecting thermal comfort – T_a, *MRT*, v_a, *RH*, clothing and activity level. It uses three building categories for assessment of different type of buildings.

CIBSE Guide A suggests both *PMV* and adaptive method as valid methods for assessing thermal comfort. Unlike the other standards it also includes an AM suited for assessment of air-conditioned buildings. The standard considers deviation of ±2 ºC from the comfort temperature to be acceptable. When the *PMV* method is to be used the standard recommends a deviation of ±0.25 in *PMV* values to be acceptable and also states that ±0.5 can also be considered acceptable for *PPD* of 80 %. For the calculation procedure of *PMV* the guide refers to ISO 7730.

Factors causing local discomfort are also considered. Guidelines are given for the effect on comfort of vertical temperature difference, horizontal temperature differences, and radiant asymmetry and the allowable *PPD* indices for each of these factors. The effect of shortwave radiation falling on the occupant is also presented in the standard.

The issue of overheating is discussed and recommendations are given that a bench mark temperature should be set and it should not be exceeded for a certain number or percentage of occupied hours.

Table 6. Summary of standards conserning thermal comfort

	EN 15251	**ASHRAE standard 55**	**CIBSE guide A**
Building categories	I, II, III	90% and 80% acceptancy	90% and 80% acceptancy
Use of AM	Non-conditioned buildings	Non-conditioned buildings	Conditioned and non-conditioned buildings
AM	$T_{comf} = (0.33 \times T_{rm}) + 18.8$	$T_{comf} = (0.31 \times T_{rm}) + 17.5$	$T_{comf} = (0.33 \times T_{rm}) + 18.8$ $T_{comf} = (0.9 \times T_{rm}) + 22.6$*
Long term evaluation	3 methods, including limits	5 methods, limits not included	Using a recommended benchmark temperature
*For air-conditioned buildings			

2.4 Thermal comfort in transitory spaces

As mentioned before when it comes to thermal comfort the available standards require longer period of occupation - minimum 15 minutes. In transitory spaces the duration of occupancy can be much shorter and the thermal environment can be considered as less important than the environment in the rest of the building. However, these areas can have important impact on the comfort perception of the occupant for the whole building as well as on their expectation (Pitts, 2013).

The transitory spaces have some special characteristics that strongly affect the thermal perception of occupants, among those can be: strong connection to the outdoor environment, activity level higher than sedentary; clothing level similar to outdoor clothing and as mentioned short occupation period. Considering those factors, it can be concluded that in transitory spaces AM is an appropriate choice for predicting comfort (Pitts, 2013).

Three types of transitory spaces have been recognized by Pitts, shows the type of spaces and the suggested method for assessing thermal comfort and the respective limits. In another field study for using AM for assessment of the thermal environment in transitory space is was concluded that the comfort limits of T_{op} for transitory spaces can be extended by 10 % of what is recommended in ASHRAE standard 55 (Hui & Jie, 2014).

In the method developed within this thesis an AM for non-conditioned spaces with 10% extended comfort limits is used for spaces that have connection with the exterior and the clothing level of the occupants is influenced by the outdoor conditions.

Table 7. Groups of transitory spaces, their characteristics and comfort limits

Type of space	**Characteristics**		**Comfort model**	**limits**
Entrance zones	activity	1.2 to 2.6 met,	AM	10 % wider span from the T_{op} limits suggested in standards
	clothing	0.5 to 2.0 or higher clo (likely to be higher than indoors)		
	occupancy	5 min residence.		
Circulation zones	activity	1.0 to 2.0 met	PMV	±1,5
	clothing	clothing likely to be as indoors 0.5 to 1.0 clo		
	occupancy	5-10 min		
Longer-term occupancy zones (atria)	activity	depending on the function	PMV	±1
	clothing	0.5-1.0 clo - likely to be as indoors		
	occupancy	10-30 min residence		

2.5 Thermal comfort in semi-external spaces

Concerning thermal comfort in semi-external or external spaces there are no standards to give recommendations or guidelines for the comfort limits. For evaluation of the thermal conditions outdoors different thermal indices have been used, among which is the UTCI index, which is also implemented in the method developed within this work. An assessment scale has been developed that can be used to evaluate the thermal stress imposed on humans (Bröde, et al., 2012). In a study of outdoor comfort it was concluded that UTCI was an appropriate index for this purpose (Park, et al., 2014).

Outdoor comfort is different from indoors not only because of the much larger deviation in the environmental factors but also because of the psychological factors that affect human thermal perception (Honjo, 2009). This is confirmed in another study, where the authors also state that it is presently not possible to quantify the effect of these psychological factors (Nikolopoulou & Steemers, 2003).

It is considered that in environments perceived as natural the tolerance to different thermal conditions is very wide. It has been shown that by adding vegetation into an empty space the tolerance towards variation in thermal environment has increased significantly (Nikolopoulou & Steemers, 2003). This is an important factor for planning of semi-external and external spaces, however the limited knowledge in this area does not allow for this factor to be included in the method developed within this work.

3 Methodology

In the following sections the methodology of this work is presented. The comfort models used, the steps of the methodology, and suggested methods for acquiring necessary input data, are described in detail.

3.1 Grouping of spaces

A rather exhaustive list of possible architectural spaces was created using an architectural handbook (Neufert & Neufert, 2000). Further for each space a typical group for activity and clothing group was assigned as well as the level of adaptation possibility and if the space is internal or external. Groups of spaces with similar characteristics were created and assigned to specific models for predicting thermal comfort by following the guidelines of EN 15251 and the literature review carried out. Table 8 summarizes the resulting groups of spaces, their characteristics and the thermal comfort models considered appropriate to describe the requirements of the space.

It should be noted that the choice of comfort model also will depend on the environmental factors that have most significant effect on the comfort, considering the space of question. For example, in a highly glazed atrium the solar component will play significant role in defining the thermal environment, therefore a model that incorporates the effect of shortwave radiation should be used. This can be achieved by including the solar component in the calculation of *MRT* and using the prescribed model. Another example can be given with a courtyard area where, besides the solar radiation, an important factor also is the v_a, thus a model which considers the effect of both factors should be used - *UTCI*.

Table 8. Summary of space groups, their characteristics and comfort models

Spaces	**Subgroup**	**Characteristics**	**Models**
Specialized spaces	Sports halls	high activity level (heavy work) , limited adaptation	*PMV*
	Special exam rooms	Low activity, no adaptation possibility, low clothing level	*PMV*
Spaces for low activity	Institutional spaces (lecture halls/reading areas)	Low (close to resting) activity level, typical indoor clothing, limited adaptation possibility; typically indoors	*PMV*/AM
	Recreational (coffee, restaurants, theatre halls)	Low (close to resting) activity level, adjustable clothing level, limited adaptation possibility; indoors	*PMV*/AM
Spaces for sedentary activity	Office work space	Light (sedentary) activity; typical indoor clothing; adaptation can be limited; indoors	*PMV*/AM
	Residential	Diversity of activities; clothing level depending on preferences; fool control over the environment; indoors	*PMV*/AM
Semi-external spaces	Court yards; extensions of cafés; recreational/ waiting areas; retail	Light (sedentary) activity or resting; clothing level according to outdoor conditions; control only to the personal factors (clothing and activity); outdoors	UT*CI*
Transitory spaces	Entrance areas	Light (walking) activity; clothing corresponding to outdoor conditions; limited adaptation; indoors	*PMV*/AM (transitory)
	Connecting corridors	Light (walking) activity; typically indoor clothing; limited adaptation; indoors	*PMV*/AM
	Atria; waiting areas	Low (close to resting) to light (walking) activity; clothing level depending on preferences; limited adaptation; indoors/outdoors	*PMV*/AM (transitory)/ *UTCI*

3.2 Models used

Three different AMs and two thermal indices were used for developing the method. The *PMV* index and the AM for non-conditioned spaces are standard recommended (EN 15251, 2007), while the other two AMs and the *UTCI* index used for defining comfort in semi-external spaces were chosen based on the background literature review.

The standards EN 15251 and ISO 7730 were used as guidelines for defining comfort limits. Only in the case of *UTCI* method the comfort boundaries are based on literature. The three space categories described in EN 15251 were used to define comfort limits for different expectation and design goals. The models used are further described in the following sections.

3.2.1 PMV

As stated in the standards (EN 15251, 2007) the *PMV* method should be used for air-conditioned buildings. For the calculation of *PMV* computer code was used, which is included in the ISO 7730, it was suited for Visual Basic for Applications - VBA (Farini, n.d.).

In calculation of *PMV* all the six parameters, affecting comfort, were considered. Clothing and activity level are set as inputs from the user. T_a, *MRT* and v_a are also inputs from the user, but can be changed interactively, for finding combinations of those parameters, that are within comfort limits. *RH* is set to 50 % for all calculations of *PMV* as this is the standard value used in calculating examples of PMV in ISO 7730, but can also be adjusted by the user, if the specific case requires it. This was considered to be reasonable simplification as often RH is not known by the designers and as discussed before it has limited effect to thermal sensation, when the conditions are close to comfort.

Comfort limits suggested in EN 15251 are used, incorporating the three categories of spaces suggested in the standard. The values of *PMV* for the different categories are presented in Table 9.

Table 9. *PMV* limits for the three categories stated in EN 15251

	Category I	**Category II**	**Category III**
PMV limitations	-0.2 to + 0.2	-0.5 to + 0.5	-0.7 to + 0.7

3.2.2 AM for non-conditioned buildings (EN 15251)

For non-conditioned buildings the recommended AM from EN 15251 was used. The comfort temperature is defined by equation 7, presented in section 2.2.3.

The method of calculating T_{op} and T_{rm} are defined in sections 3.3 and 3.4 respectively.

Comfort limits are defined by using the standard recommendations for the three categories. The allowable deviations for the different categories are presented in Table 10. Using the above mentioned formula - equation 7 and comfort limits, upper and lower limits were defined for different categories. This is presented in Figure 1, where the *x*-axis presents the outdoor running mean temperature, T_{rm} and on the *y*-axis is presented the comfortable operative temperature, T_{comf} . The red lines show the upper comfort limits for the three categories. The number of the category is indicated next to the line which represents it. In the same way the lower comfort limits are presented in blue with a number beside them indicating the corresponding category. For example, if the T_{rm} is 20 °C and the required category is I, the lower limit for T_{op} is 23.4 °C and the upper limit is 27.4 °C.

The codes for calculating the T_{comf} , upper and lower boundaries are included in Appendix C.

Table 10. Allowable deviation from T_{comf} for three different categories according to EN 15251

	Category I	**Category II**	**Category III**
Allowable deviations form T_{comf} / °C	±2	±3	±4

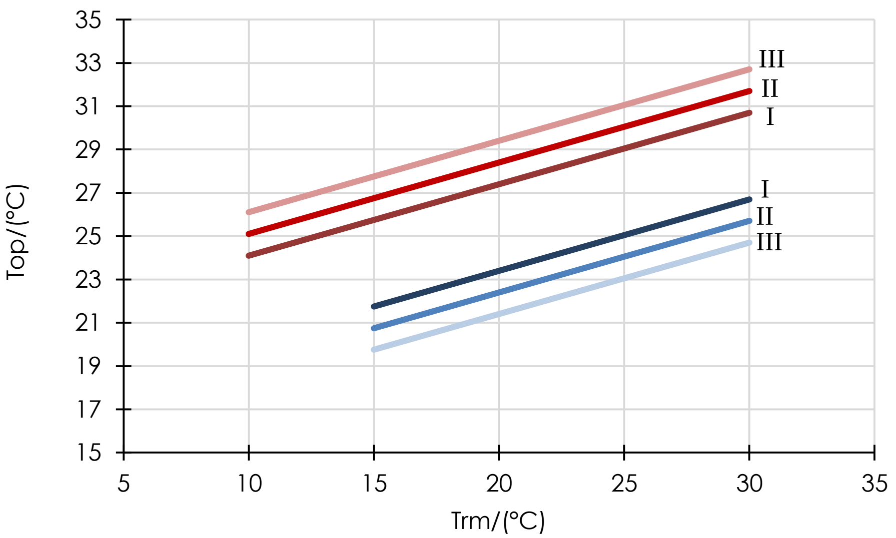


Figure 1. Comfort limits for T_{op} for non-conditioned spaces.

3.2.3 AM for conditioned buildings (Adaptive thermal comfort)

Even though the standards do not recommend using an AM for defining comfort limits in conditioned buildings, Nicol, et al., 2012 has suggested that there is no reason to consider it is a problem. CIBSE Guide A also includes the formula of AM for conditioned spaces. Therefore, AM for conditioned buildings was adopted for this method. The model is described by equation 8, presented in section 2.2.3.

To define the comfort limits for the different building categories the allowable deviations from T_{comf} recommended in the standard were used, as presented previously in Table 10. The comfort model is graphically presented in Figure 2, where the *x*-axis presents the outdoor running mean temperature, T_{rm} and on the *y*-axis is presented the comfortable operative temperature, T_{comf} . The figure can be read in similar way as Figure 1, explained in the previous section for AM for non-conditioned spaces.

The codes for calculating the T_{comf}, upper and lower boundaries are included in Appendix D.

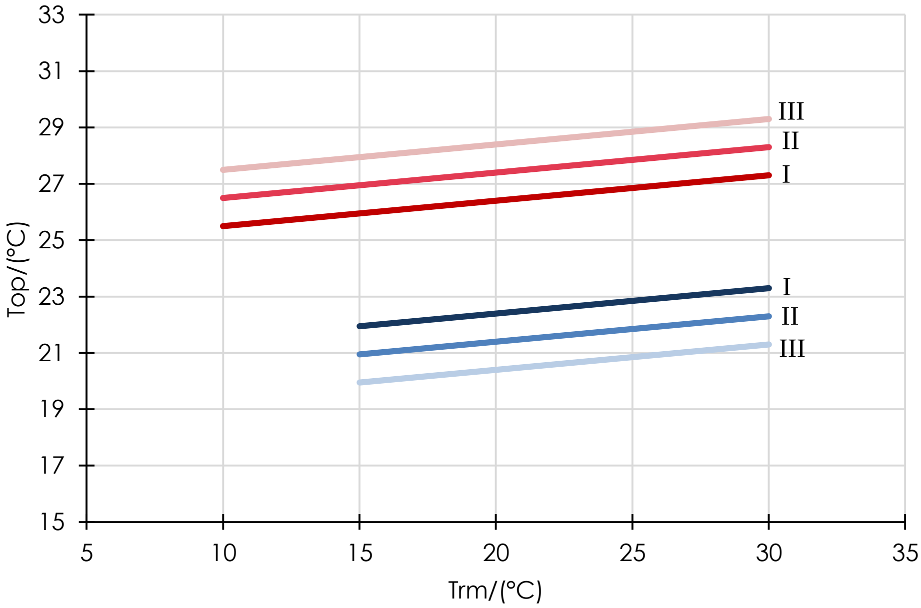


Figure 2. Comfort limits for T_{op} for conditioned spaces.

3.2.4 Extended AM for transitory spaces

For transitory spaces the standards do not specify a different model, this spaces are addressed in the same way as the normal environment of light sedentary work with typical indoor clothing. However, the transitory spaces differ from the typical work environment in activity and clothing level. Another important factor for thermal comfort in transitory spaces is the close connection to the exterior and the effect of outdoor conditions to the thermal comfort in such spaces. Hui & Jie (2014) has suggested that for transitory spaces an AM for non-conditioned buildings should be used and the comfort limits can be extended by 10 %. Therefore, the comfort model for transitory spaces used in this method is described by the equation 7 presented in section 2.2.3. The comfort limits for the different categories are increased by 10 % and are presented in Table 11. The graphical presentation of the model can be seen in Figure 3, where the *x*-axis presents the outdoor running mean temperature, T_{rm} and on the *y*-axis is presented the comfortable operative temperature, T_{comf} . The figure is to be interpreted similar way as explained in section 3.2.2 for AM for non-conditioned buildings. The codes for calculating the T_{comf} , upper and lower boundaries are included in Appendix E.

Table 11. Allowable deviations form T_{comf} for three different categories

	Category I	**Category II**	**Category III**
Allowable deviations form T_{com} / °C	±2.2	±3.3	±4.4

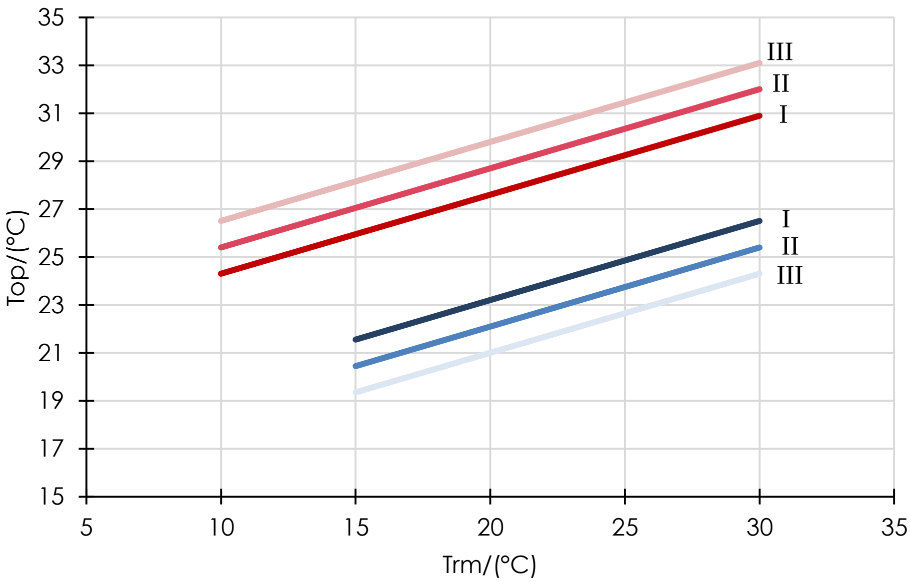


Figure 3. Comfort limits for T_{op} for transitory spaces.

3.2.5 UTCI

As mentioned before the *UTCI* was chosen to define thermal comfort in semi-external spaces. It was chosen because of the wide range of conditions for which it is suitable and also the adaptiveness of clothing level included in the index by the clothing model used to calculate the clothing level as function of the air temperature. The activity level assumed in the model is also suitable for the current use.

The *UTCI* is calculated as the air temperature of a reference environment that will result in the same thermal sensation as the actual environment. The conditions for the reference environment are explained previously in section 2.2.6.4. It can be defined by equation 9. (Bröde, et al., 2012).

$$UTCI\ (T_a; MRT; v_a; p_a) = T_a + Offset(T_a; MRT; v_a; p_a) \qquad (9)$$

The computer code for calculating *UTCI* in Fortran is provided by the *UTCI* web page and is translated into C# by James Ramsden (Ramsden, n.d.), this was used further to develop a VBA code suitable for use in this method. The full VBA code used in this work can be found in Appendix E. It should be noted that the limits for the environmental parameters for which the code is valid are as follows:

- T_a between -50 °C and +50 °C
- *MRT* between T_a – 30 °C and T_a + 70 °C
- v_a between 0.1 m/s and 17 m/s.

To evaluate the comfort using *UTCI* a scale suggested by Bröde, et al., 2012 was used. It was previously described in section 2.2.6.

3.3 Steps of the method

The method developed within this work summarizes the different comfort models used in international and European standards, as well as some findings from literature available on the topic. The models included in the method were described in the previous section. By following this method, a designer should be able to find an appropriate comfort model for a space with given characteristics and explore the limitations for the environmental parameters: T_a, *MRT*, v_a and *RH*. Further it is possible to assess the thermal conditions in a space according the different models.

The method is organized in the following steps:

- Based on the space type, clothing and activity, comfort models are recommended. Information is given on standard recommendation for using different comfort models.
- Comfort boundaries for T_a, *MRT* and v_a are defined based on the recommended models. It is possible to test different combinations of these parameters.
- Long term evaluation of the thermal comfort is achieved by evaluating the thermal conditions for occupied hours during one year.
- Deviation from comfort are plotted on a chart for different occupant's locations.

Figure 4 provides an overview of the method steps and the necessary input data needed in the different steps. Each step is further described in detail in the following sections. In the figure the abbreviations AMN, AMC and AMT are used for Adaptive Model for Non-conditioned spaces, Adaptive Model for Conditioned spaces and Adaptive Model for Transitory spaces respectively.

In order to access specific design in step 3 it is necessary to input view factors, surface temperatures, *MRT*, T_a, solar irradiation – *Q*, v_a, *RH* and T_{rm}. For these inputs the user needs to use other tools or simulation programs. Suggested methods for acquiring input data for this step are presented in section 3.4.

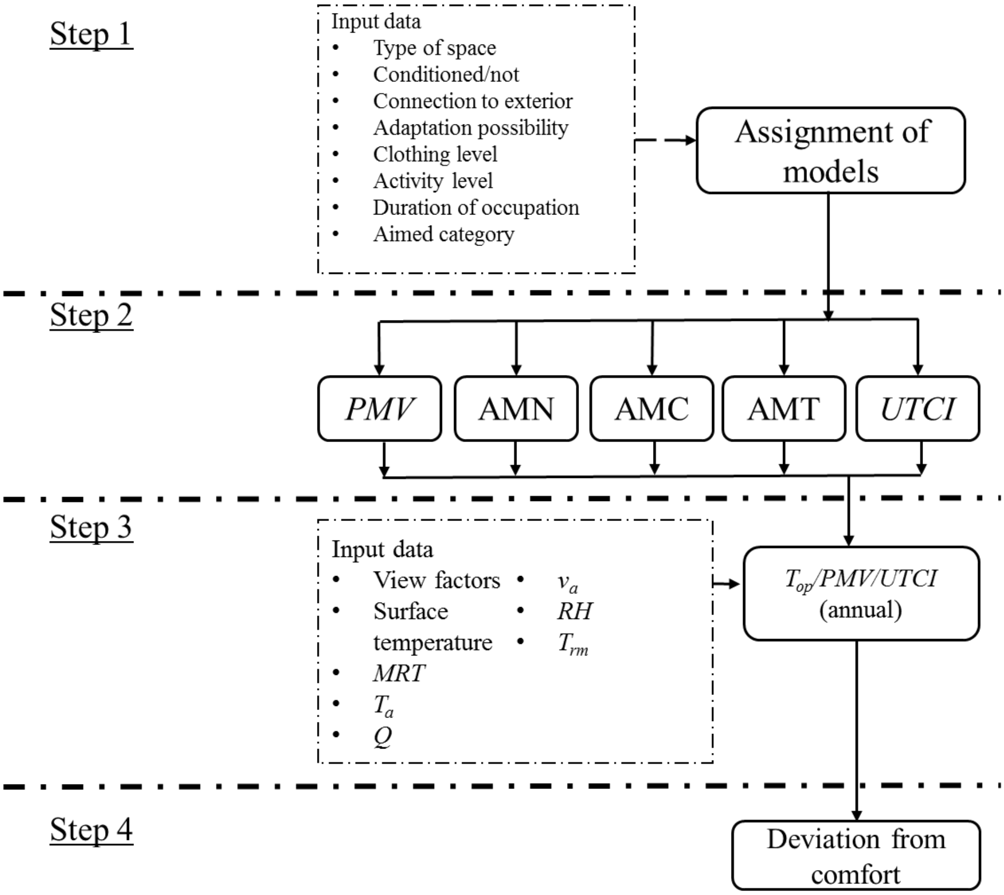


Figure 4. Overview of the methodology plan

3.3.1 Step 1 - assignment of models

In this step basic design information is required in order to recommend a specific model to describe the thermal comfort in a particular space. The input parameters and their lists of options are presented in Table 12. The number of clothing and activity level group corresponds to a group of clothing assembly and activity type as described in Table 13 and Table 14.

Table 12.Input parameters and the respective lists of options for step 1 - assigning comfort models

Input parameter	**Options**
space type	Internal / Semi-external
conditioned	Yes / Part time/ No
adaptation possibilities	full control / partial control / no control
typical clothing level group	1 / 2 / 3 / weather dependent *
typical activity group	1 / 2 ‡
duration of occupation	Short / Long
connected to exterior	Yes / No
estimated clothing	Number in clo given by the designer
estimated activity level	Number in met given by the designer
category	I/ II / III
* The different groups, the clothing assemblies and insulation values are presented in Table 13 ‡The different groups, the activities and the metabolic rates are presented in Table 14	

Table 13. Clothing level groups and typical clothing assemblies

Group	number	ensembles	clo
Light clothing	1	panties, T-shirt, light socks, sandals	0.3
Indoor clothing	2	underpants, shirt with short sleeves, light trousers, light socks, shoes	0.5
		panties, petticoat, stockings, dress, shoes	0.7
		underwear, shirt, trousers, socks, shoes	0.7
		underpants, boiler suit, socks, shoes	0.7
		underpants, shirt, boiler suit, socks, shoes	0.8
		underpants, shirt, trousers, smock, socks, shoes	0.9
		panties, shirt, trousers, jacket, socks, shoes	1
		underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1
		Panties, stockings, blouse, long skirt, jacket, shoes	1.1
Heavy outdoor clothing	3	underwear with long sleeves and legs, thermo-jacket, socks, shoes	1.2
		underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes	1.3
		Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	1.4
		Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1.5
		Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves, socks, shoes	2
		Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quitting, overalls with heave quilting, socks, shoes, cap, gloves	2.55

Table 14. Activity level group and typical activities

group	**number**	**activity**	**met**
resting	1	sleeping	0.7
		reclining	0.8
		seated, quiet	1
		seated reading or writing	1
Light work	2	typing	1.1
		standing, relaxed	1.2
		filing, seated	1.2
		filing, standing	1.4
		cooking	1.6
		walking about	1.7
		sawing (table saw)	1.8
		walking, 0.9 m/s, 3,2 km/h	2
		house cleaning	2
		machine work (light electrical industry)	2
Heavy work	3	Lifting packing	2.1
		seated, heavy limb movement	2.2
		dancing, social	2.4
		walking, 1.2 m/s, 4.3 km/h	2.6
		calisthenics/exercise	3
		tennis	3.6
		walking, 1.8m/s, 6.8 km/h	3.8

As outcome of this step, three values are given: standard recommended model, suitable model and type of AM to be used, if an adaptive approach is standard recommended or suitable. Graphic presentation of the algorithm for choice of comfort model is presented in Figure 5.

In the figure with black outline are presented the steps taken to identify the comfort model that is recommended by the standards. In case the standards do not cover the type of space in question the value “---“ is given. In the figures with blue outline are the steps necessary to determine a suitable comfort model based on the background literature review. In green outline are the steps taken to define the type of AM to be used, when it is suitable or standard recommended. The VBA codes for defining these values can be found in Appendix A.

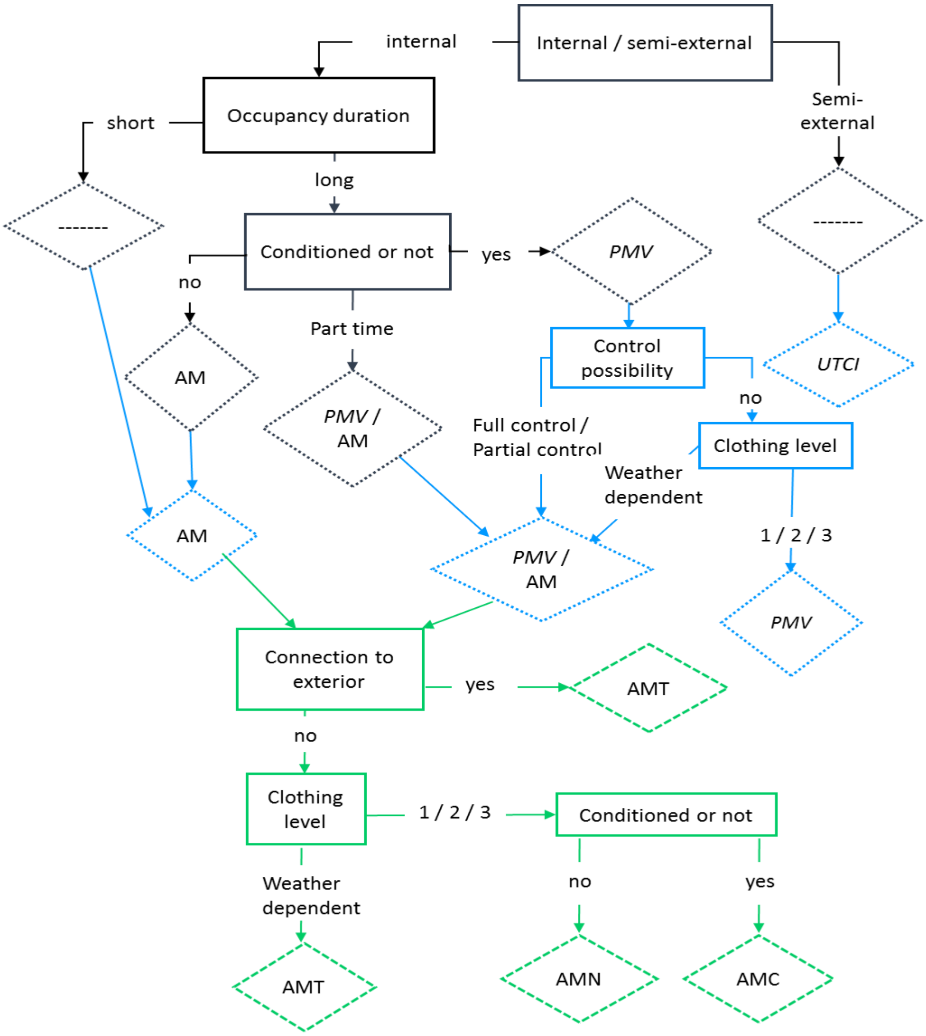


Figure 5. Overview of the algorithm for assigning comfort models

3.3.2 Step 2 - defining comfort boundaries

Different sheets in the excel file are developed for each comfort model. After guiding the user to a comfort model he/she is given a possibility to test different combinations of *Ta*, *MRT* and v_a and *RH*. A value for *PMV*, T_{op} or *UTCI* is calculated for each combination of parameters. Indicative colors are used to notify if the value is within, above or below the comfort limits, blue – below; green – within comfort, red- above.

The limits for the parameters are presented in Table 15 and are according to the recommended limits for calculating PMV in ISO 7730. It should be noted that v_a can be up to 1 m/s, but EN 15251 has stated that 0.8 m/s is the limit for comfort conditions. This limits were also used for calculations for AMs. For the calculation of *UTCI* the limitations were expanded as the *UTCI* was used for evaluation of outdoor conditions where the variations of environmental parameters are larger than indoors.

Table 15. Limitations for the environmental parameters for different comfort models adopted in the method

Parameter	**Limits for *PMV* and AMs**	**Limits for *UTCI***
T_a	10 ºC to 30 °C	0 °C to 40 °C
MRT	10 ºC to 40 ºC	0 °C to 50 °C
v_a	0 to 1 m/s (0,8 m/s is the limit for comfort)	0 m/s to 1 m/s
RH	0 to 100 %	0 % to 100 %

For *PMV* and *UTCI* calculations the VBA codes mentioned before were used. Where the recommended model was adaptive T_{op} was calculated using equation 10 (ISO 7726, 1998).

$$T_{op} = \frac{T_a * \sqrt{v_a} + MRT}{1 + \sqrt{10 * v_a}} \tag{10}$$

Furthermore informative graphs were created where for a certain value of v_a combinations of *MRT* and T_a within comfort limits were presented, see Figure 6 and Figure 7. Standard guidelines are shown for the maximum and minimum recommended *MRT* as it is calculated in the ISO 7730, where the *PMV* example values are calculated with difference between *MRT* and T_a no larger than 5 ºC. These guidelines are also shown for AMs, as it is recommended that in indoor environments there should not be too large difference between *MRT* and T_a. The VBA codes for calculating the combinations for each of the comfort models can be found in Appendix B for PMV, Appendix C for AM for non-conditioned spaces, Appendix D for AM for conditioned spaces, Appendix E for AM for transitory spaces, and Appendix F for *UTCI* model.

The first informative graph presents *MRT* and v_a for given T_a and in the case of *PMV* and *UTCI* also given *RH*. An example is shown in Figure 6, where *MRT* and v_a for given T_a = 25°C and *RH* = 50% are presented. The green bars of the graph represent the *MRT* values for different v_a that result in comfortable conditions. The area highlighted in green is the area where *MRT* is within the limit of T_a ±5 °C. The areas highlighted in light red include values of *MRT* that are within the comfort limits but are outside the limit of T_a ± 5 °C. The purple area of the graph indicates that the air velocity is higher than the limit for comfort of 0.8 m/s. The areas are indicated with limit lines that are calculated for each value of T_a examined. The different areas of the graph would not be colored when presenting results, for simplicity reasons. From the graph it can be read for the given T_a what the limits are for *MRT* at which for example natural ventilation can be sufficient and when it is necessary to add solar control in order to reduce the *MRT*.

The second informative graph presents *MRT* and T_a for given v_a and in the case of *PMV* and *UTCI* also given *RH*. An example is shown in Figure 7, where *MRT* and T_a are presented, for given v_a = 0.1 m/s and *RH* = 50 %. In this graph the limits for *MRT* of T_a ± 5 °C are shown with red lines. The green area shows values of *MRT* within this limit. The light red areas show *MRT* values that would still result in comfort conditions but are outside the limit of T_a ± 5 °C. This information is useful for finding appropriate cooling/heating set point and the allowable span of *MRT*. This can inform the designer of possibility to use passive measures as using shading devises or solar gains, and when active heating or cooling needs to be applied.

When *UTCI* is used as comfort model the limitations for *MRT* and v_a are not considered as wider variations are acceptable in external or semi-external environments.

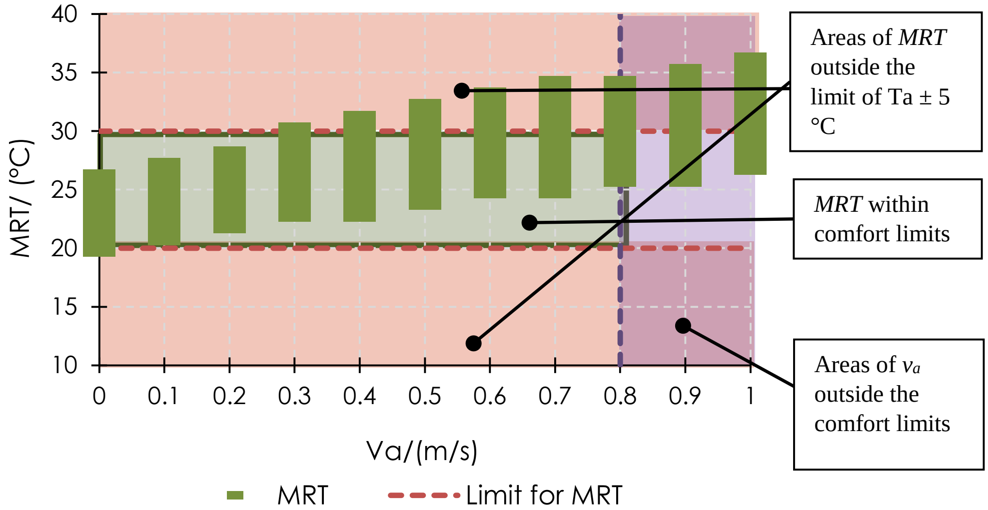


Figure 6. Example of informative graph, presenting *MRT* and v_a for given T_a = 25°C and *RH* = 50%

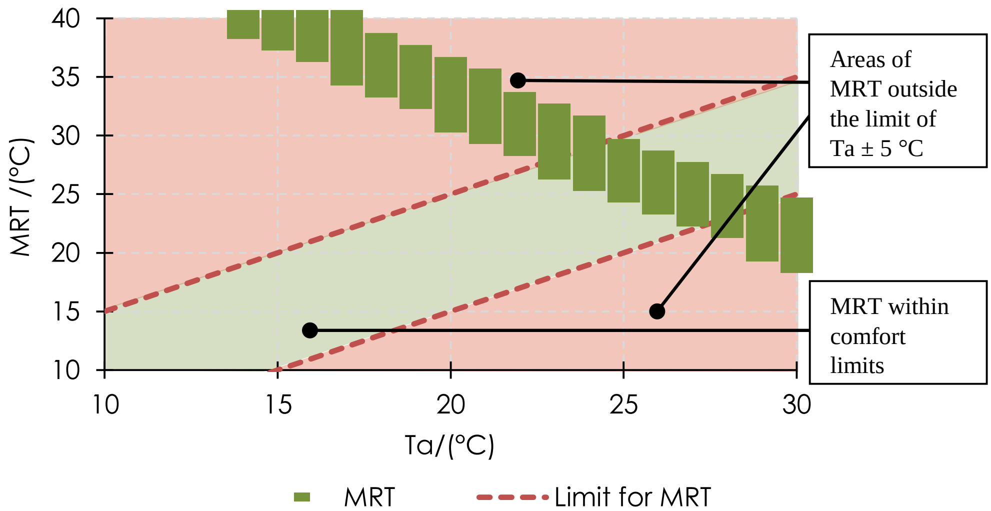


Figure 7. Example of informative graph, presenting *MRT* and T_a for given v_a = 0.1 m/s and *RH* = 50%

3.3.3 Step 3 and 4 - Design assessment

In the excel tool a separate sheet is created for annual assessment of the comfort for all occupant positions. In this sheet the user is given the option to input the view factors to the surrounding surfaces and the surface temperatures for each hour; or the hourly *MRT*, T_a and the solar irradiation or directly the hourly T_{op}. For the cases where *PMV* is the recommended model *MRT* and T_a are required. For the cases where the recommended model is adaptive T_{rm} is a necessary input in order to calculate the comfort limits. V_a is set to 0.1 m/s but can also be inserted as hourly input from the user. For RH a standard value of 50% is set and can also be changed by the user.

From the calculated comfort indices and limits a deviation from the comfort is calculated. When the *PMV* method is used for assessment the deviation from comfort is equal to the *PMV*; when AM is used the deviation is calculated as difference between the hourly T_{op} and the calculated neutral temperature. For *UTCI* model, when the index is within the comfort limits the deviation is zero, when outside the limits the deviation is calculated as the difference between *UTCI* and the upper or lower limit depending on if it is above or below the comfort conditions. The VBA codes for calculating hourly deviation from comfort can be found in Appendix G.

It should be noted that for the annual assessment the restrictions for *MRT* to be within the limits of T_a ± 5°C are not considered, neither is the limit for v_a of 0.8 m/s. Radiant asymmetry is also not assessed.

The hourly data is analyzed by creating a histogram with steps corresponding to the comfort requirements for different building categories and comfort models, described in section 3.2. Figure 8 shows example graphs where the data is plotted for the cases where the *PMV* model is used. Figure 9 shows example graphs where the data is plotted for the cases where the AM for conditioned and non-conditioned or the *UTCI* model is used. Figure 10 shows example graphs where the data is plotted for the cases where AM for transitory spaces is used. The number of hours and the percentage can be read in the graph. Figure 10 presents an example graph where an AM is used to assess the comfort conditions. The values falling within a certain category are indicated with different shades of green, as can be seen from the graphs. The specified categories are not used when the *UTCI* model is implemented as the standards do not deal with outdoor comfort. The blue color indicates values lower than any category and the red color indicates values higher than any category.

It should be noted that the steps at which the data is divided are not the same for all the graphs and this is due to the specific comfort limits for the different models described in section 3.2. The steps within a graph are not always equal due to the same reason. For example in Figure 10, when looking to the value of 0 °C deviation this step includes the hours with deviation from -2.2 °C to 0 °C. The next step includes the hours with deviation of 0 °C to 2.2 °C. Those two steps represent category I as indicated in Figure 10. Category II includes the hours with deviation ± 3.3 °C and category III includes the hours with deviation of ± 4.4 °C.

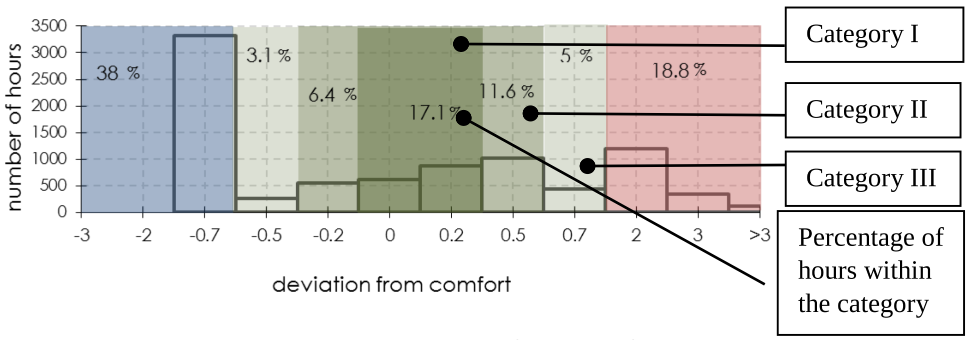


Figure 8. Example graph showing deviation from comfort temperature in °C, when *PMV* for transitory spaces is used for assessment of thermal comfort.

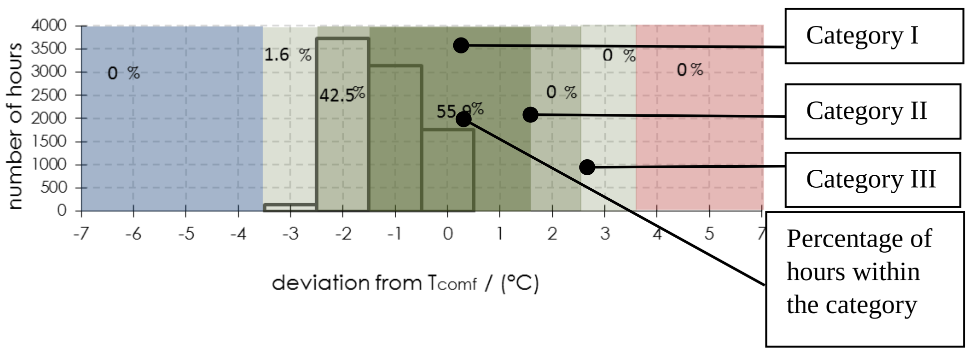


Figure 9. Example graph showing deviation from comfort temperature in °C, when AM for conditioned and non-conditioned spaces or *UTCI* is used for assessment of thermal comfort.

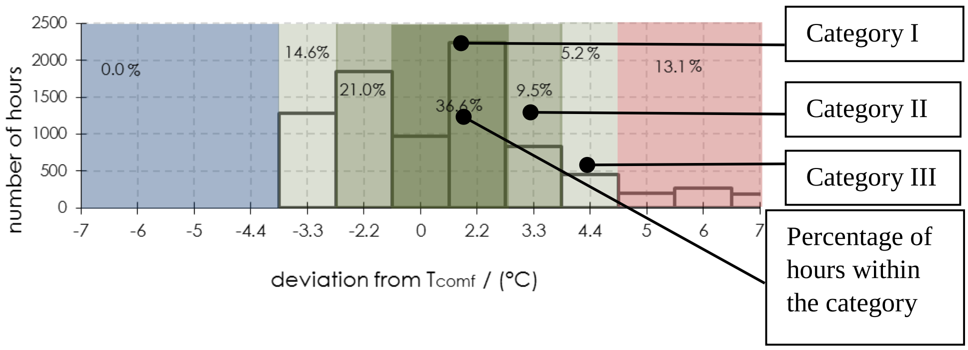


Figure 10. Example graph showing deviation from comfort temperature in °C, when AM for transitory spaces is used for assessment of thermal comfort.

3.4 Suggested methods for acquiring necessary input data

3.4.1 Surface temperature and Ta

For providing surface temperatures and T_a for annual assessment dynamic thermal simulation tools can be used. In this work the software Oasys ROOM was considered appropriate, as it allows evaluation of different occupant's positions (Holmes & Conner, 1991).

3.4.2 *MRT*

For calculation of *MRT* for different occupant positions, it is recommended that the floor of the space examined is divided into grid with a desired size, as shown in Figure 11 in order to have more accurate assessment of different occupant positions in the space. Each grid cell represents an occupant for which view factors to the surrounding surfaces and the surface temperature is required as an input. *MRT* is calculated for each occupant using the formula stated in ISO 7726 – equation 11.

$$T_{mrt}{}^4 = T_1^4 \cdot F_1 + T_2^4 \cdot F_2 + T_3^4 \cdot F_3 + \cdots + T_n^4 \cdot F_n \qquad (11)$$

Where T_{mrt} is the *MRT* in K; T_n is the surface temperature in K; F_n – is the view factor to the respective surface.

For more precise calculation of *MRT*, where the solar radiation is also included, solar irradiation in W/m^2 that is falling on the occupant is also required as an input. The *MRT_corrected* is calculated using equation 12 (Arens , et al., 2015). This is necessary in cases where the solar component has significant effect on the thermal environment.

$$MRT\_corrected = (MRT^4 + 0.65 \cdot Q/(6.57 \cdot 10^{-8}))^{0.25} \qquad (12)$$

Where Q is the solar irradiation in W/m^2.

Dynamic thermal simulation tools are also an appropriate way to acquire MRT for use in the annual assessment.

3.4.3 View factors

In order to calculate the MRT it is necessary to have the temperatures of the surrounding surfaces and the view factors for each of them. The standards provide equations and graphs for calculating the view factors for specific standard positions of the occupant to the surface in question (ISO 7726, 1998). This can be helpful in very limited amount of situations and most often cannot be used for more complicated designs. Therefore, for this study a method was developed using the plugin for Rhino

– Grasshopper. The method uses a sphere, with diameter of 1 m and distance from the floor to the center of the sphere of 1 m, to represent an occupant. The outlines of the surrounding surfaces are projected onto the sphere's surface and the resulted curves are used to split the surface into segments. The area of each segment is divided by the total area of the sphere, resulting in the view factor. This method was originally developed by building designers in ARUP (ARUP, 2015).

By using Grasshopper for this purpose a grid can be created on the floor surface, where at the center of each grid cell a sphere is placed, representing an occupant. Thus the view angles for all the surrounding surfaces can be calculated for multiple occupant positions. Figure 11 illustrates the method implemented to a rectangular space with a window on one wall and a skylight, where six occupant positions are created. The projections of the window and the wall containing the window on one of the occupants are presented in Figure 12 a) and b) - highlighted in green.

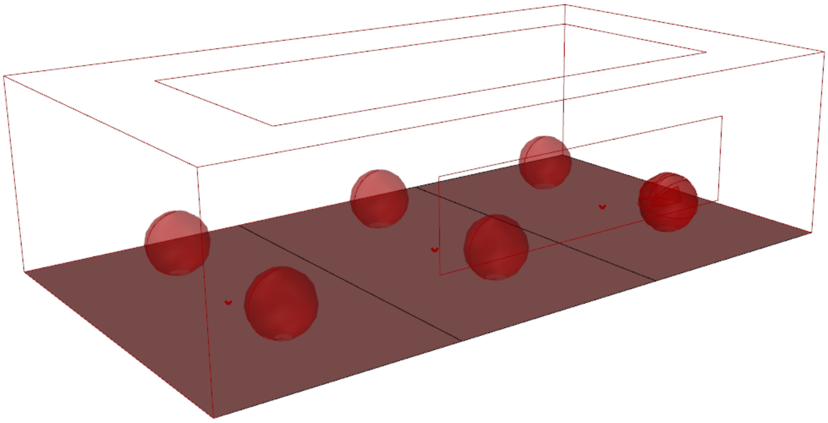


Figure 11. Example of a grid and spheres representing different occupant positions in a space

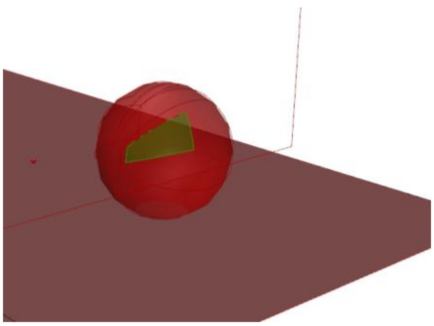
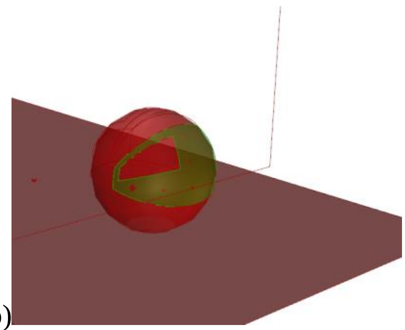
a)  b) 

Figure 12. Projection of a) window and b) wall containing window to the sphere, which represents an occupant

It should be noted that a sphere does not represent perfectly a standing or seated person, therefore the view factors derived through this method will have slight deviations from the real view factors for a person. However, the flexibility for occupant positions and space design that this method gives was considered more important for this work.

3.4.4 Outdoor running mean temperature, T_{rm}

When calculating the limits for T_{op} by using the AMs, T_{rm} is required. The outdoor running mean temperature or T_{rm} is an exponentially-weighted running mean outdoor temperature. This means that it depends on the mean air temperature for several days before, as each previous day has less significant effect. It is calculated by equation 13, included in EN 15251, where the mean air temperature for seven days' period is taken in consideration. A VBA code was developed to calculate the T_{rm} from hourly outdoor temperature, it is presented in Appendix H.

$$T_{rm} = (1-\alpha)\cdot(T_{ed-1} + \alpha T_{ed-2} + \alpha^2 T_{ed-3} + \alpha^3 T_{ed-4} + \alpha^4 T_{ed-5} + \alpha^5 T_{ed-6} + \alpha^6 T_{ed-7}) \quad (13)$$

T_{rm} is the outdoor running mean temperature, T_{ed-1} is the daily mean outdoor temperature one day before, T_{ed-2} is the daily mean outdoor temperature two days before and so on, and α is a constant between 0 and 1.

As recommended in the standard α is taken as 0.8 and the T_{rm} is calculated by including data for seven days before.

3.5 Test/case study

In this section the implementation of the MS excel tool is described with a case study. The study is a project of an indoor zoo complex in south Sweden. It would consist of entrance area, cafeteria, theatre area, play area, and the actual zoo area, which will be thematically divided to different environments. Three types of spaces were examined – the entrance area, the dark theatre area, and area part of the zoo, which should represent an African sunset environment. The following sections describe the methodology of the case study.

3.5.1 Entrance area

The entrance area of this building should be designed so that people will have the opportunity to adjust for the specific indoor environment. Wardrobes will be provided so that the visitors can leave the heavy clothing and prepare for the warm indoor conditions. The thermal environment in this area should also encourage the transition between outdoor and indoor climate. The input data assumed for the first step of the method is presented in Table 16.

The combinations of environmental parameters that fulfill the thermal climate requirements were examined and analyzed. The value for T_{rm} was set to 15°C as an input.

Combinations for *MRT* and T_a were tested for three values of v_a: 0.1 m/s; 0.4 m/s and 0.8 m/s, which cover the tolerable span for v_a. . Further the combinations of *MRT* and v_a for the span of T_a that was recorded were also examined, by looking into three values for T_a: 18 °C; 24 °C and 29°C.

Table 16. Assumed characteristics of the entrance area of the case study

Characteristics of the space	**value**
space type (internal/semi-external)	internal
conditioned	part time
adaptation possibilities	partial control
typical clothing level group	weather dependent
typical activity group	2
duration of occupation	short
connected to exterior	yes
Category	2

3.5.2 Theatre area

The theatre area is characterized with low activity and also low clothing level due to the fact that the visitors of the complex are encouraged to adjust their clothing for the warm conditions in the zoo part. The zone is also conditioned and with no possibility of occupant control over the environment. The assumptions considered for this space are presented in Table 17.

Table 17. Assumed characteristics of the theatre area of the case study

Characteristics of the space	**value**
space type (internal/semi-external)	internal
conditioned	part time
adaptation possibilities	no control
typical clothing level group	1
typical activity group	2
duration of occupation	long
connected to exterior	yes
estimated clothing	0.5 clo
estimated activity level	1 met
category	2

The combinations of environmental parameters that fulfill the thermal climate requirements were examined and analyzed. *RH* in the calculations is considered to be 50% and is not varied as several sources have suggested that it has limited effect to thermal perception while the conditions are close to comfort (Nicol, et al., 2012).

Combinations for *MRT* and T_a were tested for three values of v_a : 0.1 m/s; 0.4 m/s and 0.8 m/s, which cover the tolerable span for v_a. . Further the combinations of *MRT* and v_a for the span of T_a that was recorded were also examined, by looking into three values for T_a = 23 °C; 26 °C and 30 °C.

3.5.3 African sunset area

In this area visitors were encouraged to stay for longer period of time and experience the African environment. The space was internal and conditioned in order to achieve the environmental conditions typical for the desired African setting. However the fact that there would be a lot of vegetation and the environment should be as close to natural as possible the space was considered as semi-external. Some studies have suggested that people have different perception of thermal comfort when the spaces are perceived as natural and it is closer to the thermal comfort of outdoor spaces (Nikolopoulou & Steemers, 2003). Table 18 summarizes the input data used for this space in the first step of the method. Since the space was considered as semi-external the rest of the characteristics were not relevant.

Table 18. Assumed characteristics of the African sunset area of the case study

Characteristics of the space	**value**
space type (internal/semi-external)	semi-external
conditioned	----
adaptation possibilities	----
typical clothing level group	----
typical activity group	----
duration of occupation	----
connected to exterior	----
estimated clothing	----
estimated activity level	----
category	----

The combinations of environmental parameters that fulfill the thermal climate requirements were examined and analyzed. In this area it is important to find environmental conditions, which will be on the lower limit of comfort. The idea was to create a thermal experience for the visitors that mimics the conditions during sunset, meaning that the occupants would feel colder than in the rest of the complex. The specific characteristics of a sunset environment was considered as lowered *MRT* and increased v_a. These conditions were considered for only this part of the zoo; in other spaces the conditions would depend on the theme of the area.

Line was drawn showing *MRT* equal to T_a, thus the combinations of values for *MRT* lower than T_a could be examined as shown in Figure 13.

For this area combinations of *MRT* and T_a were examined for three values of v_a – 0.1 m/s; 0.5 m/s and 1.0 m/s; and for *RH* – 50% and 70%.

Figure 13 shows the informative graph where *MRT* and T_a are examined, modified for the purpose of this case. The green bars represent the allowable *MRT* for different values of T_a. The dotted line indicates the values of $MRT = T_a$. The highlighted area of the chart is where *MRT* is lower than T_a, this will be the zone of interest for this case. It should be noted that this approach is specific for the space in question and this limitation is not necessary to be followed when *UTCI* is used for assessment of thermal conditions. Values for v_a and *MRT* were examined for T_a of 18 °C; 25 °C and 33 °C; and *RH* of 70%; 60% and 50% respectively.

Figure 14 shows the informative graph where *MRT* and v_a are examined, modified for the purpose of this case. The green bars represent the allowable *MRT* for different values of v_a. The dotted line indicates the values of $MRT = T_a$. The highlighted area of the chart is where *MRT* is lower than T_a, this will be the zone of interest for this case. The results are presented in section4.3.

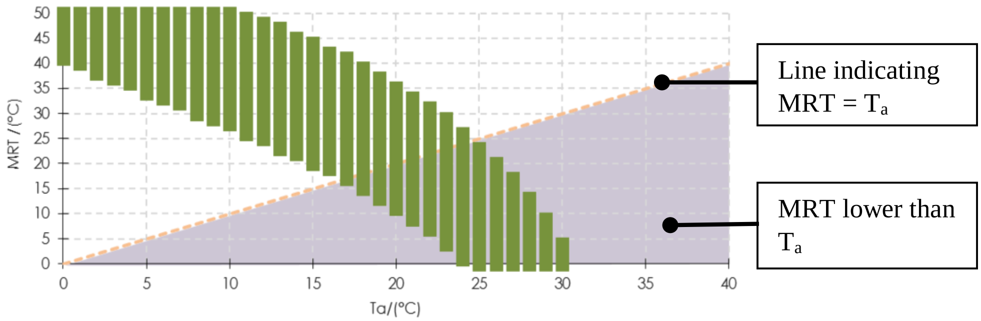


Figure 13. Example graph presenting *MRT* and T_a for given v_a = 0.1 m/s and *RH* = 70 %, when *UTCI* is used for assessing thermal comfort.

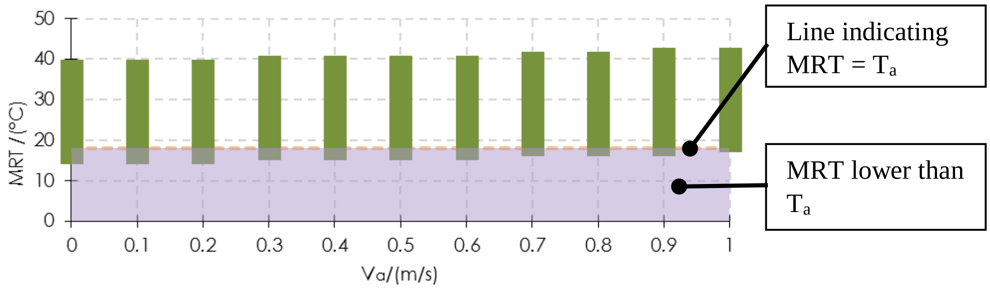
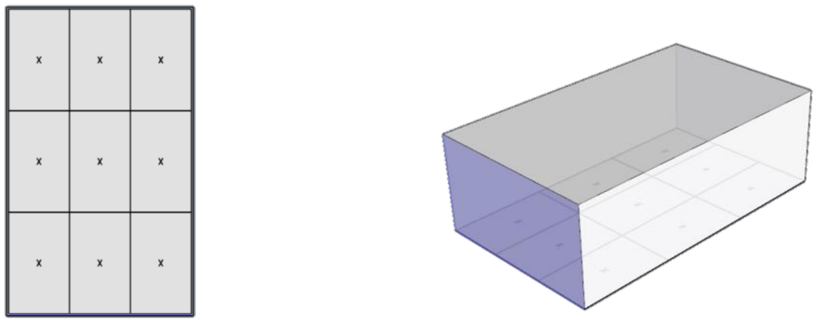


Figure 14. Example graph presenting *MRT* and v_a for given T_a = 18 °C and *RH* = 70 %, when *UTCI* is used for assessing thermal comfort

3.5.4 Annual assessment

In order to demonstrate how the method can be used for annual assessment of specific designs, a room with simple rectangular geometry was chosen. The floor was divided in nine grid cells, the center of each representing an occupant position, Figure 15. The thermal environment in the space was simulated using Oasys ROOM software (Holmes & Conner, 1991). Hourly values for *MRT* and T_a were gathered for each occupant position for one year and were used for assessment of the thermal comfort. For the calculation of T_{op} the value of 0.1 m/s was used for $v_{a.}$

The simulated room was considered to represent the entrance area of the zoo project described in section 3.5.1, with desired category II. AM for transitory spaces was chosen to describe the comfort and to assess the actual thermal conditions. Deviation from T_{comf} was calculated and plotted on informative chart, showing the amount of hours with specific deviation and the standard recommendations for the three categories, see section 3.3.3, for description of the informative chart. An evaluation is made if the specific occupant position classifies for the desired category or not. The requirement stated in EN 15251, that the conditions should be within the category limits for 95% of the time, is used. The comfort limits for transitory spaces, described in section 3.2.4 were used for calculating the hours within the limits.



a) b)

Figure 15. Space used for demonstrating the annual assessment step of the method a) plan view with the created grid and b) 3D view.

4 Results

In the following sections the results from the case study are presented. The figures presented in this section should be read as it is described in section 3.3.2. For the specific case of the African sunset area a description of the informative graphs is given in section 3.5.3. For the annual assessment the graph's description can be found in section 3.3.3.

4.1 Entrance area

With the before mentioned assumptions for this space the standard recommended model is *PMV* during the time it is conditioned and AM during the rest of the year. Since this is a transitory space the suitable model was AMT during the whole period and that is the model used to examine the limits of the environmental parameters.

In the following section the environmental parameters fulfilling the comfort requirements for the entrance area considering AMT and T_{rm} of 15 °C are presented. For the assumed T_{rm} and the desired building category the comfort limits for T_{op} are from 20.45 °C to 27.05 °C.

For v_a of 0.1 m/s the minimum value of T_a that falls within the comfort limits is 18°C and the maximum is 29 °C, see Figure 16. For these values of T_a the *MRT* can be 23 °C and 24 °C respectively. The largest spans for MRT are form 18 °C to 28 °C and from 19 °C to 29 °C and correspond to T_a of 23 °C and 24 °C respectively.

For v_a of 0.4 m/s the minimum value of T_a that falls within the comfort limits is 19 °C and the maximum is 28 °C, see Figure 17. For these values of T_a the *MRT* can be 24 °C and 23 °C respectively. The largest spans for *MRT* are form 18 °C to 28 °C and; 19 °C to 29 °C and 20 °C to 30 °C and correspond to T_a of 23 °C; 24 °C and 25 °C respectively.

For v_a of 0.8 m/s the minimum value of T_a that falls within the comfort limits is 20 °C and the maximum is 28 °C, see Figure 18. For these values of T_a the *MRT* can be 22 °C to 24 °C and 23 °C to 24 °C respectively. The largest spans for *MRT* are form 18 °C to 28 °C and; 19 °C to 29 °C and 20 °C to 30 °C and correspond to T_a of 23 °C; 24 °C and 25 °C respectively.

From the figures it can be noted that with higher v_a wider spans of *MRT* for specific value of T_a are falling within comfort limits. However limitation set by ISO 7730 for *MRT* to be within the limits of $T_a \pm 5$ °C restricts the *MRT* span.

This graphs can aid design decision, when thermal comfort is considered. For example if v_a of 0.8 m/s can be achieved with natural ventilation then T_a can rise up to 28 °C. However in order to keep the T_{op} within the comfort limits for these values of v_a and T_a, *MRT* cannot exceed 24 °C. If that cannot be achieved with solar control, then active cooling will be necessary.

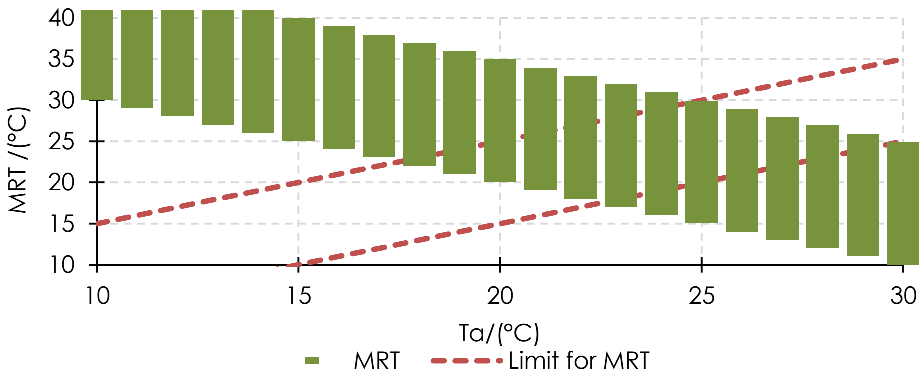


Figure 16. *MRT* and T_a for given v_a = 0.1 m/s.

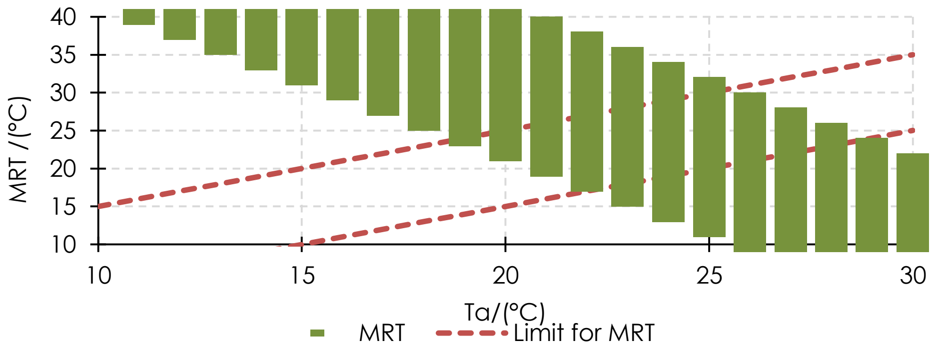


Figure 17. *MRT* and T_a for given v_a = 0.4 m/s.

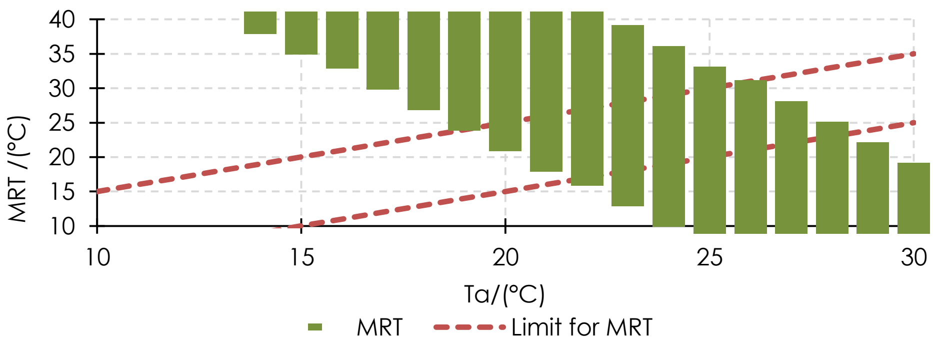


Figure 18. *MRT* and T_a for given v_a = 0.8 m/s.

When the combinations for *MRT* and v_a are examined results show that for the minimum T_a = 18 °C the only possible values of v_a are 0 m/s and 0.1 m/s requiring MRT of 23 °C, higher *MRT* is not acceptable due to the limitation of T_a ±5 °C, see Figure 19.

For T_a of 24 °C the span of permissible v_a is from 0 to 0.8 m/s, with MRT of 19 °C to 29 °C, see Figure 20. In this case all values for v_a are possible and the only limitation is the one given by standards for the limit of v_a for comfort conditions. It can be noted from the graph that the span of MRT is increasing with higher v_a and the limiting factor for all values of v_a in this case is the maximum of 5 °C difference from T_a.

For T_a of 29 °C the span of permissible v_a is from 0 to 0.2 m/s, with *MRT* of 24 °C to 25 °C. Since T_a is rather high lower *MRT* values are needed to achieve comfort, see Figure 21.

This results can be useful for a designer when deciding on passive cooling strategies. They can give information if solar protection is needed or natural or forced ventilation is preferable choice. When considering passive cooling, natural ventilation is often the first option, however the formula for calculation of T_{op} does not incorporate the entire cooling effect of the increased velocity and that can be noticed with higher T_a.

From Figure 21 it is noticeable that in this case with higher v_a the maximum *MRT* allowed is also lower. This can be explained with the fact that with higher velocities T_{op} tends to be closer to T_a which in this case is higher than *MRT* and the result is that with higher v_a the allowable span for *MRT* is restricted rather than expanded. This problem has been noted by Nicol & Spires (2013) and is due to the fact that within the formula of T_{op} only part of the effect of increased v_a is included (the increase of convective heat transfer), however the effect of the v_a to the heat loss through evaporation is not considered. This problem can be seen also in Figure 20 where with higher v_a values for *MRT* down to 10 °C are possible. Instead of the *MRT* span to be moved to the higher values, with higher v_a the span of *MRT* is increased in both directions, thus a higher v_a can result in both higher and lower *MRT*, see Figure 20.

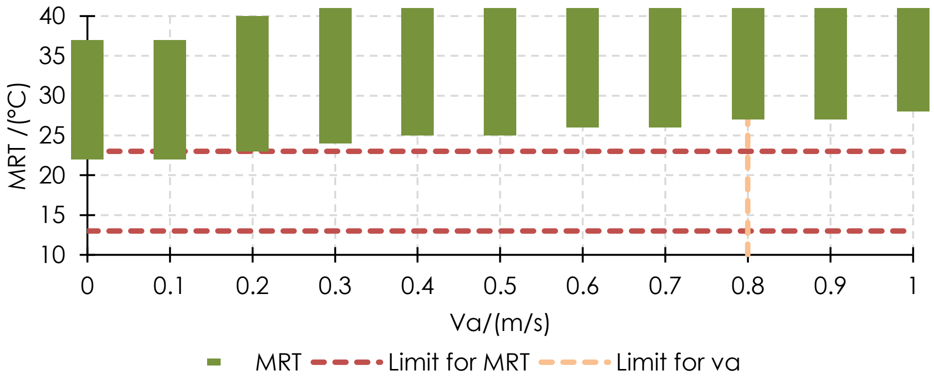


Figure 19. *MRT* and v_a for given T_a = 18 °C

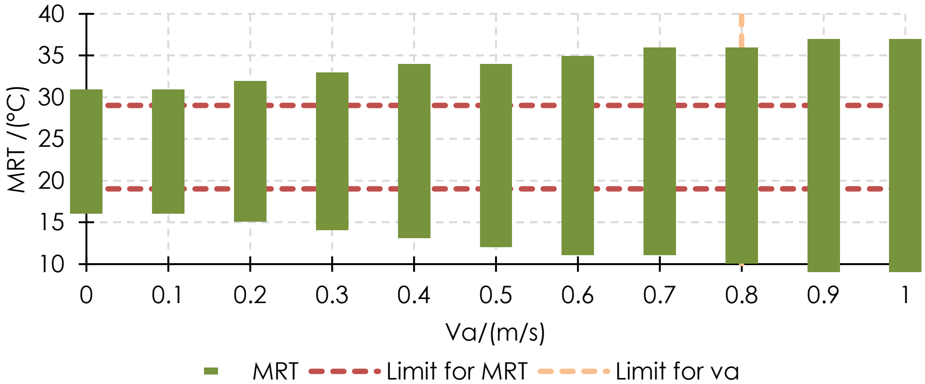


Figure 20. *MRT* and v_a for given T_a = 24 °C

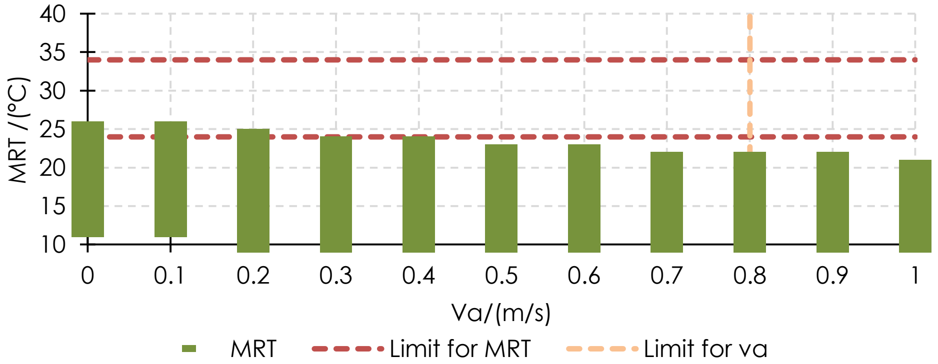


Figure 21. *MRT* and v_a for given T_a = 29 °C

4.2 Theatre area

With the before mentioned assumptions for this space the standard recommended model is *PMV*. The only suitable model is also *PMV*, due to the fact that the space is conditioned, there is no possibility for adaptation and it is intended to be occupied for long period of time – more than 15 minutes.

In the following section the environmental parameters fulfilling the comfort requirements for the theatre area considering *PMV* comfort model are presented. For the desired building category the comfort limits for *PMV* are ±0.5.

For v_a of 0.1 m/s the minimum value of T_a that falls within the comfort limits is 23 °C and the maximum is 29 °C, see Figure 22. For these values of T_a the MRT can be 27 °C and 25 °C respectively. The largest spans for *MRT* are from 25 °C to 29 °C; from 24 °C to 28 °C and 23 °C to 27 °C and correspond to T_a of 25 °C; 26 °C and 27 °C respectively.

For v_a of 0.4 m/s the minimum value of T_a that falls within the comfort limits is 25 °C and the maximum is 30 °C, see Figure 23. For these values of T_a the *MRT* can be 30 °C and 25 °C respectively. The largest spans for *MRT* are from 26 °C to 31 °C and 24 °C to 29 °C and correspond to T_a of 27 °C and 28 °C respectively.

For v_a of 0.8 m/s the minimum value of T_a that falls within the comfort limits is 26 °C and the maximum is 30 °C, see Figure 24. For these values of T_a the *MRT* can be 31 °C and 25 °C to 26 °C respectively. The largest span for *MRT* is from 25 °C to 32 °C and corresponds to T_a of 23 °C. It is clear that with higher v_a the required T_a and *MRT* are also higher, due to the cooling effect of increased air movement.

Description of how to read the graphs is given in section 3.3.2. From the above mentioned figures can be seen that the maximum T_a of 30 °C is reached with v_a = 0.4 m/s, even if v_a is increased to 0.8 m/s it cannot compensate for temperatures higher than 30 °C.

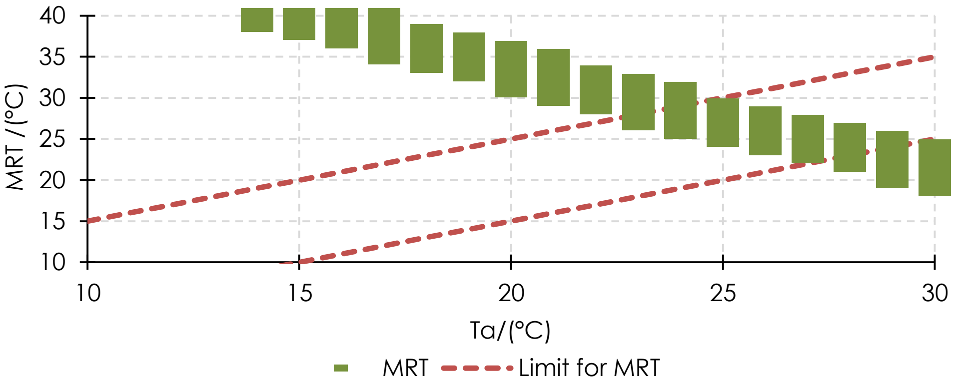


Figure 22. *MRT* and T_a for given v_a = 0.1 m/s and *RH* = 50%.

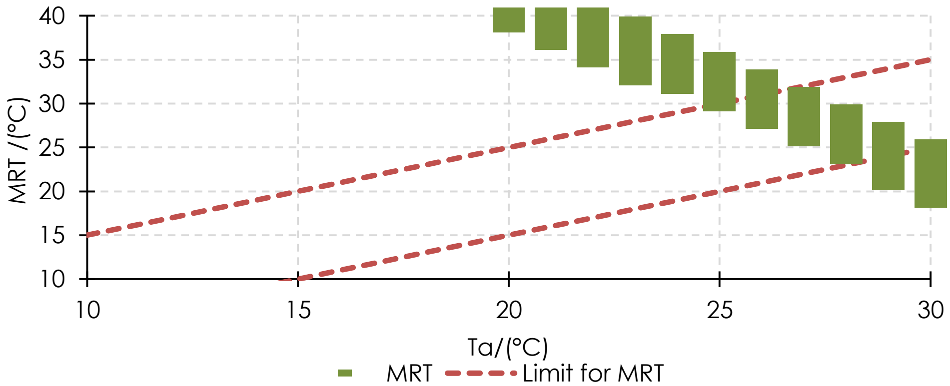


Figure 23. *MRT* and T_a for given v_a= 0.4 m/s and *RH* = 50 %.

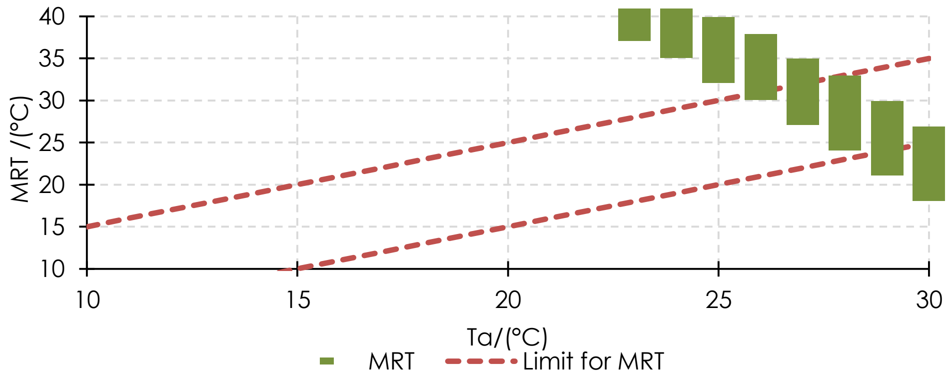


Figure 24. *MRT* and T_a for given v_a= 0.8 m/s and *RH* = 50 %.

When the combinations for *MRT* and v_a were examined, results showed that for the minimum T_a = 23 °C the only possible values of v_a are 0 m/s and 0.1 m/s requiring *MRT* of 27 °C. Higher MRT is not acceptable due to the limitation of T_a ±5 °C, see Figure 25.

For T_a of 26 °C the span of permissible v_a is form 0 to 0.8 m/s, with *MRT* of 23 °C to 31 °C, see Figure 26. In this case all values for v_a are possible and the only limitation is the one given by standards for the limit of v_a for comfort conditions. It can be noted from the graph that required *MRT* values are increasing with higher v_a.

This information can be compared with the three figures before, by looking only to the *MRT* for T_a = 26 °C. The same results are recorded. In Figure 22 for T_a of 26 °C and v_a=0.1 m/s, the span for *MRT* is between 24 °C and 28 °C. In Figure 23 for T_a of 26 °C and v_a=0.4 m/s, the span for *MRT* is between 28 °C and 31 °C. In Figure 24 for T_a of 26 °C and v_a=0.8 m/s, the only possible value for *MRT* is 31 °C. This shows good correspondence between the two types of informative graphs developed within the method.

For T_a of 30 °C the span of permissible v_a is from 0.2 m/s to 0.8 m/s, with *MRT* of 25 °C to 26 °C, see Figure 27. Since T_a is rather high, lower *MRT* values are needed to achieve comfort. It can be noted from the graph that at high T_a, the cooling effect of increased v_a is limited compared to lower air temperatures.

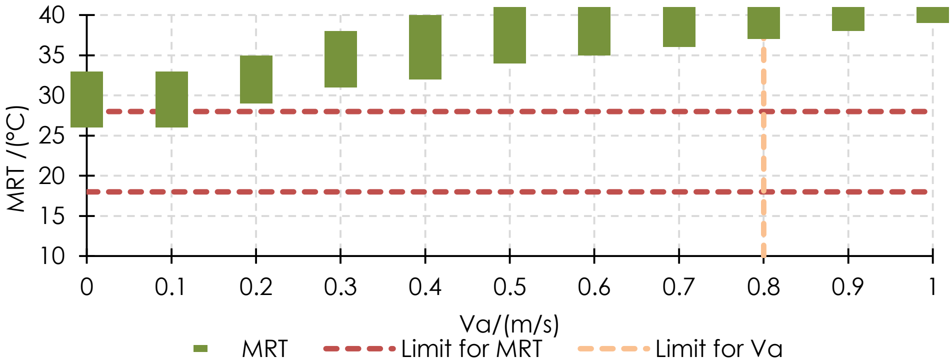


Figure 25. *MRT* and v_a for given T_a= 23°C and *RH* = 50 %.

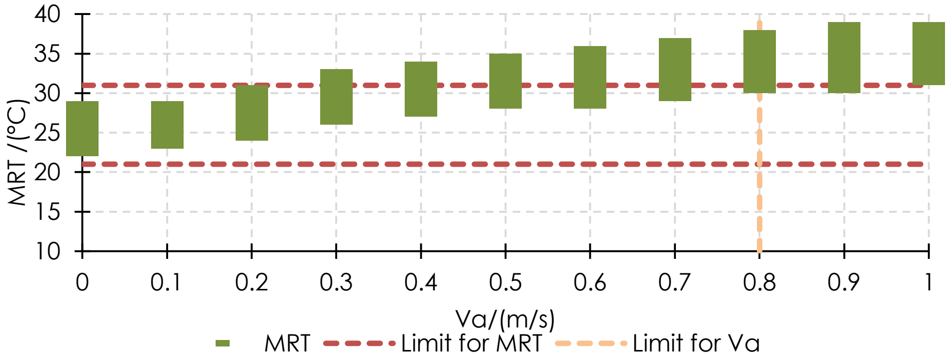


Figure 26. *MRT* and v_a for given T_a= 26°C and *RH* = 50 %.

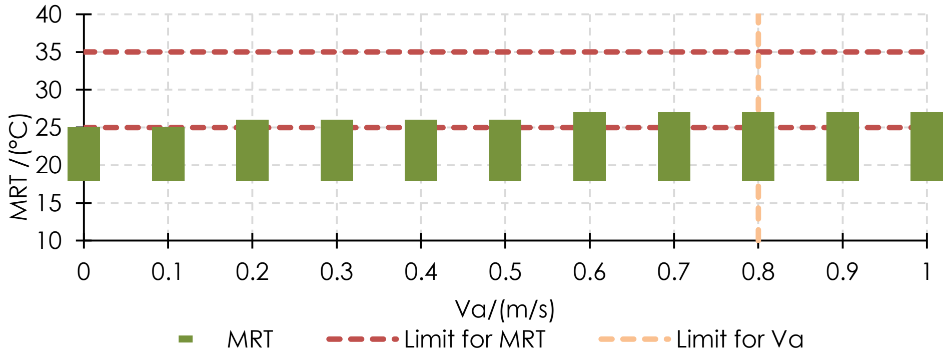


Figure 27. *MRT* and v_a for given T_a = 30°C and *RH* = 50 %.

4.3 African sunset area

As mentioned before in section 3.5.3, this area was considered closer to semi-external setting, therefore the standards do not give recommendations for thermal comfort model. In this case *UTCI* is used to describe the thermal comfort.

When using *UTCI* index, the comfort limits for the index are from 18 °C to 26 °C.

For v_a of 0.1 m/s and *RH* of 50% the minimum value of T_a that falls within the desired area is 19°C and the maximum is 33 °C, see Figure 28. For v_a of 0.1 m/s and *RH* of 70 % the minimum value of T_a that falls within the desired area is 18°C and the maximum is 30 °C, see Figure 29. It should be noted that higher T_a would be possible if *MRT* lower than zero was considered. However, this method considers only values of *MRT* higher than zero and for this case they are also not relevant as it is artificially created thermal environment mimicking the natural conditions in warm climates.

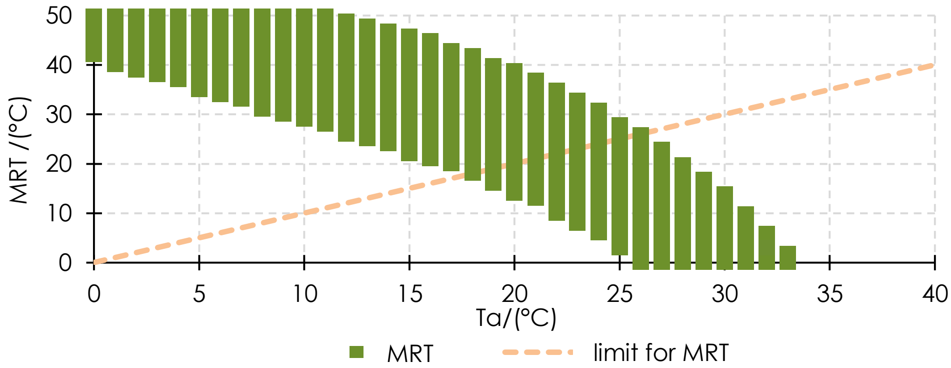


Figure 28. *MRT* and T_a for given v_a= 0.1 m/s and *RH* = 50 %.

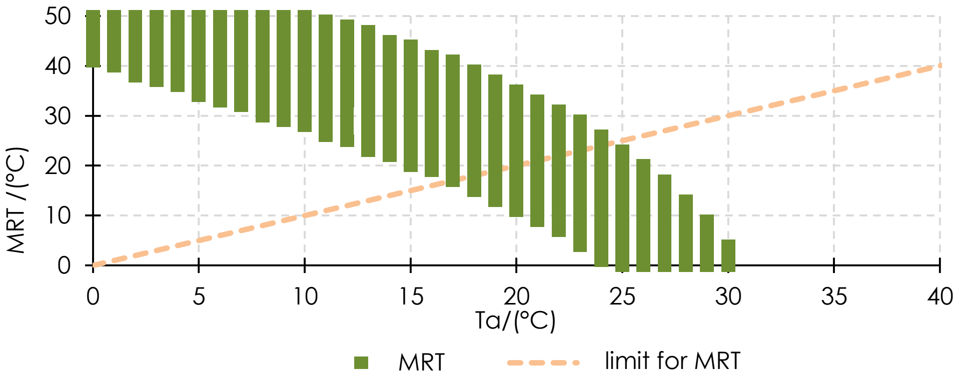


Figure 29. *MRT* and *Ta* for given *va*= 0.1 m/s and *RH* = 70 %.

For v_a of 0.5 m/s and *RH* of 50 % the minimum value of T_a that falls within the desired area is 19 °C and the maximum is 33 °C, see Figure 30. For v_a of 0.1 m/s and *RH* of 70 % the minimum value of T_a that falls within the desired area is 18 °C and the maximum is 30 °C, see Figure 31.

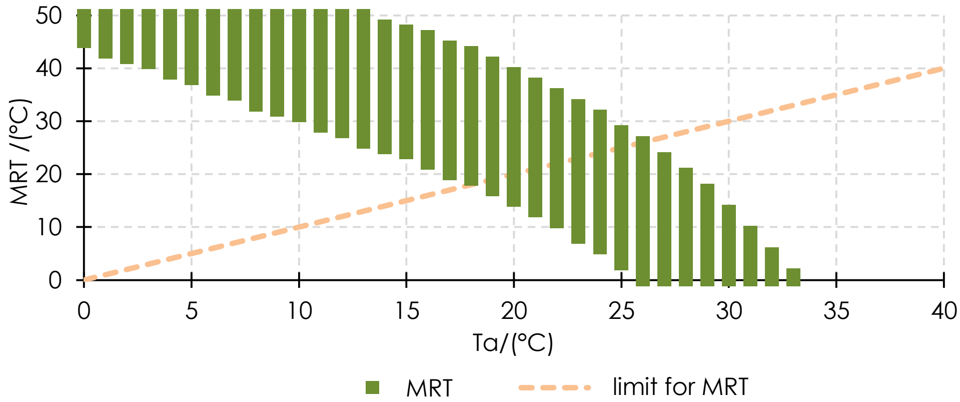


Figure 30. *MRT* and T_a for given v_a= 0.5 m/s and *RH* = 50 %.

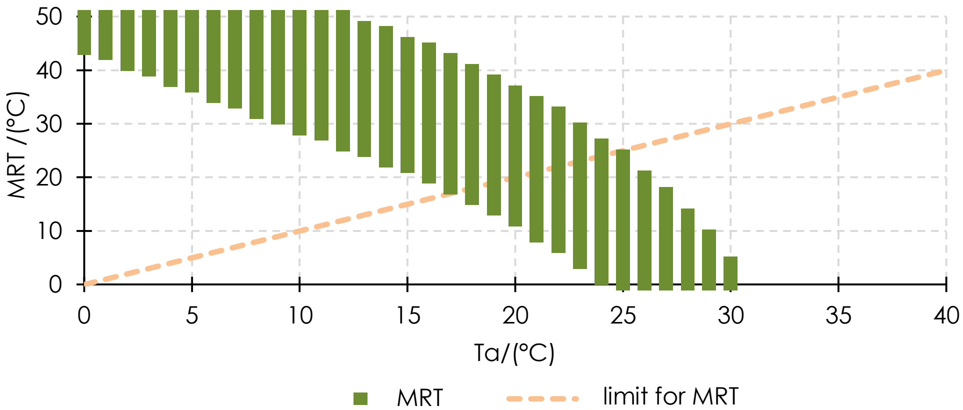


Figure 31. *MRT* and T_a for given v_a= 0.5 m/s and *RH* = 70 %.

For v_a of 1.0 m/s and *RH* of 50 % the minimum value of T_a that falls within the desired area is 19 °C and the maximum is 33 °C, see Figure 32. For v_a of 1.0 m/s and *RH* of 70 % the minimum value of T_a that falls within the desired area is 19 °C and the maximum is 30 °C, see Figure 33.

From the graphs it can be noticed that T_a can vary from 18 °C to 33 °C. However, with higher *RH* lower *MRT* is needed for specific T_a.

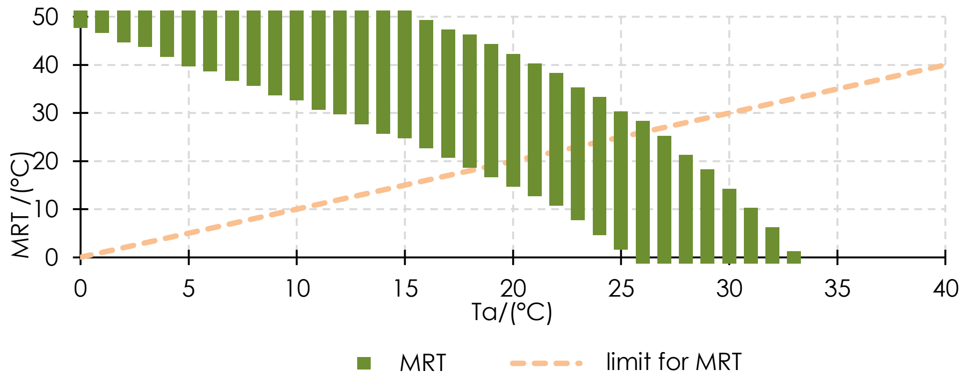


Figure 32. *MRT* and T_a for given v_a= 1 m/s and *RH* = 50 %.

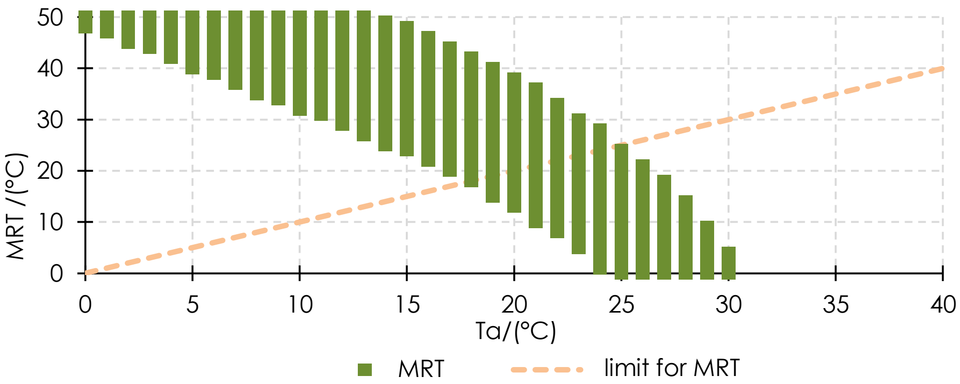


Figure 33. *MRT* and T_a for given v_a= 1 m/s and *RH* = 70 %.

Further examination of the *MRT* and va for the range of T_a was carried out. The following combinations of T_a and *RH* were examined: T_a=18 °C / *RH* = 70 %; T_a= 25 °C / *RH* = 60 %; T_a = 33 °C / *RH*=50 %.

For T_a=18 °C and *RH* = 70 % possible combinations of v_a and *MRT*, where *MRT* is below T_a and within the comfort limits exist for v_a spanning from 0.0 m/s to 0.9 m/s, see Figure 34. For this set of T_a and *RH* the *MRT* values lower than T_a are close to the lower limit of comfort. If the condition of T_a>*MRT* is to be fulfilled *MRT* can vary from 15 °C to 17 °C.

For T_a= 25 °C and *RH* = 60 % all values for v_a are possible and the span for *MRT* is from 0 °C to 24 °C as the upper limit is set by the limitation of T_a>*MRT* considered, see Figure 35. For this set of parameters 25 °the *MRT* values resulting to *UTCI* close to the lower limit of comfort are close to zero, which might not be possible to reach. This gives information to the designer that T_a should not be too high in order to reach the effect of the desired thermal environment. Further investigation can be made for T_a values between 18° and 25 °C that will result in achievable values of *MRT* close to the lower limit of comfort.

For T_a= 33 °C and *RH* = 50 % all values for v_a will result in *MRT* close to zero, see Figure 36. These conditions might be hard to reach, as noted before, and also are on the upper limit of comfort, which is not the desired effect of the thermal environment.

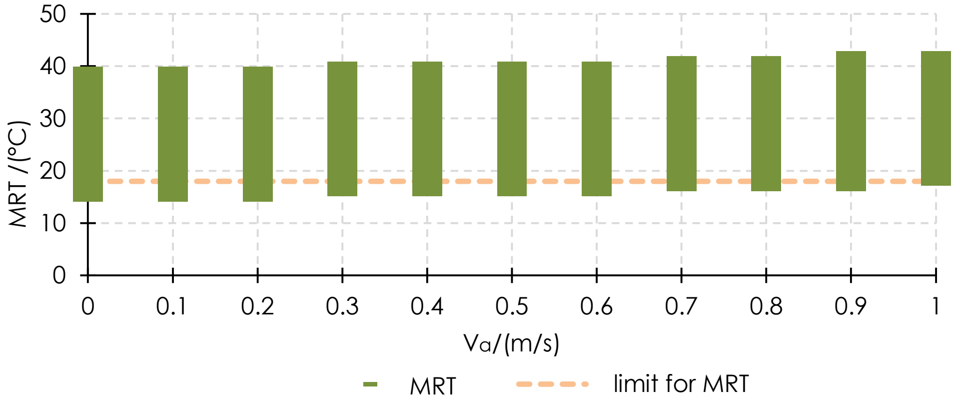


Figure 34. *MRT* and v_a for given T_a = 18 °C and *RH* = 70 %.

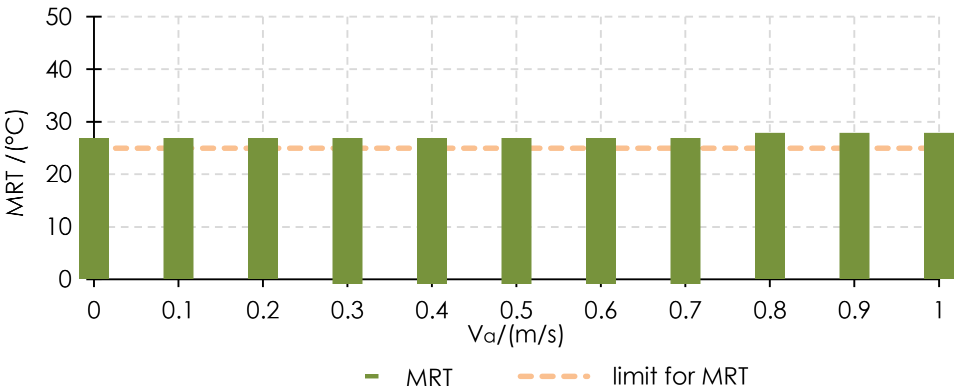


Figure 35. *MRT* and v_a for given T_a = 25 °C and *RH* = 60 %.

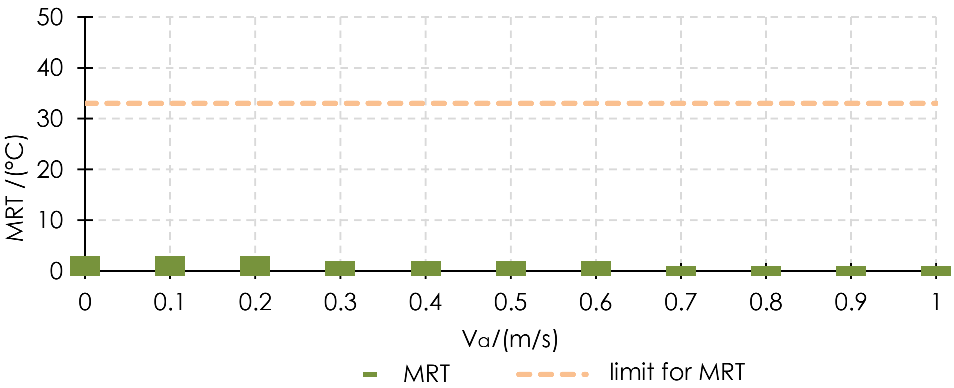


Figure 36. *MRT* and v_a for given T_a = 33 °C and *RH* = 50 %.

4.4 Annual assessment

The hourly values for *MRT* and T_a acquired from simulation of the simple room with the program Oasys ROOM were inserted into the excel spread sheet. The deviation from T_{comf} was calculated as well as the percentage of hours when thermal conditions are within the desired category. Figure 37 presents the results for all occupant positions considered. None of the occupant positions in this case can be classified for category II as the percentage of hours with the comfort limits for this category is lower than 95 % throughout the whole room. The results for the different positions are quite similar ranging from 63.2 % to 69.4 % of hours within comfort limits for category II. Figure 38 presents the detailed graph with the hourly distribution of deviations from T_{comf}, for the occupant position highlighted in Figure 37. For description of the figure and how to be read see section 3.3.3. It can be noted from the graph that for this occupant the hours outside the comfort limits are only on the positive side of the scale, which means that the main problem would be overheating. The results are similar for the rest of the positions.

Further investigations can be carried out in order to understand when the overheating happens and what the appropriate measures to alleviate the problem are.

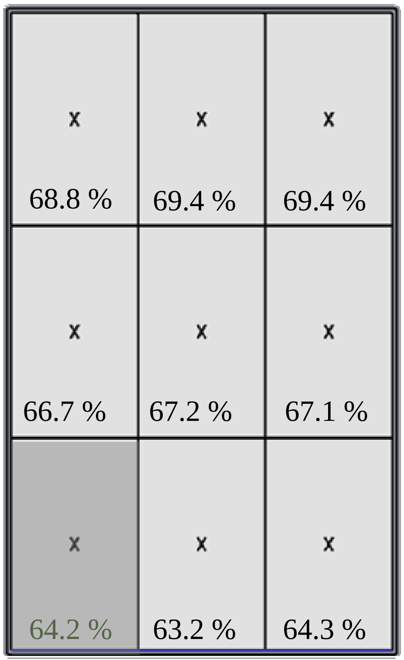


Figure 37. Percentage of hours within the comfort limits for category II, for the different occupant positions.

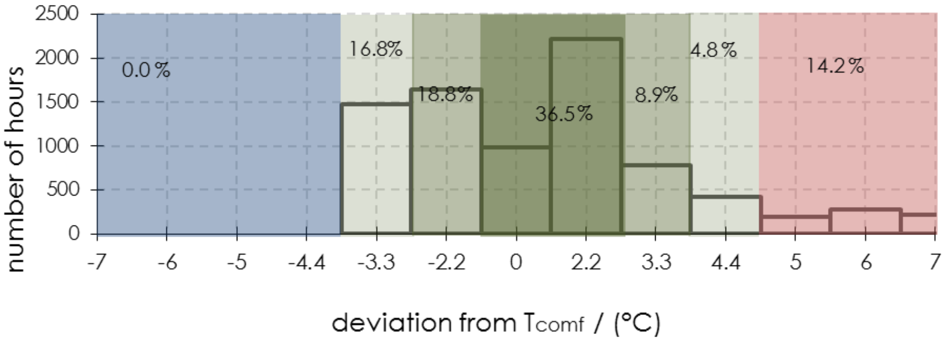


Figure 38. Number of hours and corresponding deviation from T_{comf} in °C for one occupant position.

5 Discussion

5.1 Comfort models

The main focus of this thesis was understanding thermal comfort and the parameters affecting the perception of thermal comfort for humans. Different comfort models and some of the comfort indices developed in the last century were examined. The *PMV* is the most widely used model and is also adapted by international standards regarding thermal comfort as the main method to be used when assessing thermal comfort. An alternative approach has been developed called adaptive thermal comfort. In developing AM the equation of thermal balance has been omitted and the model is based entirely on statistics.

The thermal comfort in transitory spaces has been focus of several researches. The parameters that affect the perception of the thermal environment in transitory spaces are different than in office areas. Previous thermal experiences as well as psychological and psychosocial factors can play significant role in defining the comfort conditions. It has been suggested that AM is suitable to describe the thermal comfort in this type of spaces and that the suggested limits from the standards can be extended with 10% and this was adopted for developing of the current method. However due to the differences between transitory and office spaces, for which the model is developed, the prediction might not be accurate. It would be beneficial to develop AM specifically for transitory spaces, where statistics only from spaces of the same type are used for deriving the formula for T_{comf}.

The last method that was implemented in this work was the *UTCI*. It is mainly used for assessment of thermal comfort in outdoor spaces. In this work it was used only for semi-external spaces, this type of spaces was not addressed in the standards and no standard recommended method for assessing thermal comfort outdoors is present. The method is also based on the thermal balance equation, using a multi node model to predict thermal sensation (Blazejczyk, et al., 2010). The *UTCI* incorporates an AM when calculating the clothing insulation of the occupant (Havenith, et al., 2012). In this model the clothing insulation is dependent on the T_a . This can account for only part of the adaptation practices that people have, which are connected to the behavioral response of humans to thermal environments. The physiological and psychological adaptation is not included. Another concern about the model for clothing insulation is that the clothing level is not always dependent only on the T_a, but the culture and traditions are often a factors that affect it.

From the comfort models examined within this thesis only the AM claims to incorporate the effect of psychological factors to human perception of thermal comfort. However, this method neglects the effect of RH and does not include the whole effect of increased v_{a}. As discussed also in section 4.1.

5.2 The method for assigning comfort models

An algorithm was created, which would assign a specific comfort model for different types of spaces based on EN 15751 and other literature. The recommendations from the standard were taken into consideration when the models recommended from standards were defined. Suggestions from literature were considered, when the suitable models were assigned. This method does not cover all types of spaces and is mainly focused on transitory and semi-external spaces. As mentioned before when AM is used for spaces with different activity and typical clothing it would be appropriate to develop different comfort models. However, the standards provide only one formula suitable for non-conditioned spaces, accept for the CIBSE Guide A, where a formula for conditioned spaces is also suggested. However, no differentiation is made between spaces with different activity or clothing level.

The *UTCI* method is only suggested when semi-external spaces are considered. However, in some peculiar cases, as it was demonstrated with the African sunset area from the case study, an internal, conditioned space is more similar to an outdoor environment due to its specific characteristics which mimic a natural environment. Therefore it can be considered as semi-external when assessing thermal comfort. This shows that this method does not take the decision making role from the designer and thorough consideration of the space characteristics should be given, when deciding on a comfort model to be used.

5.3 Defining comfort boundaries

5.3.1 Use and information communicated to the designers

The second step of the method provides useful information for designers on the comfort limits for different parameters. This is achieved by giving them the opportunity to test different combinations of environmental parameters. Two types of informative charts present to the users the allowable span for these parameters. The first graph presents *MRT* and v_a for given T_a and *RH*. The second graph presents *MRT* and T_a for given v_a and *RH*.

It was demonstrated in the three spaces examined in the case study, combinations of T_a and *MRT* or v_a and *MRT* are derived for given v_a and *RH* or T_a and *RH* respectively, using the chosen comfort models and recommended limits. This information can be helpful to designers to identify the need of solar protection, natural ventilation and active cooling.

5.3.2 Limits for environmental parameters

As described in section 0 certain limitations were considered for the different environmental parameters when calculating the necessary indices. Those limitations are suggested for calculation of *PMV* in ISO 7730. It was considered appropriate to use the same limitations when the AM was used for assessment of the comfort conditions, as the model is used only for indoor spaces where the variation of the environmental parameters is similar to the limits described in ISO 7730. It should be noted that combinations of the different parameters outside the limitations can still result in comfortable conditions according to the models, but it was considered that in practice the values of the different parameters will be within these limits in any indoor environment, where thermal comfort is of consideration.

When thermal comfort is assessed in outdoor spaces the variation of the environmental parameters can be much larger. Therefore, the limitations are extended. The limits given by developers of the *UTCI* index are larger than those implemented in the method, see section3.2.5 and section 0. However, it was considered appropriate to have stricter limitations as this method is focusing on thermal comfort and does not aim to evaluate conditions of extreme heat stress or freezing.

5.4 Annual assessment

For the annual assessment of a design, deviation from comfort was calculated as described in section 3.3.3. However, when assessing the comfort on hourly bases consideration is not given to the limitations of environmental parameters that are considered in the previous step of the method, meaning that the *MRT* can span wider than the limit of T_a ± 5 °C and the v_a can be higher than 0.8 m/s. Adding these limitations to the annual assessment of thermal comfort can be a subject of future development of the method. When assessing specific design solutions, the standards recommend also looking into local discomfort caused by draft or radiant asymmetry, however this is also not included in the method and need to be considered separately, possibly for specific design conditions.

The deviation from comfort that is used in this method is a simple method to assess the comfort conditions, when information is plotted on the informative graph the user is informed about the amount of hours - the duration, when the deviation is within specific limits. It informs about the amount of overheating or too cold hours according to the different standard categories. It does not inform when the conditions outside comfort are occurring. Other methods for evaluation of thermal conditions for longer periods of time have also been suggested in EN15251, which might be more appropriate. However, the simplicity of this method was considered as an important factor when deciding on which method to be implemented.

Better graphical presentation of the results in plan view is considered to be valuable as it will add great value to communicating of the information to the users. However, time limitations did not allow for further development.

6 Conclusions

Within this thesis a methodology has been developed, which uses the available knowledge on thermal comfort to inform designers about the parameters affecting thermal comfort and the extent of their influence. This methodology was implemented into an excel tool that includes algorithm for finding appropriate comfort models for spaces with specific characteristics, based on recommendations from standards and literature.

The tool further allows examination of the comfort limits for the different environmental parameters used within the specified comfort model. This is achieved by plotting the combinations of these parameters that result in comfortable conditions in informative graphs. These graphs inform the user of the limits for each parameter and how it can affect the thermal comfort. Using this information designers are able to plan for prospective measures to ensure comfortable thermal environment.

The tool also includes evaluation of given designs, by using hourly data of the T_a, *MRT*, v_a an *RH*. This is achieved by calculating the respective index using the chosen comfort model and finding the deviation from comfort conditions in Celsius or in *PMV* scales. These calculations are carried out for different occupant positions and the results are plotted on informative graphs indicating the limits for the deviation for different categories of spaces defined by the standards. Further development for this part of the method would be beneficial for better communication of the results.

The tool is flexible in the way that it allows users to change all the different environmental parameters and examine their effect to the thermal comfort and it also includes assessment of specific design. The value of the tool was demonstrated through a case study where comfort conditions for three different cases were examined and one example of annual assessment of specific design was given.

It can be concluded that for the entrance area T_a can rise up to 28 °C if v_a can be increased up to 0.8 m/s and *MRT* of 24 °C can be achieved. For the theatre area it was demonstrated that the maximum T_a was 30 °C and it was reached with v_a of 0.4 m/s, increasing the air velocity further did not compensate for air temperatures above 30 °C. For the African sunset area the maximum T_a was shown to be 33 °C for *RH* of 50 % and it is reached at v_a = 0.5 m/s. For RH = 70 % the maximum of Ta was 30 °C.

The annual assessment of thermal comfort in the simple space examined showed that none of the occupant’s positions within the space can be classified for building category II.

7 Future work

Through the process of developing the method several problems have raised, for which the literature available on the subjects was not sufficient. As mentioned before this thesis focused on transitory and semi-external spaces where previous thermal experiences, psychological and psychosocial factor can have significant effect to the perception of thermal comfort. In order to fully understand their influence and create a method where it will be accounted for further research is necessary. Further the research needs to focus on specific space types as part of the psychological factors are occupant's expectations and these are different for different spaces even within the same building. Specifically for the AMs that are developed based on statistic data, it would be beneficial to differentiate between space types and carry out surveys specific for transitory spaces, deriving the necessary formula for T_{comf}.

Within the method there are several points which were not included or developed to the desired level. It is considered important to include them in further development.

- The effect of drafts and radiant asymmetry on thermal comfort needs to be included in the annual assessment.
- Better visualization of the results from design assessment is necessary. It will be beneficial to work on different methods of annual assessment and elaborate a method for presenting the results in plan view, including indicative colors for better communication of the information.
- A goal which was not reach is to develop a method for interpolation between comfort models. This is very important in the case where buildings are part time conditioned, meaning that in one part of the year the thermal comfort needs to be assessed with one model e.g. PMV and in the rest of the year with another e.g. AM. This can result in sharp change of predicted comfort temperature from one day to another, which can have negative impact on both comfort and energy use. Therefore, it is considered important to find comfortable temperatures that will result in smoother transition between conditioned and no conditioned periods.
- The current methodology is based on ISO 7730 and EN 15251. It might be beneficial to include other standards and their requirements as ASHAE standard 55 and CIBSE guide A. This will contribute to wider use of the methodology.
- At last it would be beneficial for engineers and designers to link this methodology with existing dynamic thermal simulation tool. This will allow for easier assessment of different designs and better visualization of the results.

8 Summary

In recent years attention has been focused on energy efficiency in buildings and this is often in conflict with the comfort conditions, if appropriate design is not considered from the begging. Defining the comfortable conditions in early stages of the building planning is essential for achieving good indoor environment as well as energy efficiency.

There is a necessity for a method that informs designers on the issue of thermal comfort and can assist them in making informed design decisions. This thesis focused on examining thermal comfort models and implementing them in a tool that informs designers on comfort limits for the different environmental parameters and allows for design assessment.

The tool, developed within this work, includes Predicted Mean Vote and adaptive comfort models for defining comfort boundaries for indoor spaces with specified activity and clothing levels. Standard recommended comfort models (EN 15251; ISO 7730) were used, as well as an extended adaptive model for transitory spaces. For semi-external spaces was used a recently developed thermal index called Universal Thermal Climate Index.

Annual assessment of thermal comfort in a space was included. It was carried out by calculating hourly deviation from comfort and presenting the requirements for the different categories specified in EN 15251.

By using a case study of an indoor zoo project, it was demonstrated that the tool is valuable for building designers in understanding thermal comfort and the effect of different environmental parameters as air temperature, mean radiant temperature, air velocity and relative humidity. The tool can help designers in finding appropriate measures for avoiding thermal discomfort, by defining the limits for the environmental parameters. For example, appropriate cooling and heating set points can be found for considered air velocity; need for use of shading devises can be defined by exploring the limits of mean radian temperature.

The tool is flexible in a way that it allows designers to dynamically change all environmental parameters, explore their limits and find combinations that provide comfort conditions. The tool is also valuable as it uses standard recommendations for comfort limits as described in EN 15251 and ISO 7730.

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Appendix A

A.1. VBA code for finding standard recommended comfort model

```
Function StRec(a, b)
If (a = "internal") Then
 If b = "yes" Then StRec = "PMV"
 If b = "part time" Then StRec = "PMV,Adaptive model"
 If b = "no" Then StRec = "Adaptive model"
Else: StRec = "---"
End If
End Function
```

A.2 VBA code for assigning suitable comfort models

```
Function Suitable(a, c, d, e)
If a = "semi-external" Then Suitable = "UTCI" Else If c = "no control" And (d = "2" Or d =
"1" Or d = "3") And e = "PMV" Then Suitable = "PMV" Else If e = "Adaptive model" Then
Suitable = "Adaptive model" Else: Suitable = "PMV, Adaptive model"
End Function
```

A.3 VBA code for assigning suitable AM

```
Function FindAM(AM, a, b, c, d)
If AM = "PMV" Or AM = "UTCI" Then FindAM = "----" Else: check = True
If check = True Then
   If c = "long" And a = "yes" And d = "no" Then FindAM = "AM for conditioned spaces"
   If c = "long" And (a = "no" Or a = "part time") And d = "no" Then FindAM = "AM for not
conditioned spaces"
   If c = "short" Or b = "weather dependant" Or d = "yes" Then FindAM = "AM for transitory
spaces"
End If
End Function
```

Appendix B

B.1. Calculation of possible variation of *MRT* and v_a for PMV method

```
Sub MRTPMVrange()
 clo = Worksheets("input data").Range("B14").Value
 met = Worksheets("input data").Range("B15").Value
 lb = Worksheets("PMV").Range("C13").Value
 ub = Worksheets("PMV").Range("J13").Value
 lrow = 2
 Ta = Worksheets("PMV").Range("C2").Value
 RH = Worksheets("PMV").Range("C8").Value
 Worksheets("PMV").Range("AA2:AA400").ClearContents
 Worksheets("PMV").Range("AB2:AB400").ClearContents
 Worksheets("PMV").Range("AC2:AC400").ClearContents
       For Tr = 10 To 40 Step 1
          For va = 0 To 1 Step 0.1
             tt = Module2.PMV(Ta, Tr, va, RH, clo, met, 0)
             'Range("A" & lRow)
             If tt >= lb And tt <= ub Then
             Worksheets("PMV").Range("AA" & lrow).Value = tt
             Worksheets("PMV").Range("AB" & lrow).Value = Tr
             Worksheets("PMV").Range("AC" & lrow).Value = va
             lrow = lrow + 1
             End If
          Next va
       Next Tr
End Sub
```

B.2. Calculation of possible variation of *MRT* and T_a for PMV method

```
Sub MRTTaRange()
clo = Worksheets("input data").Range("B14").Value
 met = Worksheets("input data").Range("B15").Value
 lb = Worksheets("PMV").Range("C13").Value
 ub = Worksheets("PMV").Range("J13").Value
 lrow = 2
 va = Worksheets("PMV").Range("C6").Value
 RH = Worksheets("PMV").Range("C8").Value
 Worksheets("PMV").Range("AO2:AO1200").ClearContents
 Worksheets("PMV").Range("AP2:AP1200").ClearContents
 Worksheets("PMV").Range("AQ2:AQ1200").ClearContents
       For Tr = 10 To 40 Step 1
          For Ta = 1 To 30 Step 1
             tt = Module2.PMV(Ta, Tr, va, RH, clo, met, 0)
             If tt >= lb And tt <= ub Then
             Worksheets("PMV").Range("AO" & lrow).Value = tt
```

```
            Worksheets("PMV").Range("AP" & lrow).Value = Tr
            Worksheets("PMV").Range("AQ" & lrow).Value = Ta
            Worksheets("PMV").Range("AR" & lrow).Value = va
            lrow = lrow + 1
            End If
        Next Ta
    Next Tr
End Sub
```

Appendix C

C.1. VBA code for calculation of lower comfort boundary for adaptive comfot model for non-conditioned spaces

```
Function AMlower(class, Trm)
  If class = 1 Then
    If Trm < 15 Then AMlower = (0.33 * 15) + 18.8 - 2
    If Trm >= 15 And Trm <= 30 Then AMlower = (0.33 * Trm) + 18.8 - 2
    If Trm > 30 Then AMlower = (0.33 * 30) + 18.8 - 2
  End If
  If class = 2 Then
    If Trm < 15 Then AMlower = (0.33 * 15) + 18.8 - 3
    If Trm >= 15 And Trm <= 30 Then AMlower = (0.33 * Trm) + 18.8 - 3
    If Trm > 30 Then AMlower = (0.33 * 30) + 18.8 - 3
  End If
  If class = 3 Then
    If Trm < 15 Then AMlower = (0.33 * 15) + 18.8 - 4
    If Trm >= 15 And Trm <= 30 Then AMlower = (0.33 * Trm) + 18.8 - 4
    If Trm > 30 Then AMlower = (0.33 * 30) + 18.8 - 4
  End If
End Function
```

C.2. VBA code for calculation of upper comfort boundary for AM for non-conditioned spaces

```
Function AMupper(class, Trm)
  If class = 1 Then
    If Trm < 10 Then AMupper = (0.33 * 10) + 18.8 + 2
    If Trm >= 10 And Trm <= 30 Then AMupper = (0.33 * Trm) + 18.8 + 2
    If Trm > 30 Then AMupper = (0.33 * 30) + 18.8 - 2
  End If
  If class = 2 Then
    If Trm < 10 Then AMupper = (0.33 * 10) + 18.8 + 3
    If Trm >= 10 And Trm <= 30 Then AMupper = (0.33 * Trm) + 18.8 + 3
    If Trm > 30 Then AMupper = (0.33 * 30) + 18.8 + 3
  End If
  If class = 3 Then
    If Trm < 10 Then AMupper = (0.33 * 10) + 18.8 + 4
    If Trm >= 10 And Trm <= 30 Then AMupper = (0.33 * Trm) + 18.8 + 4
    If Trm > 30 Then AMupper = (0.33 * 30) + 18.8 + 4
  End If
End Function
```

C.3 Calculation of possible variation of *MRT* and v_a for AMN

C.3. Calculation of possible variation of *MRT* and v_a for AM for non-conditioned spaces

```
Sub MRTSAMrange()
```

```
 Ta = Worksheets("Standart AM").Range("F4").Value
 lb = Worksheets("Standart AM").Range("F11").Value
 ub = Worksheets("Standart AM").Range("N11").Value
 Worksheets("Standart AM").Range("AA2:AA400").ClearContents
 Worksheets("Standart AM").Range("AB2:AB400").ClearContents
 Worksheets("Standart AM").Range("AC2:AC400").ClearContents
 Worksheets("Standart AM").Range("AD2:AD400").ClearContents
 lrow = 2
     For Tr = 10 To 40 Step 1
       For va = 0 To 1 Step 0.1
         tt = Module6.Top(Ta, Tr, va)
         If tt >= lb And tt <= ub Then
         Worksheets("Standart AM").Range("AA" & lrow).Value = tt
         Worksheets("Standart AM").Range("AB" & lrow).Value = Tr
         Worksheets("Standart AM").Range("AC" & lrow).Value = va
         lrow = lrow + 1
         End If
       Next va
     Next Tr
End Sub
```

C.4. Calculation of possible variation of *MRT* and T_a for AM for non-conditioned spaces

```
Sub MRTTaSAMrange()
 va = Worksheets("Standart AM").Range("F8").Value
 lb = Worksheets("Standart AM").Range("F11").Value
 ub = Worksheets("Standart AM").Range("N11").Value
 Worksheets("Standart AM").Range("BA2:BA400").ClearContents
 Worksheets("Standart AM").Range("BB2:BB400").ClearContents
 Worksheets("Standart AM").Range("BC2:BC400").ClearContents
 lrow = 2
     For Tr = 10 To 40 Step 1
       For Ta = 10 To 30 Step 1
         tt = Module6.Top(Ta, Tr, va)
         If tt >= lb And tt <= ub Then
         Worksheets("Standart AM").Range("BA" & lrow).Value = tt
         Worksheets("Standart AM").Range("BB" & lrow).Value = Tr
         Worksheets("Standart AM").Range("BC" & lrow).Value = Ta
         lrow = lrow + 1
         End If
       Next Ta
     Next Tr
   End Sub
```

Appendix D

D.1. VBA code for calculation of lower comfort boundary for AM for conditioned spaces

```
Function AMClower(class, Trm)
  If class = 1 Then
    If Trm < 15 Then AMClower = (0.09 * 15) + 22.6 - 2
    If Trm >= 15 And Trm <= 30 Then AMClower = (0.09 * Trm) + 22.6 - 2
    If Trm > 30 Then AMClower = (0.09 * 30) + 22.6 - 2
  End If
  If class = 2 Then
    If Trm < 15 Then AMClower = (0.09 * 15) + 22.6 - 3
    If Trm >= 15 And Trm <= 30 Then AMClower = (0.09 * Trm) + 22.6 - 3
    If Trm > 30 Then AMClower = (0.09 * 30) + 22.6 - 3
  End If
  If class = 3 Then
    If Trm < 15 Then AMClower = (0.09 * 15) + 22.6 - 4
    If Trm >= 15 And Trm <= 30 Then AMClower = (0.09 * Trm) + 22.6 - 4
    If Trm > 30 Then AMClower = (0.09 * 30) + 22.6 - 4
  End If
End Function
```

D.2. VBA code for calculation of upper comfort boundary for AM for conditioned spaces

```
Function AMCupper(class, Trm)
  If class = 1 Then
    If Trm < 10 Then AMCupper = (0.09 * 10) + 22.6 + 2
    If Trm >= 10 And Trm <= 30 Then AMCupper = (0.09 * Trm) + 22.6 + 2
    If Trm > 30 Then AMCupper = (0.09 * 30) + 22.6 - 2
  End If
  If class = 2 Then
    If Trm < 10 Then AMCupper = (0.09 * 10) + 22.6 + 3
    If Trm >= 10 And Trm <= 30 Then AMCupper = (0.09 * Trm) + 22.6 + 3
    If Trm > 30 Then AMCupper = (0.09 * 30) + 22.6 + 3
  End If
  If class = 3 Then
    If Trm < 10 Then AMCupper = (0.09 * 10) + 22.6 + 4
    If Trm >= 10 And Trm <= 30 Then AMCupper = (0.09 * Trm) + 22.6 + 4
    If Trm > 30 Then AMCupper = (0.09 * 30) + 22.6 + 4
  End If
End Function
```

D.3. Calculation of possible variation of *MRT* and v_a for AM for conditioned spaces

```
Sub MRTCAMrange()
 Ta = Worksheets("Conditioned AM").Range("F4").Value
```

```
 lb = Worksheets("Conditioned AM").Range("F11").Value
 ub = Worksheets("Conditioned AM").Range("N11").Value
 Worksheets("Conditioned AM").Range("AA2:AA400").ClearContents
 Worksheets("Conditioned AM").Range("AB2:AB400").ClearContents
 Worksheets("Conditioned AM").Range("AC2:AC400").ClearContents
 Worksheets("Conditioned AM").Range("AD2:AD400").ClearContents
 lrow = 2
        For Tr = 10 To 40 Step 1
            For va = 0 To 1 Step 0.1
                tt = Module6.Top(Ta, Tr, va)
                If tt >= lb And tt <= ub Then
                Worksheets("Conditioned AM").Range("AA" & lrow).Value = tt
                Worksheets("Conditioned AM").Range("AB" & lrow).Value = Tr
                Worksheets("Conditioned AM").Range("AC" & lrow).Value = va
                lrow = lrow + 1
                End If
            Next va
        Next Tr
End Sub
```

D.4. Calculation of possible variation of *MRT* and T_a for AM for conditioned spaces

```
Sub MRTTaCAMrange()
 va = Worksheets("Conditioned AM").Range("F8").Value
 lb = Worksheets("Conditioned AM").Range("F11").Value
 ub = Worksheets("Conditioned AM").Range("N11").Value
 Worksheets("Conditioned AM").Range("BA2:BA400").ClearContents
 Worksheets("Conditioned AM").Range("BB2:BB400").ClearContents
 Worksheets("Conditioned AM").Range("BC2:BC400").ClearContents
 lrow = 2
        For Tr = 10 To 40 Step 1
            For Ta = 1 To 30 Step 1
                tt = Module6.Top(Ta, Tr, va)
                If tt >= lb And tt <= ub Then
                Worksheets("Conditioned AM").Range("BA" & lrow).Value = tt
                Worksheets("Conditioned AM").Range("BB" & lrow).Value = Tr
                Worksheets("Conditioned AM").Range("BC" & lrow).Value = Ta
                lrow = lrow + 1
                End If
            Next Ta
        Next Tr
End Sub
```

Appendix E

E.1. VBA code for calculation of lower comfort boundary for AM for transitory spaces

```
Function AMTlower(class, Trm)
  If class = 1 Then
    If Trm < 15 Then AMTlower = (0.33 * 15) + 18.8 - 2.2
    If Trm >= 15 And Trm <= 30 Then AMTlower = (0.33 * Trm) + 18.8 - 2.2
    If Trm > 30 Then AMTlower = (0.33 * 30) + 18.8 - 2.2
  End If
  If class = 2 Then
    If Trm < 15 Then AMTlower = (0.33 * 15) + 18.8 - 3.3
    If Trm >= 15 And Trm <= 30 Then AMTlower = (0.33 * Trm) + 18.8 - 3.3
    If Trm > 30 Then AMTlower = (0.33 * 30) + 18.8 - 3.3
  End If
  If class = 3 Then
    If Trm < 15 Then AMTlower = (0.33 * 15) + 18.8 - 4.4
    If Trm >= 15 And Trm <= 30 Then AMTlower = (0.33 * Trm) + 18.8 - 4.4
    If Trm > 30 Then AMTlower = (0.33 * 30) + 18.8 - 4.4
  End If
End Function
```

E.2. VBA code for calculation of upper comfort boundary for AM for transitory spaces

```
Function AMTupper(class, Trm)
  If class = 1 Then
    If Trm < 10 Then AMTupper = (0.33 * 10) + 18.8 + 2.2
    If Trm >= 10 And Trm <= 30 Then AMTupper = (0.33 * Trm) + 18.8 + 2.2
    If Trm > 30 Then AMTupper = (0.33 * 30) + 18.8 - 2.2
  End If
  If class = 2 Then
    If Trm < 10 Then AMTupper = (0.33 * 10) + 18.8 + 3.3
    If Trm >= 10 And Trm <= 30 Then AMTupper = (0.33 * Trm) + 18.8 + 3.3
    If Trm > 30 Then AMTupper = (0.33 * 30) + 18.8 + 3.3
  End If
  If class = 3 Then
    If Trm < 10 Then AMTupper = (0.33 * 10) + 18.8 + 4.4
    If Trm >= 10 And Trm <= 30 Then AMTupper = (0.33 * Trm) + 18.8 + 4.4
    If Trm > 30 Then AMTupper = (0.33 * 30) + 18.8 + 4.4
  End If
End Function
```

E.3. Calculation of possible variation of *MRT* and v_a for AM for transitory spaces

```
Sub MRTTAMrange()
 Ta = Worksheets("Transitory AM").Range("F4").Value
```

```
 lb = Worksheets("Transitory AM").Range("F11").Value
 ub = Worksheets("Transitory AM").Range("N11").Value
 Worksheets("Transitory AM").Range("AA2:AA400").ClearContents
 Worksheets("Transitory AM").Range("AB2:AB400").ClearContents
 Worksheets("Transitory AM").Range("AC2:AC400").ClearContents
 Worksheets("Transitory AM").Range("AD2:AD400").ClearContents
 lrow = 2
       For Tr = 10 To 40 Step 1
          For va = 0 To 1 Step 0.1
             tt = Module6.Top(Ta, Tr, va)
             If tt >= lb And tt <= ub Then
             Worksheets("Transitory AM").Range("AA" & lrow).Value = tt
             Worksheets("Transitory AM").Range("AB" & lrow).Value = Tr
             Worksheets("Transitory AM").Range("AC" & lrow).Value = va
             lrow = lrow + 1
             End If
          Next va
       Next Tr
   End Sub
```

E.4. Calculation of possible variation of *MRT* and T_a for AM for transitory spaces

```
Sub MRTTaTAMrange()
 va = Worksheets("Transitory AM").Range("F8").Value
 lb = Worksheets("Transitory AM").Range("F11").Value
 ub = Worksheets("Transitory AM").Range("N11").Value
 Worksheets("Transitory AM").Range("BA2:BA400").ClearContents
 Worksheets("Transitory AM").Range("BB2:BB400").ClearContents
 Worksheets("Transitory AM").Range("BC2:BC400").ClearContents
 lrow = 2
       For Ta = 10 To 30 Step 1
          For Tr = 10 To 40 Step 1
             tt = Module6.Top(Ta, Tr, va)
             If tt >= lb And tt <= ub Then
              'If Tr >= Ta - 5 And Tr <= Ta + 5 Then
              Worksheets("Transitory AM").Range("BA" & lrow).Value = tt
              Worksheets("Transitory AM").Range("BB" & lrow).Value = Tr
              Worksheets("Transitory AM").Range("BC" & lrow).Value = Ta
              lrow = lrow + 1
              'End If
             End If
          Next Tr
       Next Ta
End Sub
```

Appendix F

F.1. VBA code for calculation of UTCI

```
Function CalcUTCI(Ta As Double, va As Double, Tmrt As Double, RH As Double) As
Double
'   If CheckIfInputsValid(Ta, va, Tmrt, RH) <> InputsChecks.Pass Then
'       CalcUTCI = MinDouble()
'       Exit Function
'   End If

    Dim ehPa As Double
    ehPa = es(Ta) * (RH / 100)

    Dim D_Tmrt As Double
    D_Tmrt = Tmrt - Ta

    Dim Pa As Double
    Pa = ehPa / 10
    '  convert vapour pressure to kPa
    '#Region "whoa_mamma"
    Dim UTCI_approx As Double
    UTCI_approx = Ta + _
            (0.607562052) + _
            (-0.0227712343) * Ta + _
            (8.06470249 * (10 ^ (-4))) * Ta * Ta + _
            (-1.54271372 * (10 ^ (-4))) * Ta * Ta * Ta + _
            (-3.24651735 * (10 ^ (-6))) * Ta * Ta * Ta * Ta + _
            (7.32602852 * (10 ^ (-8))) * Ta * Ta * Ta * Ta * Ta + _
            (1.35959073 * (10 ^ (-9))) * Ta * Ta * Ta * Ta * Ta * Ta + _
            (-2.2583652) * va + _
            (0.0880326035) * Ta * va + _
            (0.00216844454) * Ta * Ta * va + _
            (-1.53347087 * (10 ^ (-5))) * Ta * Ta * Ta * va + _
            (-5.72983704 * (10 ^ (-7))) * Ta * Ta * Ta * Ta * va + _
            (-2.55090145 * (10 ^ (-9))) * Ta * Ta * Ta * Ta * Ta * va + _
            (-0.751269505) * va * va + _
            (-0.00408350271) * Ta * va * va + _
            (-5.21670675 * (10 ^ (-5))) * Ta * Ta * va * va + _
            (1.94544667 * (10 ^ (-6))) * Ta * Ta * Ta * va * va + _
            (1.14099531 * (10 ^ (-8))) * Ta * Ta * Ta * Ta * va * va + _
            (0.158137256) * va * va * va + _
            (-6.57263143 * (10 ^ (-5))) * Ta * va * va * va + _
            (2.22697524 * (10 ^ (-7))) * Ta * Ta * va * va * va + _
            (-4.16117031 * (10 ^ (-8))) * Ta * Ta * Ta * va * va * va + _
            (-0.0127762753) * va * va * va * va + _
            (9.66891875 * (10 ^ (-6))) * Ta * va * va * va * va

      UTCI_approx = UTCI_approx + _
            (2.52785852 * (10 ^ (-9))) * Ta * Ta * va * va * va * va + _
```

```
    (4.56306672 * (10 ^ (-4))) * va * va * va * va * va + _
    (-1.74202546 * (10 ^ (-7))) * Ta * va * va * va * va * va + _
    (-5.91491269 * (10 ^ (-6))) * va * va * va * va * va * va + _
    (0.398374029) * D_Tmrt + _
    (1.83945314 * (10 ^ (-4))) * Ta * D_Tmrt + _
    (-1.7375451 * (10 ^ (-4))) * Ta * Ta * D_Tmrt + _
    (-7.60781159 * (10 ^ (-7))) * Ta * Ta * Ta * D_Tmrt + _
    (3.77830287 * (10 ^ (-8))) * Ta * Ta * Ta * Ta * D_Tmrt + _
    (5.43079673 * (10 ^ (-10))) * Ta * Ta * Ta * Ta * Ta * D_Tmrt + _
    (-0.0200518269) * va * D_Tmrt + _
    (8.92859837 * (10 ^ (-4))) * Ta * va * D_Tmrt + _
    (3.45433048 * (10 ^ (-6))) * Ta * Ta * va * D_Tmrt + _
    (-3.77925774 * (10 ^ (-7))) * Ta * Ta * Ta * va * D_Tmrt + _
    (-1.69699377 * (10 ^ (-9))) * Ta * Ta * Ta * Ta * va * D_Tmrt + _
    (1.69992415 * (10 ^ (-4))) * va * va * D_Tmrt + _
    (-4.99204314 * (10 ^ (-5))) * Ta * va * va * D_Tmrt + _
    (2.47417178 * (10 ^ (-7))) * Ta * Ta * va * va * D_Tmrt + _
    (1.07596466 * (10 ^ (-8))) * Ta * Ta * Ta * va * va * D_Tmrt + _
    (8.49242932 * (10 ^ (-5))) * va * va * va * D_Tmrt + _
    (1.35191328 * (10 ^ (-6))) * Ta * va * va * va * D_Tmrt + _
    (-6.21531254 * (10 ^ (-9))) * Ta * Ta * va * va * va * D_Tmrt + _
    (-4.99410301 * (10 ^ (-6))) * va * va * va * va * D_Tmrt + _
    (-1.89489258 * (10 ^ (-8))) * Ta * va * va * va * va * D_Tmrt

UTCI_approx = UTCI_approx + _
    (8.15300114 * (10 ^ (-8))) * va * va * va * va * va * D_Tmrt + _
    (7.5504309 * (10 ^ (-4))) * D_Tmrt * D_Tmrt + _
    (-5.65095215 * (10 ^ (-5))) * Ta * D_Tmrt * D_Tmrt + _
    (-4.52166564 * (10 ^ (-7))) * Ta * Ta * D_Tmrt * D_Tmrt + _
    (2.46688878 * (10 ^ (-8))) * Ta * Ta * Ta * D_Tmrt * D_Tmrt + _
    (2.42674348 * (10 ^ (-10))) * Ta * Ta * Ta * Ta * D_Tmrt * D_Tmrt + _
    (1.5454725 * (10 ^ (-4))) * va * D_Tmrt * D_Tmrt + _
    (5.2411097 * (10 ^ (-6))) * Ta * va * D_Tmrt * D_Tmrt + _
    (-8.75874982 * (10 ^ (-8))) * Ta * Ta * va * D_Tmrt * D_Tmrt + _
    (-1.50743064 * (10 ^ (-9))) * Ta * Ta * Ta * va * D_Tmrt * D_Tmrt + _
    (-1.56236307 * (10 ^ (-5))) * va * va * D_Tmrt * D_Tmrt + _
    (-1.33895614 * (10 ^ (-7))) * Ta * va * va * D_Tmrt * D_Tmrt + _
    (2.49709824 * (10 ^ (-9))) * Ta * Ta * va * va * D_Tmrt * D_Tmrt + _
    (6.51711721 * (10 ^ (-7))) * va * va * va * D_Tmrt * D_Tmrt + _
    (1.94960053 * (10 ^ (-9))) * Ta * va * va * va * D_Tmrt * D_Tmrt + _
    (-1.00361113 * (10 ^ (-8))) * va * va * va * va * D_Tmrt * D_Tmrt + _
    (-1.21206673 * (10 ^ (-5))) * D_Tmrt * D_Tmrt * D_Tmrt + _
    (-2.1820366 * (10 ^ (-7))) * Ta * D_Tmrt * D_Tmrt * D_Tmrt + _
    (7.51269482 * (10 ^ (-9))) * Ta * Ta * D_Tmrt * D_Tmrt * D_Tmrt + _
    (9.79063848 * (10 ^ (-11))) * Ta * Ta * Ta * D_Tmrt * D_Tmrt * D_Tmrt + _
    (1.25006734 * (10 ^ (-6))) * va * D_Tmrt * D_Tmrt * D_Tmrt + _
    (-1.81584736 * (10 ^ (-9))) * Ta * va * D_Tmrt * D_Tmrt * D_Tmrt + _
    (-3.52197671 * (10 ^ (-10))) * Ta * Ta * va * D_Tmrt * D_Tmrt * D_Tmrt + _
    (-3.3651463 * (10 ^ (-8))) * va * va * D_Tmrt * D_Tmrt * D_Tmrt
```

```
 UTCI_approx = UTCI_approx + _
     (1.35908359 * (10 ^ (-10))) * Ta * va * va * D_Tmrt * D_Tmrt * D_Tmrt + _
     (4.1703262 * (10 ^ (-10))) * va * va * va * D_Tmrt * D_Tmrt * D_Tmrt + _
     (-1.30369025 * (10 ^ (-9))) * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt + _
     (4.13908461 * (10 ^ (-10))) * Ta * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt + _
     (9.22652254 * (10 ^ (-12))) * Ta * Ta * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt + _
     (-5.08220384 * (10 ^ (-9))) * va * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt + _
     (-2.24730961 * (10 ^ (-11))) * Ta * va * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt + _
     (1.17139133 * (10 ^ (-10))) * va * va * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt + _
     (6.62154879 * (10 ^ (-10))) * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt + _
     (4.0386326 * (10 ^ (-13))) * Ta * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt
+ _
     (1.95087203 * (10 ^ (-12))) * va * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt
+ _
     (-4.73602469 * (10 ^ (-12))) * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt *
D_Tmrt + _
     (5.12733497) * Pa + _
     (-0.312788561) * Ta * Pa + _
     (-0.0196701861) * Ta * Ta * Pa + _
     (9.9969087 * (10 ^ (-4))) * Ta * Ta * Ta * Pa + _
     (9.51738512 * (10 ^ (-6))) * Ta * Ta * Ta * Ta * Pa + _
     (-4.66426341 * (10 ^ (-7))) * Ta * Ta * Ta * Ta * Ta * Pa + _
     (0.548050612) * va * Pa + _
     (-0.00330552823) * Ta * va * Pa + _
     (-0.0016411944) * Ta * Ta * va * Pa + _
     (-5.16670694 * (10 ^ (-6))) * Ta * Ta * Ta * va * Pa + _
     (9.52692432 * (10 ^ (-7))) * Ta * Ta * Ta * Ta * va * Pa + _
     (-0.0429223622) * va * va * Pa

 UTCI_approx = UTCI_approx + _
     (0.00500845667) * Ta * va * va * Pa + _
     (1.00601257 * (10 ^ (-6))) * Ta * Ta * va * va * Pa + _
     (-1.81748644 * (10 ^ (-6))) * Ta * Ta * Ta * va * va * Pa + _
     (-1.25813502 * (10 ^ (-3))) * va * va * va * Pa + _
     (-1.79330391 * (10 ^ (-4))) * Ta * va * va * va * Pa + _
     (2.34994441 * (10 ^ (-6))) * Ta * Ta * va * va * va * Pa + _
     (1.29735808 * (10 ^ (-4))) * va * va * va * va * Pa + _
     (1.2906487 * (10 ^ (-6))) * Ta * va * va * va * va * Pa + _
     (-2.28558686 * (10 ^ (-6))) * va * va * va * va * va * Pa + _
     (-0.0369476348) * D_Tmrt * Pa + _
     (0.00162325322) * Ta * D_Tmrt * Pa + _
     (-3.1427968 * (10 ^ (-5))) * Ta * Ta * D_Tmrt * Pa + _
     (2.59835559 * (10 ^ (-6))) * Ta * Ta * Ta * D_Tmrt * Pa + _
     (-4.77136523 * (10 ^ (-8))) * Ta * Ta * Ta * Ta * D_Tmrt * Pa + _
     (8.6420339 * (10 ^ (-3))) * va * D_Tmrt * Pa + _
     (-6.87405181 * (10 ^ (-4))) * Ta * va * D_Tmrt * Pa + _
     (-9.13863872 * (10 ^ (-6))) * Ta * Ta * va * D_Tmrt * Pa + _
     (5.15916806 * (10 ^ (-7))) * Ta * Ta * Ta * va * D_Tmrt * Pa + _
     (-3.59217476 * (10 ^ (-5))) * va * va * D_Tmrt * Pa + _
     (3.28696511 * (10 ^ (-5))) * Ta * va * va * D_Tmrt * Pa + _
```

```
        (-7.10542454 * (10 ^ (-7))) * Ta * Ta * va * va * D_Tmrt * Pa + _
        (-1.243823 * (10 ^ (-5))) * va * va * va * D_Tmrt * Pa + _
        (-7.385844 * (10 ^ (-9))) * Ta * va * va * va * D_Tmrt * Pa + _
        (2.20609296 * (10 ^ (-7))) * va * va * va * va * D_Tmrt * Pa

    UTCI_approx = UTCI_approx + _
        (-7.3246918 * (10 ^ (-4))) * D_Tmrt * D_Tmrt * Pa + _
        (-1.87381964 * (10 ^ (-5))) * Ta * D_Tmrt * D_Tmrt * Pa + _
        (4.80925239 * (10 ^ (-6))) * Ta * Ta * D_Tmrt * D_Tmrt * Pa + _
        (-8.7549204 * (10 ^ (-8))) * Ta * Ta * Ta * D_Tmrt * D_Tmrt * Pa + _
        (2.7786293 * (10 ^ (-5))) * va * D_Tmrt * D_Tmrt * Pa + _
        (-5.06004592 * (10 ^ (-6))) * Ta * va * D_Tmrt * D_Tmrt * Pa + _
        (1.14325367 * (10 ^ (-7))) * Ta * Ta * va * D_Tmrt * D_Tmrt * Pa + _
        (2.53016723 * (10 ^ (-6))) * va * va * D_Tmrt * D_Tmrt * Pa + _
        (-1.72857035 * (10 ^ (-8))) * Ta * va * va * D_Tmrt * D_Tmrt * Pa + _
        (-3.95079398 * (10 ^ (-8))) * va * va * va * D_Tmrt * D_Tmrt * Pa + _
        (-3.59413173 * (10 ^ (-7))) * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (7.04388046 * (10 ^ (-7))) * Ta * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (-1.89309167 * (10 ^ (-8))) * Ta * Ta * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (-4.79768731 * (10 ^ (-7))) * va * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (7.96079978 * (10 ^ (-9))) * Ta * va * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (1.62897058 * (10 ^ (-9))) * va * va * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (3.94367674 * (10 ^ (-8))) * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (-1.18566247 * (10 ^ (-9))) * Ta * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (3.34678041 * (10 ^ (-10))) * va * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * Pa + _
        (-1.15606447 * (10 ^ (-10))) * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt *
Pa + _
        (-2.80626406) * Pa * Pa + _
        (0.548712484) * Ta * Pa * Pa + _
        (-0.0039942841) * Ta * Ta * Pa * Pa + _
        (-9.54009191 * (10 ^ (-4))) * Ta * Ta * Ta * Pa * Pa

  UTCI_approx = UTCI_approx + _
        (1.93090978 * (10 ^ (-5))) * Ta * Ta * Ta * Ta * Pa * Pa + _
        (-0.308806365) * va * Pa * Pa + _
        (0.0116952364) * Ta * va * Pa * Pa + _
        (4.95271903 * (10 ^ (-4))) * Ta * Ta * va * Pa * Pa + _
        (-1.90710882 * (10 ^ (-5))) * Ta * Ta * Ta * va * Pa * Pa + _
        (0.00210787756) * va * va * Pa * Pa + _
        (-6.98445738 * (10 ^ (-4))) * Ta * va * va * Pa * Pa + _
        (2.30109073 * (10 ^ (-5))) * Ta * Ta * va * va * Pa * Pa + _
        (4.1785659 * (10 ^ (-4))) * va * va * va * Pa * Pa + _
        (-1.27043871 * (10 ^ (-5))) * Ta * va * va * va * Pa * Pa + _
        (-3.04620472 * (10 ^ (-6))) * va * va * va * va * Pa * Pa + _
        (0.0514507424) * D_Tmrt * Pa * Pa + _
        (-0.00432510997) * Ta * D_Tmrt * Pa * Pa + _
        (8.99281156 * (10 ^ (-5))) * Ta * Ta * D_Tmrt * Pa * Pa + _
        (-7.14663943 * (10 ^ (-7))) * Ta * Ta * Ta * D_Tmrt * Pa * Pa + _
        (-2.66016305 * (10 ^ (-4))) * va * D_Tmrt * Pa * Pa + _
        (2.63789586 * (10 ^ (-4))) * Ta * va * D_Tmrt * Pa * Pa + _
```

```
        (-7.01199003 * (10 ^ (-6))) * Ta * Ta * va * D_Tmrt * Pa * Pa + _
        (-1.06823306 * (10 ^ (-4))) * va * va * D_Tmrt * Pa * Pa + _
        (3.61341136 * (10 ^ (-6))) * Ta * va * va * D_Tmrt * Pa * Pa + _
        (2.29748967 * (10 ^ (-7))) * va * va * va * D_Tmrt * Pa * Pa + _
        (3.04788893 * (10 ^ (-4))) * D_Tmrt * D_Tmrt * Pa * Pa + _
        (-6.42070836 * (10 ^ (-5))) * Ta * D_Tmrt * D_Tmrt * Pa * Pa + _
        (1.16257971 * (10 ^ (-6))) * Ta * Ta * D_Tmrt * D_Tmrt * Pa * Pa

UTCI_approx = UTCI_approx + _
        (7.68023384 * (10 ^ (-6))) * va * D_Tmrt * D_Tmrt * Pa * Pa + _
        (-5.47446896 * (10 ^ (-7))) * Ta * va * D_Tmrt * D_Tmrt * Pa * Pa + _
        (-3.5993791 * (10 ^ (-8))) * va * va * D_Tmrt * D_Tmrt * Pa * Pa + _
        (-4.36497725 * (10 ^ (-6))) * D_Tmrt * D_Tmrt * D_Tmrt * Pa * Pa + _
        (1.68737969 * (10 ^ (-7))) * Ta * D_Tmrt * D_Tmrt * D_Tmrt * Pa * Pa + _
        (2.67489271 * (10 ^ (-8))) * va * D_Tmrt * D_Tmrt * D_Tmrt * Pa * Pa + _
        (3.23926897 * (10 ^ (-9))) * D_Tmrt * D_Tmrt * D_Tmrt * D_Tmrt * Pa * Pa + _
        (-0.0353874123) * Pa * Pa * Pa + _
        (-0.22120119) * Ta * Pa * Pa * Pa + _
        (0.0155126038) * Ta * Ta * Pa * Pa * Pa + _
        (-2.63917279 * (10 ^ (-4))) * Ta * Ta * Ta * Pa * Pa * Pa + _
        (0.0453433455) * va * Pa * Pa * Pa + _
        (-0.00432943862) * Ta * va * Pa * Pa * Pa + _
        (1.45389826 * (10 ^ (-4))) * Ta * Ta * va * Pa * Pa * Pa + _
        (2.1750861 * (10 ^ (-4))) * va * va * Pa * Pa * Pa + _
        (-6.66724702 * (10 ^ (-5))) * Ta * va * va * Pa * Pa * Pa + _
        (3.3321714 * (10 ^ (-5))) * va * va * va * Pa * Pa * Pa + _
        (-0.00226921615) * D_Tmrt * Pa * Pa * Pa + _
        (3.80261982 * (10 ^ (-4))) * Ta * D_Tmrt * Pa * Pa * Pa + _
        (-5.45314314 * (10 ^ (-9))) * Ta * Ta * D_Tmrt * Pa * Pa * Pa + _
        (-7.96355448 * (10 ^ (-4))) * va * D_Tmrt * Pa * Pa * Pa + _
        (2.53458034 * (10 ^ (-5))) * Ta * va * D_Tmrt * Pa * Pa * Pa + _
        (-6.31223658 * (10 ^ (-6))) * va * va * D_Tmrt * Pa * Pa * Pa + _
        (3.02122035 * (10 ^ (-4))) * D_Tmrt * D_Tmrt * Pa * Pa * Pa

UTCI_approx = UTCI_approx + _
        (-4.77403547 * (10 ^ (-6))) * Ta * D_Tmrt * D_Tmrt * Pa * Pa * Pa + _
        (1.73825715 * (10 ^ (-6))) * va * D_Tmrt * D_Tmrt * Pa * Pa * Pa + _
        (-4.09087898 * (10 ^ (-7))) * D_Tmrt * D_Tmrt * D_Tmrt * Pa * Pa * Pa + _
        (0.614155345) * Pa * Pa * Pa * Pa + _
        (-0.0616755931) * Ta * Pa * Pa * Pa * Pa + _
        (0.00133374846) * Ta * Ta * Pa * Pa * Pa * Pa + _
        (0.00355375387) * va * Pa * Pa * Pa * Pa + _
        (-5.13027851 * (10 ^ (-4))) * Ta * va * Pa * Pa * Pa * Pa + _
        (1.02449757 * (10 ^ (-4))) * va * va * Pa * Pa * Pa * Pa + _
        (-0.00148526421) * D_Tmrt * Pa * Pa * Pa * Pa + _
        (-4.11469183 * (10 ^ (-5))) * Ta * D_Tmrt * Pa * Pa * Pa * Pa + _
        (-6.80434415 * (10 ^ (-6))) * va * D_Tmrt * Pa * Pa * Pa * Pa + _
        (-9.77675906 * (10 ^ (-6))) * D_Tmrt * D_Tmrt * Pa * Pa * Pa * Pa + _
        (0.0882773108) * Pa * Pa * Pa * Pa * Pa + _
        (-0.00301859306) * Ta * Pa * Pa * Pa * Pa * Pa + _
```

```
        (0.00104452989) * va * Pa * Pa * Pa * Pa * Pa + _
        (2.47090539 * (10 ^ (-4))) * D_Tmrt * Pa * Pa * Pa * Pa * Pa + _
        (0.00148348065) * Pa * Pa * Pa * Pa * Pa * Pa
  '#End Region

  CalcUTCI = UTCI_approx
End Function

Function es(Ta As Double) As Double
  'calculates saturation vapour pressure over water in hPa for input air temperature (ta) in celsius according to:
  'Hardy, R.; ITS-90 Formulations for Vapor Pressure, Frostpoint Temperature, Dewpoint Temperature and Enhancement Factors in the Range -100 to 100 °C;
  'Proceedings of Third International Symposium on Humidity and Moisture; edited by National Physical Laboratory (NPL), London, 1998, pp. 214-221
  'http://www.thunderscientific.com/tech_info/reflibrary/its90formulas.pdf (retrieved 2008-10-01)
  Dim g(7) As Double
  g(0) = -2836.5744
  g(1) = -6028.076559
  g(2) = 19.54263612
  g(3) = -0.02737830188
  g(4) = 0.000016261698
  g(5) = CDbl(7.0229056 * (10 ^ (-10)))
  g(6) = CDbl(-1.8680009 * (10 ^ (-13)))
    Dim tk As Double
  tk = Ta + 273.15
    Dim es1 As Double
  es1 = 2.7150305 * Math.Log(tk)
  'for count, i in enumerate(g):
  For Count = 0 To UBound(g)
    Dim i As Double
    i = g(Count)
    es1 = es1 + (i * (tk ^ (Count - 2)))
  Next
    es1 = Math.Exp(es1) * 0.01
  es = es1
End Function

'Function CheckIfInputsValid(Ta As Double, va As Double, Tmrt As Double, hum As Double) As InputsChecks
'   If ((Ta < -50) Or (Ta > 50)) Then
'       CheckIfInputsValid = InputsChecks.Temp_OutOfRange
'       Exit Function
'   End If
'   If ((Tmrt - Ta < -30) Or (Tmrt - Ta > 70)) Then
'       CheckIfInputsValid = InputsChecks.Large_Gap_Between_Trmt_Ta
'       Exit Function
'   End If
'   If va < 0.5 Then
```

```
'       CheckIfInputsValid = InputsChecks.WindSpeed_Too_Low
'       Exit Function
'   End If
"   If va > 17 Then
'       CheckIfInputsValid = InputsChecks.WindSpeed_TooHigh
'       Exit Function
'   End If
'   CheckIfInputsValid = InputsChecks.Pass
'End Function

Function MinDouble() As Double
   MinDouble = -1.79769313486231E+308
End Function

Public Enum InputsChecks
   Temp_OutOfRange
   Large_Gap_Between_Trmt_Ta
   WindSpeed_Too_Low
   WindSpeed_TooHigh
   Pass
   Unknown
End Enum
```

F.2. Calculation of possible variation of *MRT* and T_a for *UTCI*

```
Sub MRTUTCIrange()
 va = Worksheets("UTCI").Range("B6").Value
 lb = Worksheets("UTCI").Range("D11").Value
 ub = Worksheets("UTCI").Range("H11").Value
 RH = Worksheets("UTCI").Range("B8").Value
 Worksheets("UTCI").Range("AA2:AA2800").ClearContents
 Worksheets("UTCI").Range("AB2:AB2800").ClearContents
 Worksheets("UTCI").Range("AC2:AC2800").ClearContents
 lrow = 2
      For Tr = 0 To 50 Step 1
         For Temp = 0 To 40 Step 1
            tt = Module7.CalcUTCI(CDbl(Temp), CDbl(va), CDbl(Tr), CDbl(RH))
            If tt >= lb And tt <= ub Then
            Worksheets("UTCI").Range("AA" & lrow).Value = tt
            Worksheets("UTCI").Range("AB" & lrow).Value = Tr
            Worksheets("UTCI").Range("AC" & lrow).Value = Temp
            lrow = lrow + 1
            End If
         Next Temp
      Next Tr
   End Sub
```

F.3. Calculation of possible variation of *MRT* and v_a for *UTCI*

```
Sub MRTUTCIvarange()
 Ta = Worksheets("UTCI").Range("B2").Value
```

```
lb = Worksheets("UTCI").Range("D11").Value
ub = Worksheets("UTCI").Range("H11").Value
RH = Worksheets("UTCI").Range("B8").Value
Worksheets("UTCI").Range("BA2:BA400").ClearContents
Worksheets("UTCI").Range("BB2:BB400").ClearContents
Worksheets("UTCI").Range("BC2:BC400").ClearContents
lrow = 2
    For Tr = 0 To 50 Step 1
        For va = 0 To 1 Step 0.1
            tt = Module7.CalcUTCI(CDbl(Ta), CDbl(va), CDbl(Tr), CDbl(RH))
            If tt >= lb And tt <= ub Then
            Worksheets("UTCI").Range("BA" & lrow).Value = tt
            Worksheets("UTCI").Range("BB" & lrow).Value = Tr
            Worksheets("UTCI").Range("BC" & lrow).Value = va
            lrow = lrow + 1
            End If
        Next va
    Next Tr
```

Appendix G

G.1. VBA code for calculation of hourly deviation from comfort

```
Function Hdev(M, Top, PMV, UTCI, ll, ul, Trm)
If M = "PMV" Then Hdev = PMV
If M = "UTCI" Then
   If UTCI <= ul And UTCI >= ll Then Hdev = 0
   If UTCI > ul Then Hdev = UTCI - 26
   If UTCI < ll Then Hdev = UTCI - 18
End If
If M = "Standard AM" Or M = "Transitory AM" Then
   If Trm >= 15 And Trm <= 30 Then Hdev = Top - ((0.33 * Trm) + 18.8)
   If Trm < 15 Then Hdev = Top - ((0.33 * 15) + 18.8)
   If Trm > 30 Then Hdev = Top - ((0.33 * 30) + 18.8)
End If
If M = "Conditioned AM" Then
   If Trm >= 15 And Trm <= 30 Then Hdev = Top - ((0.09 * Trm) + 22.6)
   If Trm < 15 Then Hdev = Top - ((0.09 * 15) + 22.6)
   If Trm > 30 Then Hdev = Top - ((0.09 * 30) + 22.6)
End If
End Function
```

Appendix H

H.1. Calculation of T_{rm} from given hourly data of outdoor air temperature

```
Sub DM()
Dim myArra(365) As Double
dayAvgTemp = 0
For i = 3 To 8763 Step 24
 nrow = i + 23
 Sum = 0
 For j = i To nrow Step 1
  Sum = Sum + Worksheets(2).Range("b" & j).Value
 Next j
 Worksheets(2).Range("c" & i).Value = Sum / 24
 myArra(dayAvgTemp) = Sum / 24
 dayAvgTemp = dayAvgTemp + 1
Next i
For k = 0 To 364
    tita = 0
    alfa = 0.8
    alfaPower = 0
    For l = k - 1 To k - 7 Step -1
        lnew = l
        If l < 0 Then lnew = l + 365
        tita = tita + alfa ^ alfaPower * myArra(lnew)

        alfaPower = alfaPower + 1
    Next l
    For m = 3 To 26
    Worksheets(2).Range("d" & (k * 24) + m).Value = tita * (1 - alfa)
    Next m
Next k
End Sub
```