Master Thesis

Comfort in 3rd Space Canopies

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Preface

This project is represents a master thesis from the Department of Civil Engineering at the Technical University of Denmark. It has been done within the field of Architectural Engineering in the period from primo April to ultimo September 2016.

The project is furthermore a part of the STED/Nordic Built Program, and has been done in collaboration with White Architects.

The project was handed in at the 21st of September 2016.

Acknowledgements

I would like to thank my supervisors at the DTU, Lotte Bjerregaard Jensen and Kristoffer Negendahl for their contribution to the relisation of the project.

Futhermore I would like to thank Elise Grosse from White architect for feedback on the project and for delivery of the EKO Canopy case.

Apart from these people, I would like to thank many of my fellow students who have helped me with feedback, especially Alexander da Costa Carneiro, who provided important information on the modelling of ground temperatures, through his own thesis.

Abstract

This thesis have examined how thermal comfort can be assessed in spaces that are neither outdoors nor indoors - 3rd spaces. The approach have been to study existing thermal comfort models, to assess and discuss possibilities for application to 3rd spaces, also taking some architectural parameters into account. Based on these findings a set-up for analysis in the Rhino/Grasshopper environment have been suggested, and tested for certain issues related to 3rd space climate simulations. Finally the set up and thermal comfort models have been tested on the case of the EKO Canopy project proposal from White Architects, to try to prove the hypothesis that a set-up taking distributed comfort results into account might inform an early design phase. The study revealed that none of the examined thermal comfort models were optimal for application in 3rd spaces. It did however also show that some adjustment to the models and their use in analysis of the case might have potential to solve this issue. In terms of the validity of the chosen set-up it was found that a lack of a proper model for air flow is a serious problem. It was also shown that the use of distributed comfort result have some potential to inform the early design process. Finally the study found that the same analysis set-up is capable to perform outdoor simulations as well, which add further options to the possible design strategies of 3rd space projects.

Contents

Part I

Introduction and Background?

Chapter 1

Introduction

1.1 Motivation & Problem Statement

Canopies used as passive buffer zones between existing buildings is an interesting strategy to improve the energy consumption, the indoor climate and the general liveability. It is, however, often challenging to predict the indoor climate and general user comfort in these spaces since their characteristics often do not comply with neither classic thermal comfort models and codes nor the way most Building Performance Simulation (BPS) tools simulate indoor conditions.

An improved method for prediction of the comfort in this type of spaces - so called 3rd spaces - is therefore desirable. As is a new approach to what would be regarded comfortable in a space that is neither indoor nor outdoor.

This sparks the overall question: *How can the climatic comfort of third spaces be assessed?*

Over the last half a century multiple models of thermal comfort have been developed based on thousands of studies. These thermal comfort models do however tend to focus either on indoor **or** outdoor spaces.

But to which degree can the current models be applied to 3rd spaces or how might they be adjusted to fit these spaces?

Research done on indoor thermal comfort shows that people are willing to accept conditions that do not comply with the usual standards, when the building is more obviously in touch with the surroundings. This is for instance the case in the Adaptive Model (de Dear and Brager, 1998) where the acceptance criteria are depending on the outdoor temperature.

Many simulation programs today, such as IES VE are very good at predicting comfort in an office or housing environment than falls within standard constraints; e.g. a floor height of approx. 3 meters, well insulated walls, even solar gain distribution and primarily mechanical ventilation. None of these properties would typically be found in for example a passively controlled canopy (3rd space). Instead a lot of effects play a different and more important role in 3rd spaces.

Which sort of set-up of model and tools would be able to handle the analysis of 3rd spaces in a sufficient manner?

A well functioning method to simulate the indoor comfort in canopy spaces could impact future projects by validating a design to a larger extent on beforehand, minimizing risk for possible project participants. Furthermore it might be able to inform the design process.

1.2 Case

To test whether the hypothesis that a well functioning method for analysis of 3rd spaces can inform the design process is realistic, it makes sense to test the method through a case study of a 3rd space.

The chosen case is the EKO-canopy project connected with the renovation of Miljonprogrammet housing blocks in Sweden. The project is mostly an idea (by Elise Grosse) and thus in a very early conceptual phase.

Figure 1.1: EKO-canopy conceptual render, by White

The idea is to build canopies between the existing 1970's building blocks in various places in Sweden, as an alternative strategy compared to just increasing the amount of wall insulation in the adjacent buildings. These canopies would of course also impact the use and liveability of the building blocks a lot.

This thesis could, if successful, provide interesting inputs in regards of methods that would improve the predictability of the comfort in these canopy spaces - reducing risk for all stakeholders.

The project was also the theme of the master thesises; "Investigation of EKO-Canopy energy renovation concept for Swedish million program apartment buildings - A case study of Dragonvägen" by Knudsen et al. (2016) and "Parametric Structural Design" by Vila (2016). Both of these studies were conducted under the STED (Nordic Built) Program. This thesis is also a done within the STED Program, and since the other two previous studies inform this one, it is in line with the principle of the program to build upon earlier produced knowledge.

Another considered case was the Komsa headquater project in Wroclaw, Poland, also by White. This was however not chosen because of the time frame of the project that was set to be completed in the fall of 2016. This time frame meant that the project was already in the detailed design phase when the work on this thesis was started.

Figure 1.2: Overview of the Komsa logistics center and headquarter in Wroclaw, Poland

1.3 Approach

Through his master thesis Mikkel K. Knudsen took the overall concept of the EKO Canopy and looked at solutions i term of concretizing the project in all aspects. Everything from the shape of the canopy over choice of materials to daylight was discussed. This has provided an excellent base for further studies of the case.

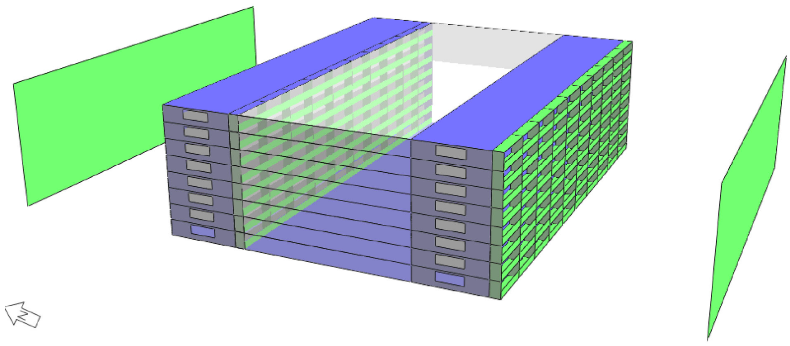

Figure 1.3: The energy model used in Knudsen et al. (2016)

Although the study is very broad, it especially goes into detail regarding the effects of the project upon daylight and energy consumption of the existing buildings.

The climate of the canopy itself was simulated in Knudsen et al. (2016) but with an output of average values of temperature for each of the horizontal zones[1] of the space, as shown in figure 1.3. The focus of the simulations is closely connected with the estimation of energy savings. In this sense the canopy is put in a position where it acts as a support function to the existing buildings' climate. This is also one of White's main goals with the project.

This study takes on a different approach to the climate of the canopy space, and focuses on thermal comfort. An important part of the approach is also that the design of the canopy should aim for creating a desirable level of comfort for the canopy itself, so that it is a mean of improving the liveability of the existing buildings as well as minimizing the energy consumption.

To produce results that might inform the design of the canopy itself, the focus on average climatic values for the space is shifted towards an aim of distributed comfort values for the space. This is based on the idea that the EKO Canopy is so large that multiple microclimatic conditions are expected to occur in many situations.

Another important approach of this thesis is that the EKO Canopy is considered to be only naturally conditioned throughout the case study. This contradicts the original proposal by White that includes excess heat from nearby industry facilities. The reason for this 'natural' approach is that is makes the result more generic in terms of conclusions regarding 3rd spaces.

[1]The space was split into zones corresponding to the floor heights of the adjacent buildings.

Part II

Method

Chapter 2

Overall Method

This study generally focuses on *simulations* as a method for analysing thermal comfort in 3rd spaces. Some would argue that simulations of such an atypical space would often result in data that is so idealised, that it has little relation to the real life space, and therefore is useless. A different approach would be to rely on tacit knowledge in the form of experience and rules of thumb for a design strategy. But the use of simulation tools for analyses of comfort does not supersede tacit knowledge. Experience and intuition are for instance quite important factors when creating simulation models for comfort, and even more when evaluating the results of them.

But simulations can, if used in a proper manner, produce interesting inputs to the early design phase, and has the ability to evaluate design options based on advanced climatic data. The reason the early design phase is considered important is because it represents a point in the design process, where changes are less costly, and will potentially have the biggest impact on the final result (see figure 2.1.

Many of the result chapters (chap. 3 to 11 discuss the method used in detail. This chapter therefore mostly describes the overall method of this thesis. The reason for splitting the descriptions this way, is to keep the methodical concerns fresh in mind for the reader through the often quite different result chapters.

Assessment and Discussion of Thermal Comfort Models

To get an overview of and insight to the three selected[1] thermal comfort models - the PMV Model, the Adaptive Model and the Universal Thermal Climate Index (UTCI) - a literature review has been carried out. The point of this literature study was to understand the models in terms of their input parameters and formal expressions, calculation methods and importantly their limitations. The results of this literature study is described in chapter 3.

A second literature study primarily based on a single source have been carried out to assess possible influences from architectural and contextual parameters. The reviewed aspects

[1] Selection criteria are explained in chapter 3

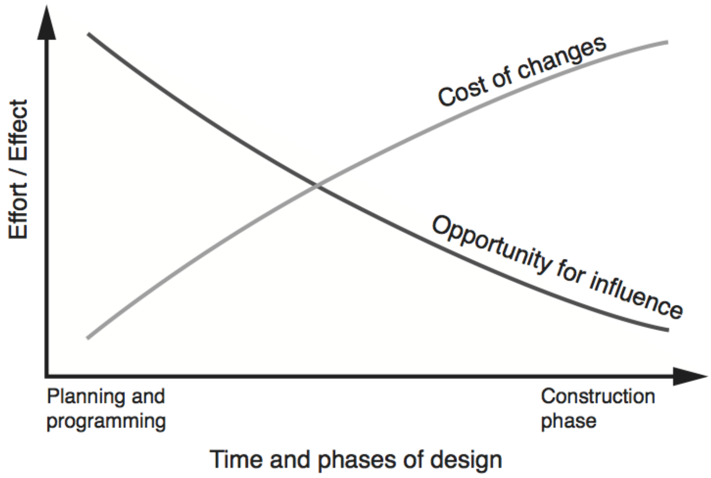

Figure 2.1: A graphical representation of the relationship between cost of changes and influence on design, throughout the entire design process

are connected to architectural, tectonic and contextual elements that would realistically be found in canopies and might affect the occupants' sense of connection with the outdoors. This study is further described in chapter 5.

To get a more practical sense of differences in the three chosen thermal models, an introductory comparison have been done using free, easy to use internet based tools. The comparison was done based on input parameter variation. Given the different nature of the three models they are not directly comparable and some measures have thus been taken to attempt to counter this problem, so the outputs of the models are comparable, either numerically or in terms of tendencies. The comparison results are shown in chapter 4.

Based on the knowledge of the thermal comfort models and the architectural parameters that might influence them it has been discussed which thermal comfort framework that might be used for an analysis of a 3rd space. This discussion is, apart from the earlier reviewed sources based on logical deduction. The discussion is described in chapter 6 and marks the end of the abstract part of the results connected directly with the overall framework for comfort analysis.

Analysis Set-Up and Test of The Set-Up

To get a deeper insight to how the selected analysis set-up handles different issues connected to simulation/analysis of climate parameters in 3rd space atrium structures a number of test simulations have been run. The tested issued were solar gain distribution, air flow and influence of ground temperature. Simulations have been done for each potential issue on a number of possible model solutions.

In a way this step is an example of a conceptual validation of the set-up. In other words since no measured data for the structure is available, it makes it possible to assess the output compared to the expected behaviour of the space, for example that the sun would heat up certain surfaces in an atrium more up than others.

Case studies

Finally a case study of White's EKO Canopy has been performed to test if the comfort framework and the analysis set-up is capable of producing viable design inputs. The emphasis of the analysis have been on producing 'result examples' to reveal the potential of the approach.

Part III

Results

Chapter 3

Thermal Comfort Models - A Literature Study

There are no 'plug-and-play' solutions available when it comes to evaluating thermal comfort in 3rd space climates, such as passively conditioned canopy structures. Numerous models does however exist for both indoor and outdoor thermal comfort.

What makes these established models hard to use in 3rd spaces, has to do with both the limitations of the existing models, but also with the occupants approach to such spaces. Do you expect such a place to behave as a well conditioned office or apartment? On the other hand, would you expect it to reflect the outdoor weather 1:1? Or does that conflict with your observations of a structure?

On the long run it would be an interesting perspective to develop a 'tailored' model for thermal comfort in 3rd spaces that takes these factors into account, or produces a statistical relationship at least. This is however a difficult task, and in the meanwhile these spaces are being built.

In some projects, such as the Komsa Head Quarter, the indoor climate control is design based on the designers experience, and then perhaps calibrated after the building is put to use. This approach is very likely to produce excellent result (assuming that the designers are skilled).

But would it be interesting to look at more standardized models for thermal comfort that are usable in simulation software? In most other types of building spaces simulations are widely used as an integral part of the design process. Although these simulations doesn't produce 'the truth' in terms of how comfortable the spaces will be in reality, it can not be denied that they can affect design decisions in a positive way if used in a proper way.

So which framework/evaluation criteria can be used for this purpose now? Does the existing indoor and outdoor thermal comfort model contain element that are meaningful for the evaluation of 3rd spaces? That is what the following chapter(s), will try to pitch in to, by looking at such models.

Selection of thermal comfort models to investigate

As mentioned above numerous models exist for both indoor and outdoor climate. This chapter deals with three of those: **The PMV Model** by Fanger, the **Adaptive Model** by de Dear, Brager et al. and the **UTCI** by Błazejczyk, Jendritzky, Bröde et al.

When looking at thermal comfort models, the PMV Model is probably the 'grand daddy' to many - the model who introduced comfort as a serious aspect of designing buildings. The model is therefore included here as a sort of benchmark and because it contain the basic mechanisms and relations that almost every other model (and certainly the other models investigated here) is built on.

The Adaptive Model is included because of its focus on natural conditioned spaces and because it suggest a strong relationship between nature and a persons sense of comfort.

The reason for including a model for outdoor comfort, is to investigate whether such a models takes certain parameters into account that specifically has to do with outdoor situations and are thus not included in the to others. Furthermore it's includes to try ensure a broader scope on comfort nor only focusing on closed building structures. The reason for choosing the UTCI is that it is currently the state of art, and was developed including aspects of many other outdoor thermal comfort models.

Hvad med andre comfort parametre end de termiske?

3.1 The PMV Model

When discussing thermal comfort models it's hard to avoid Fanger's PMV (Predicted Mean Vote) model. The model was introduced in "Thermal Comfort" by Povl Ole Fanger in 1970 based on numerous studies of human comfort and physiological responses in climatic chambers. One of the ultimate goals of the model is to provide a universal comfort model independent from age, gender, nationality, ethnicity, food consumption, etc. Since it's launch the model has reached a status as state of the art for evaluating human thermal comfort in buildings, and base for numerous standards within the indoor climate and HVAC field.

The comfort equation

What Fanger created, based on experiments on approx. 1300 test subjects, was a comfort equation, that takes four climate parameters, as well as activity level and clothing into account.

PMV inputs:

- Ambient air temperature
- Mean radiant temperature
- Air velocity
- Humidity
- Clothing factor
- Activity level

The comfort equation is quite complex and appear in many variations. In Fanger (1970) it's given as a double equation making it hard to apply directly. The following is the one used in the DS/EN ISO 7730 (Dansk Standard, 2006):

$$
\begin{aligned}
PMV = & [0,303 * \exp(-0,036 \cdot M) + 0,028] \cdot \{(M - W - 3,05 * 10^{-3} \\
& \cdot [5733 - 6,99 \cdot (M - W) - p_a[-0,42 \cdot [(M - W) - 58,15] - 1,7 \cdot 10^{-5} \\
& \cdot M \cdot (5867 - p_a) - 0,0014 \cdot M \cdot (34 - t_a) - 3,96 \cdot 10^{-8} \cdot f_{cl} \\
& \cdot \left[(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4\right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\}
\end{aligned}
\tag{3.1}
$$

where M is the metabolic rate [met], W is the effective mechanical power [W/m2], p_a is the water vapour partial pressure [Pa], t_a is the air temperature [°C], $\overline{t_r}$ is the mean radiant temperature [°C], f_{cl} is the clothing surface area factor [-] (derived in a separate equation taking clothing insulation [W/(m^2 K)] into account), h_c is the convective heat transfer coefficient [W/(m^2 K)] (derived taking relative air velocity [m/s] and other previously named parameters into account), t_{cl} is the clothing surface temperature, [°C] (derived taking clothing insulation [W/(m^2 K)] an other previously named parameters into account). The equations for the three latter can be found in the standard.

The formula above (3.1) is rather time consuming to use manually and the PMV model is therefore mostly applied as part of simulation software, or through PC tool published by ASHRAE[1] and availiable as a web version under CBE, Berkeley by Hoyt et al. (2013).

An interesting aspect of the comfort equation is that is does not only take 'linear' effects of each input into account, but also each parameters effect when combined with the other. This is also emphasized by in the introduction of "Thermal Comfort":

> *"It is impossible to consider the effect of any of the physical factors influencing thermal comfort independently, as the effect of each of them depends on the level of the other factors."*

[1] Created by Fountain and Huizenga in 1997

- Fanger (1970)

The PMV output of the comfort equation, can be converted to the PPD scale (Percentage of People Dissatisfied), which, perhaps due to it's intuitiveness, is often used as a measure for comfort as well as to define comfort standards in various standards.

Local Discomforts

Apart from deriving the overall comfort equation, Fanger also described how certain effect in the indoor climate can lead to local discomfort.

Local discomforts sources:

- Radiant asymmetry (up/down, front/back, right/left)
- Vertical air temp diff (max 3 °C, ASHRAE)
- Draft (inputs: air velocity, air turbulence)
- High floor temperatures (>29 °C)

All of these sources of local discomfort (perhaps except for the hot floor) might very well be present in a passively conditioned canopy. Whether they are as relevant to comfort as in the indoor climate is however a different question and will be discussed in chapter 6.

Field of application

The PMV model has been proven to be exact for mechanically conditioned buildings all over the world, time and time again through the years. The correlation between the PMV model and the measured data for real buildings is for instance documented in the work on the Adaptive Model by de Dear and Brager (1998).

How the model copes with more alternatively conditioned buildings or built environments, such as for example the EKO Canopy, is however a different question. In "Thermal Comfort" (Fanger, 1970) the limits of the model, as for example seen in the multiple plots, span quite wide. For instance the minimum temperatures (both radiant and air) given in the plots are 5°C and the maximum often 35°C. Other sources do however question the range for which the model is valid.

DS/EN ISO 7730 lists the ranges for each parameter for which the PMV model should be used. These ranges are listed below:

- PMV value between -2 and +2
- Activity level, M: 0.8 to 4 met
- Clothing insulation, I_{cl}: 0 to 2 clo
- Ambient temperature, t_a: 10 to 30 °C

- Mean radiant temperature, $\overline{t_r}$: 10 to 40 °C
- Air velocity, v_a: 0 to 1 m/s
- Vapour partial pressure, p_a: 0 to 2700 Pa

Humphreys and Fergus Nicol (2002) has tested the model against votes from a large amount of building occupants, and conclude that the *"PMV can be seriously misleading when used to predict the mean comfort votes of groups of people in everyday conditions in buildings, particularly in warm environments."* This paper suggest that it is necessary to go even further than then limitations of the DS/EN ISO 7730, to ensure the validity of the model.

This makes it doubtful whether the model is suited for use in 3rd spaces, since especially the three inputs t_a, $\overline{t_r}$ and v_a would be expected not always to conform to the limitations given in DS/EN ISO 7730. The issue of 3rd space applicability will be further discussed in chapter 6.

3.2 The Adaptive Model

While the PMV Model (Fanger, 1970) has generally been accepted as a good indicator for thermal comfort in mechanically conditioned building for the last 40+ years, field studies over the years have shown that it doesn't reflect the thermal comfort in naturally conditioned[2] buildings equally well.

Development of "An Adaptive Model of Thermal Comfort and Preference"

One of the first to show this discrepancy was Michael A. Humphreys, who examined huge amount of field studies from "free-running buildings"[3] and "other buildings" (Humphreys, 1978).

What Humphreys found from the large amount of field studies, was that the neutral temperature, in a naturally conditioned indoor climate, was much more dependent upon outdoor temperature than the one in a mechanically conditioned indoor climate.

Based on the work of Humphreys and others Richard de Dear, Uni. of Sydney, and Gail Brager, UC Berkeley, developed "an adaptive model of thermal comfort and preference" in 1995-1997. The development of the model was comissioned by ASHRAE and the results were published in ASHRAE Transactions vol. 104. This adaptive model was based on measured comfort in "buildings with centralized HVAC" and "buildings with natural ventilation"(de Dear and Brager, 1998).

[2] Buildings where natural ventilation is the only mean of cooling
[3] Meaning naturally cooled

De Dear and Brager differentiate their approach to thermal comfort from that of the "static"[4] models and standards. Apart from it correlating with measured field data, they argue that an adaptive approach is needed for environmental reasons.

> *"Current comfort standards are intended to optimize the thermal acceptability of indoor environments. Unfortunately, they have tended to require energy-intensive environmental control strategies and often preclude thermally variable solutions, such as many climate-responsive and energy-conserving designs, or innovative mechanical strategies that allow for personal control."*
>
> \- de Dear and Brager (1998)

The whole article "Developing an adaptive model of thermal comfort and preference" by de Dear and Brager (1998) is as much as a description of a new model a critique of the existing (static) ones.

It is however important to note that the Adaptive Model is based on the PMV Model and acts more as a complementation of this model, taking the context dependent variables into account:

> *"The static heat balance model can be viewed as a partially adaptive model, accounting for the effects of behavioral adjustments that directly affect inputs such as clothing or air velocity. An adaptive model of comfort complements this conventional approach by accounting for additional contextual factors and thermal experiences that modify building occupants' expectations and thermal preferences."*
>
> de Dear and Brager (1998)

The relationship between the PMV Model[5] and the Adaptive Model is shown for both buildings with HVAC systems and naturally ventilated ones.

Comfort calculation and inputs

The formal findings by de Dear and Brager (1998) was that the comfort temperature of people in naturally ventilated buildings can be described as:

$$t_{comf} = 18.9 + 0.255 \cdot ET{*}_{out} \tag{3.2}$$

where $ET{*}_{out}$ is the mean monthly or daily outdoor Effective Temperature, measured at 6 am (assumed min.) and 3 pm (assumed max.).

For buildings with centralized HVAC systems, the dependency on outdoor temperatures has a smaller effect on the neutral (comfort) temperature, and the relation (called the

[4] de Dear and Brager (1998)
[5] Adjusted for clothing and activity.

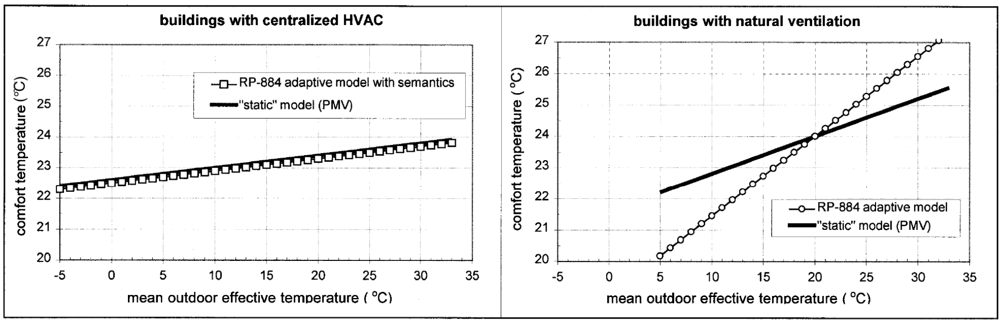

Figure 3.1: Figure from de Dear and Brager (1998) showing the correspondence and difference respectively of the (adjusted) PMV Model and the Adaptive Model based on measurements in 'real-life' buildings.

"Adaptive PMV Method for HVAC Buildings" in de Dear and Brager (1998)) can be described as:

$$t_{comf} = 22.6 + 0.04 \cdot ET{*}_{out} \quad (3.3)$$

As shown above the original measure of outdoor temperature introduced by de Dear and Brager (1998) is a mean value of outdoor Effective Temperature. Later sources such as the DS/EN ISO 15251 (Dansk Standard/CEN, 2007) defines the outdoor temperature as a weighted average over the week leading up to a given day. The formula (for naturally ventilated buildings) described in DS/EN ISO 15251 is:

$$t_{rm} = (t_{ed-1} + 0.8 \cdot t_{ed-2} + 0.6 \cdot t_{ed-3} + 0.5 \cdot t_{ed-4} + 0.4 \cdot t_{ed-5} + 0.3 \cdot t_{ed-6} + 0.2 \cdot t_{ed-7})/3.8 \quad (3.4)$$

where t_{ed-1} is the daily mean external temperature for the previous day and so on.

With this definition of temperature, the formula given in DS/EN ISO 15251, for the neutral temperature in a naturally ventilated building is:

$$t_{comf} = 18.8 + 0.33 \cdot t_{rm} \quad (3.5)$$

Limitations of the model

As mentioned earlier the adaptive model is based on field studies. The climate of the location is therefore an important factor for the bounderies of the model. Most of the cases examined are placed in warmer climates, and the range of the model towards lower outdoor temperatures is thus limited. de Dear and Brager (1998) often shows plots with a minimum outdoor temperature of 5°C. Other sources, such as ASHRAE 55, suggest that the minimum outdoor temperature for which the model has proven to be accurate is 10°C while others again suggest 15°C as the minimum[6] (Dansk Standard/CEN, 2007).

[6] The minimum outdoor temperature that affects the minimum indoor temperature.

Another limitation of the part of the model concerned with naturally ventilated buildings, is the requirement for the occupant to have some degree of personal control over their environment - e.g. the possibility to open windows.

Finally the model as a key to understanding the mechanisms of comfort for the occupants is challenged by the fact, that only half of the variance with regard to the PMV Model can be explained in strict terms:

> *"It therefore appears as if behavioral adjustments to body heat balance (clo and air speed adjustments) account for only about half of the climatic dependence of comfort temperatures within naturally ventilated buildings."*
>
> - de Dear and Brager (1998)

This is however not only a limiting conclusion, but also one that opens for further discussion in terms of what affects the thermal comfort of man. An important questions is whether the psychological effect will occur without the possibility of behavioural/technological adaptation - as discussed by Schweiker et al. (2012). This theme is dealt with in the following chapters.

3.3 UTCI - an Outdoor Comfort Model

The UTCI or Universal Thermal Comfort Index was developed as an attempt to create a standard method for evaluating comfort of outdoor occupant, based on meteorological data, by a single measure. Another important goal for the UTCI was to combine characteristics of the many previous measures as well as possible. In other words to create a sort of "Grand Unified Model" for outdoor comfort.

The UTCI model was developed by Błazejczyk, Jendritzky, Bröde et al, and was based on a number of underlying studies, such as *the multi-node model of human heat transfer and temperature regulation* (Fiala et al., 2012) or the *UTCI clothing model* (Havenith et al., 2012). What the UTCI gives is a single temperature - in "°C UTCI" - which account for the temperature you would feel in a given reference environment. It's important to note that UTCI is based on physical responses to certain climatic situations, rather than votes on perceived comfort as the Adaptive- and PMV models are.

Calculation of the UTCI

As mentioned above the UTCI is based on several sub-models, of which some, such as the UTCI-Fiala multi-node model (Fiala et al., 2012), are very complex. The calculation procedure mostly used to determine the UTCI in practice is therefore not an analytical one. Instead the offset of UTCI to the ambient temperature is expressed by polynomial regression function, derived from a large data set of analytically determined input-output responses (Bröde et al., 2012).

The regression function is used in this report, although it limits the options in terms of clothing an activity level parameters. The reason for choosing this approach is that it best reflect the situation of a 'normal, private building designer', that would probably not have access to the analytical model.

Naturally the use of a regression function will result in some deviations compared to the analytical model. These errors are however reasonably small for wind speeds below 20 m/s (Bröde et al., 2012). Using the analytical model instead of the numerical approximation would result in computation times that are at least 5 orders of magnitude longer (Bröde et al., 2012).

The following inputs are used to determine the UTCI temperature:

- Ambient air temperature
- Mean radiant temperature
- Air velocity (wind speed)
- Humidity

Note that all of these inputs are meteorological factors. The reasons for not including clothing and activity, apart for those of simplicity listed above, has to do with the developers wishes of creating a simple model, that would give an idea of outdoor occupants comfort on a large scale (as a whole city).

For these reasons the activity level in the model is fixed at 2.3 MET (walking 4 kph) (Błazejczyk et al., 2013) and the clothing level is automatically determined by the *UTCI clothing model* (Havenith et al., 2012). This model was created based on field studies of how people dress outside in multiple countries. The predicted clothing function compared to measured results is shown in figure 3.2.

Reference condition

The reference condition or environment that the UTCI temperature refers to is characterized by the following parameters:

- $v_{air} = 0.5$ m/s (at 10m height over the ground)
- $t_{mr} = t_a$
- $RH = 50\%$ ($p_a = 20$ hPa, for $t > 29$°C)

As an example a set of meteorological data - $t_a = 18, t_{mr} = 26, v_a = 4$ m/s (at 10 m) and $RH = 40\%$, yields a temperature of 20°C (UTCI), meaning that it thermal impact is equal to that temperature in the reference condition.

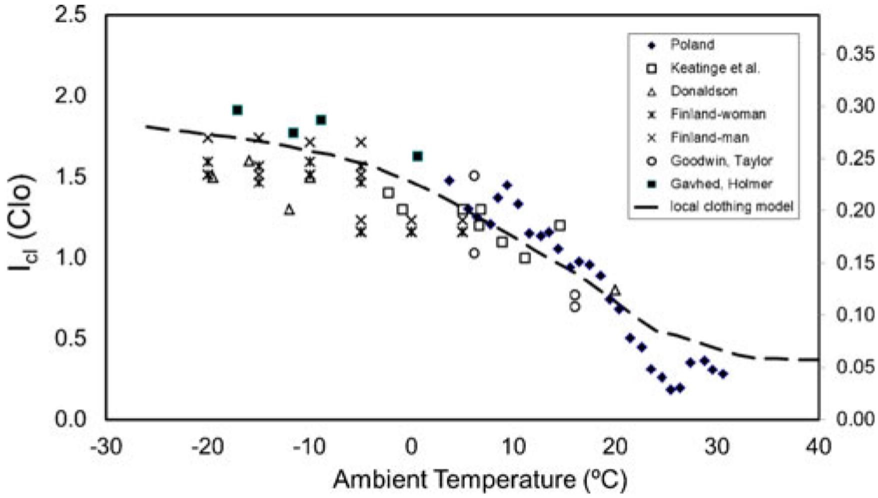

Figure 3.2: "Global thermal insulation values resulting from local quantities as a function of the ambient temperature", from Havenith et al. (2012).

Evaluation of comfort by the UTCI

After having determined the UTCI temperature it is possible to evaluate whether it reflects comfortable environment from a table (Błazejczyk et al., 2013), that takes the fixed activity level and the clothing level function into account. A simple version of the table is shown in table 3.1.

Table 3.1: Thermal stress for different UTCI ranges. Simplified from table in (Błazejczyk et al., 2013).

UTCI range (°C)	**Stress Category**
above +46	extreme heat stress
+38 to +46	very strong heat stress
+32 to +38	strong heat stress
+26 to +32	moderate heat stress
+9 to +26	**no thermal stress**
0 to + 9	slight cold stress
-13 to 0	moderate cold stress
-27 to -13	strong cold stress
-40 to -27	very strong cold stress
below - 40	extreme cold stress

Model constraints

The formal limitations of inputs to the UTCI model has to do with the data set that the previously mentioned regression is based on, and are seen below (Bröde et al., 2012):

- $-50°C \leq t_a \leq +50°C$
- $-30°C \leq t_{mr} - t_a \leq 70°C$
- 0.5 m/s $\leq v_a \leq$ 30.3 m/s,
- 5% $\leq RH \leq$ 100% (with $p_a <$ 50 hPa).

These limitations suggest that the model is applicable in every realistic outdoor situation worldwide, and even though other sources show that especially high wind speed (>20 m/s) can lead to large amounts model 'misbehaviour' (Novak, 2013), this doesn't really affect the concept of global applicability. In other words it would seem unlikely to consider whether an environment is comfortable if the wind speed is higher than 20 m/s.

Another small 'aber dabei' has to do with the minimum wind speed. As stated above it's suggested to be 0.5 m/s, by the model creators (Bröde et al., 2012), but most tools, including the official online tool[7], accepts, and accounts for, anything down to no wind at all ($v_a = 0$).

Apart from those limitations, the model does as mentioned earlier assume a fixed activity level and non-customizable clothing level.

3.4 Partial Conclusion

Different sources list different limitations of the PMV Model. Fanger (1970) suggest that the model is almost universal in terms of input, whereas e.g. the DS/EN ISO 7730 narrows the input possibilities down. This makes it hard to assess whether the model is suitable for evaluating 3rd space comfort.

The Adaptive Model is interesting because of its focus on the relations between comfort and outdoor climate. The range of outdoor temperatures for which the model has been proven is does however not overlap much, with the weather in the Nordic countries, why the model would need to be expanded, to be applicable in the case of the EKO Canopy. How the relations described in the Adaptive Model can be emphasised even further and how the model might be expanded to cover a wider range of inputs will be discussed later.

Regarding the UTCI, it is (of the three) the model with the widest span of application, which makes sense since it's an outdoor model. The challenge with this model in terms of an 3rd space environment that opts for a variety of activities, is the lack of control/customization that's possible regarding clothing and activity level.

[7] At the UTCI homepage: http://www.utci.org/utcineu/utcineu.php

Chapter 4

Comparison of the different thermal comfort models

Although many of the differences of the three thermal models, the PMV Model, the Adaptive Model and the UTCI, were implicitly discussed in chapter 5, it would be interesting to compare them on a more practical level. This chapter deals with the possible differences in input versus output for the three models.

This is done by choosing the PMV Model as a reference to which the two others can be compared. The main reason for choosing the PMV Model as reference, is that it is arguably the most flexible of the three in terms of containing the highest amount of possible inputs and is thus the most customizable. Where the Adaptive Model and the UTCI have several parameters, such as activity and clothing level, hidden away from the users influence, all relevant parameters are available to tampering in the PMV Model.

4.1 Adaptive Model vs PMV Model

Comparing the Adaptive Model to other models is both quite hard, which has to do with its empirical origin, and has already been done as part of that very origin. As mentioned earlier, de Dear and Brager discusses the difference between the PMV and Adaptive models in the article describing the latter. The Adaptive Model is described as a complementation of the existing static model (in this case the PMV model)(de Dear and Brager, 1998).

> *An adaptive model of comfort complements this conventional approach by accounting for additional contextual factors and thermal experiences that modify building occupants' expectations and thermal preferences.*
>
> de Dear and Brager (1998)

By adding an extra input the Adaptive Model creates a model for thermal comfort based on outdoor temperature. The Adaptive Model and the PMV Model primarily differ because of the deviation due to 'the other 50%' consisting of contextual and psychological adaptation in the Adaptive Model. They are however also very different in terms of how they are used. While the PMV model demand inputs of clothing factor, activity level and, less relevant perhaps, humidity, all of these parameters lie implicit in the prerequisites of the Adaptive Model.

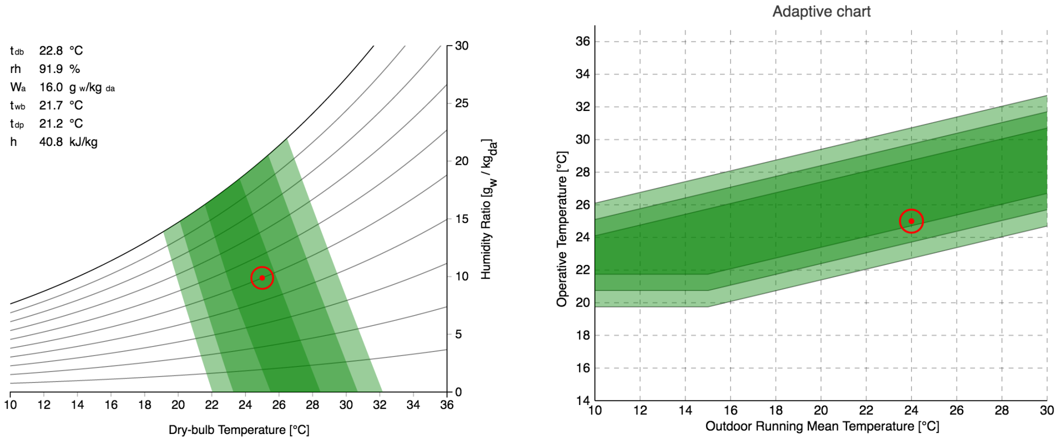

Figure 4.1: Plot of the temperature ranges for thermal comfort in the PMV Model (left) and the Adaptive Model (right), as presented by the Berkeley Comfort Tool (Hoyt et al., 2013).

If the PMV Model takes the adaptation of clothing and activity level as a function of outdoor temperature into account, it's easier to see the actual difference between the two (as shown ealier in figure 3.1).

It's interesting to note that when the weather based adaptation of clothing and activity level is included, the data supports the PMV Model, in the case of the buildings with central HVAC.

But are there other changes in inputs than the outdoor temperature, that would produce different results when input in the two models? Since the adaptive model is only related to the operative temperature, it would seem unnecessary to compare the models for different inputs of both mean radiant- and air temperature. Hence a comparison of the models for different inputs of air velocity has been conducted.

Comparison of Reactions to Different Air Speeds

Figure 4.2 shows the difference in neutral temperature based on similar inputs[1] in the two models.

Figure 4.2[2] shows neutral temperatures that are slightly different in overall magnitude.

[1]Some parameters are hard to make comparable. In the adaptive model, the clothing and activity level are functions of the outdoor temperature. So for this comparison an activity level of 1.2 met (standard office work) and a clothing factor of 1 clo is used in the Adaptive and PMV calculations.

[2]Created using the CBE/Berkeley comfort tool (Hoyt et al., 2013). Unlike for the PMV Model, the tool is unable to output a neutral temperature directly for the Adaptive Model, why the average of min. and max. temperatures is used. The neutral temperature of the PMV Model corresponds to the same average.

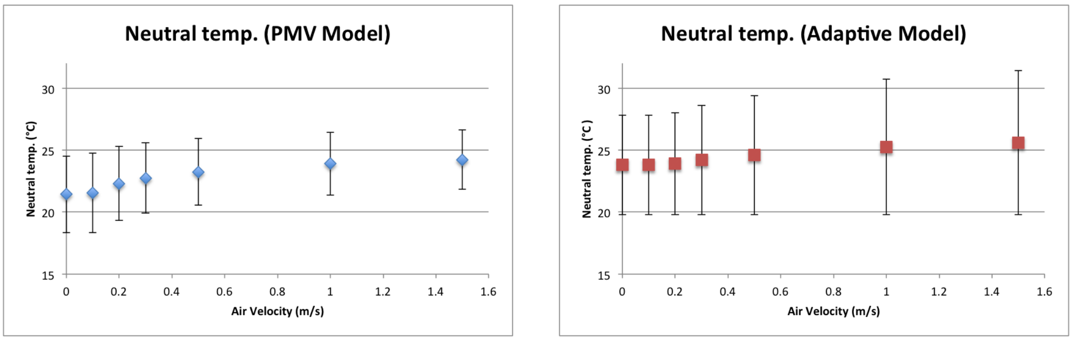

Figure 4.2: Neutral temperature as function of air velocity in the PMV and Adaptive models respectively. Plotted for comparison, using $t_{ext} = 15°C$ (relevant for the Adaptive Model), clothing factor = 1 clo and activity level 1.2 met (both relevant to the PMV Model). The error bars indicate the min. and max. temperatures for compliance to category III (PPD = 15%) according to each model.

This difference is however not as important as the changes in neutral temperature pr. unit of air velocity. The plots show that the PMV model seems to react more to changes in air velocity in the lower end of the spectrum (0 - 0.3 m/s) than the Adaptive Model. The reason for this is that the Adaptive Model allows raising the upper air temperature limit for 'elevated air speeds'[3] (ASHRAE, 2013) - meaning air speeds above 0.3 m/s. This is the only influence of air velocity upon the acceptable temperature spectrum of the Adaptive Model - which as earlier mentioned also affects the neutral temperature in this comparison.

It's also interesting to note how the PMV Model moves towards a more narrow range of acceptable temperatures as the air velocity increases whereas the Adaptive Model reacts in an opposite way. This highlight a basic difference. In the Adaptive Model increased air speed would allow for warmer conditions, since the increased amount air would cool you off because of the increased heat transfer coefficient. The PMV Model on the contrary suggest that the band for thermal comfort is more narrow since temperature changes have a larger effect at higher airflows, because of a reduces boundary layer and increased convective heat flux.

One issue this comparison does not consider since it is not part of the Adaptive model, is that the effect of wind would be likely to change based on the ambient temperature. This effect does occur in the PMV Model.

4.2 UTCI vs PMV

Comparing UTCI and the PMV Model is not completely straight forward since they have very different prerequisites and output a temperature and a comfort value respectively. It's important to note that while the main focus of the PMV Model is *perceived* comfort, UTCI focuses on physical responses to certain climatic conditions.

[3] Given that the user has individual control over the air flow.

Both their outputs (temperature and PMV) are however linear values that express the relation of certain weather parameters to different classes of thermal comfort/stress. So while the values themselves are incomparable the way the values change given different input variations should give some information to how the models react to changes in each of the meteorological inputs.

To make the models comparable a number of things need considering:

1. The UTCI uses an activity level of 2.3 met as standard. This has been input to the PMV calculation as well.

2. The UTCI uses a function for clothing(Havenith et al., 2012) as mentioned in chapter 3. To align the clothing factor of the two models, the following expression[4]has been use to find the input for the PMV calculation:

$$I_{cl} = 1.372 - 0.01866 \cdot t_a - 0.0004849 \cdot t_a^2 - 0.000009333 \cdot t_a^3 \tag{4.1}$$

where t_a is the ambient air temperature.

3. The UTCI uses wind speeds at 10 meters height over ground, whereas the PMV Model used air speeds at 1.1 meters. To estimate the wind speed at 10 meters the following expression[5] is used:

$$v_a = v_{a_x m} \cdot \frac{\log(10/0.01)}{\log(x/0.01)} \tag{4.2}$$

where v_a is the wind speed at 10 meters, $v_{a_x m}$ is the wind speed at x meters over ground.

The PMV calculations have again been again been done via the CBE/Berkeley comfort tool (Hoyt et al., 2013) and the UTCI calculations via the calculator at UTCI.org[6].

Reactions to Changes in Temperature Inputs

Figure 4.3 shows the PMV and UTCI outputs for variation of air temperatures. Both models display an approx. linear response to the variation.

Figure 4.4 shows the output from the two models for various mean radiant temperatures. Again both models display an approx. linear response. By comparison with figure 4.3 it's seen that the degree of response to radiant temperature seems lower than to air temperature. In the case of the PMV Model this makes sense since an air speed of 0.5 should shift the emphasis towards air temperature, because of the increased convective heat flow.

[4]Eq. (3) in Havenith et al. (2012)

[5]Eq. (3) in (Bröde et al., 2012)

[6]More precisely: http://www.utci.org/utcineu/utcineu.php. Based on the F77 UTCI source code (Wojtach, n.d.)

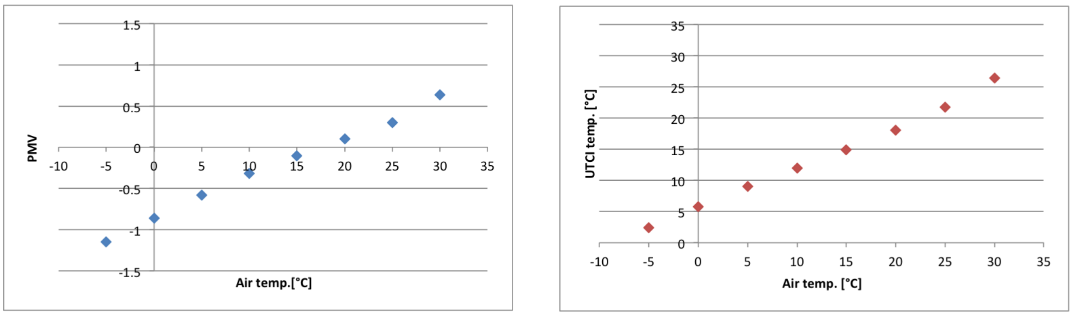

Figure 4.3: PMV (left) and UTCI temp. (right) values as function of air temperature. All other parameters are set to be constant at: MRT = 15°C, wind speed = 0.5 m/s), RH = 50 %. Note that as explained above the clothing factor changes as function of air temperature.

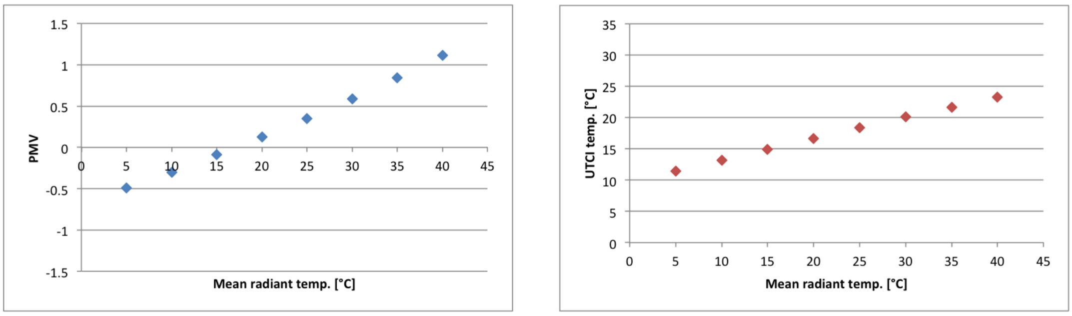

Figure 4.4: PMV and UTCI temp. values as function of mean radiant temperature. All other parameters are set to be constant at: Air temp. = 15°C, wind speed = 0.5 m/s), RH = 50 %. There is no change in clothing factor inputs.

Reactions to Changes in Wind Speeds

To consider the effects of changes in wind speed the issue is examined at different temperatures, since this might have a significant effect on the wind speeds influence. The UTCI model does of course allow for much higher wind speeds than the ones tested here. The tested values reflect the allowed air speeds in the PMV Model.

Figures 4.5 and 4.6 shows the effect of wind upon the outputs of the PMV model and UTCI respectively. Interestingly the models display quite different behaviour in two ways: 1. In the PMV Model the wind has decreasing influence with higher wind speeds, whereas the wind has higher influence on the UTCI temperature with higher wind speeds. 2. The PMV Model seems to show similar reactions to wind speeds at both high and low temperatures and a less steep relation for the moderate temperature, whereas the UTCI shows an decreasing effect of wind with higher temperatures.

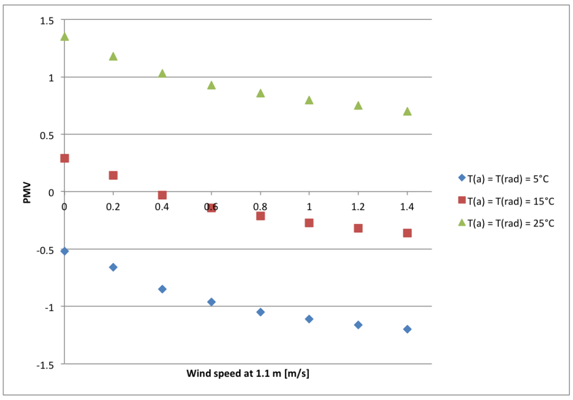

Figure 4.5: PMV values as function of wind speed for three different ambient temperatures. The humidity is constant at 50 %. Note that clothing factor inputs change as function of the air temperature.

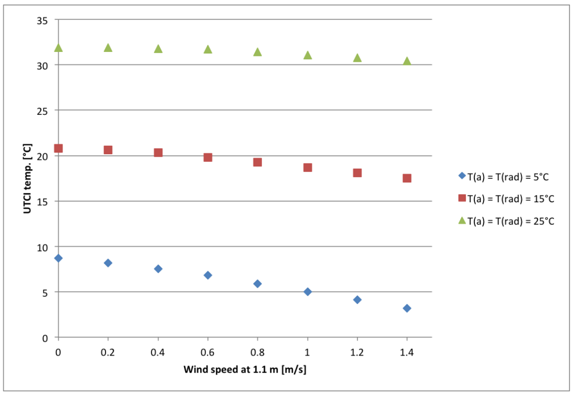

Figure 4.6: UTCI values as function of wind speed for three different ambient temperatures. The humidity is constant at 50 %. Note that the clothing factor changes as function of the air temperature, and that the wind speed of 0 is not strictly includes in the UTCI model cf. chapter 3.

Reactions to Changes in Relative Humidity

As seen in figure 4.7 the output reactions to variations in relative humidity for the two models are quite similar, and very small. The effect is larger at very high temperatures, but still not very significant.

4.3 Partial Conclusion

Comparison of the Adaptive Model to the PMV model in terms of reactions to various air speeds showed that the models differ in two ways: 1. At lower air speeds where PMV reacts more dramatically to changes than the Adaptive model, that only reacts to inputs above 0.3 m/s. 2. The bandwidth of acceptable temperatures changes in opposite ways for

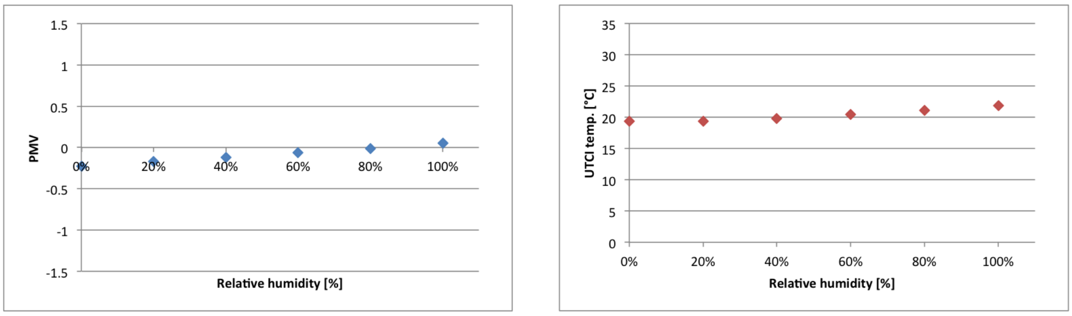

Figure 4.7: PMV and UTCI temp. values as function of relative humidity. All other parameters are set to be constant at: Air temp. = 15°C, MRT = 15°C, wind speed = 0.5 m/s).

the two models. In the Adaptive Model the bandwidth widens with higher temperature, in the PMV Model it narrows.

The UTCI and PMV Model display similar reactions to variation of every input except wind speeds. The effect of wind increases with higher wind speeds in the UTCI, whereas it decreases in the PMV Model.

Chapter 5

Influence of Architectural/Tectonic Parameters Upon Expectations

The previous chapter dealt with issues related to the thermal comfort of occupants in a 3rd space climate - among these the influence of the outdoor temperature on thermal comfort. But what about other (less measurable) contextual factors? As stated by Błazejczyk et al. (2013), changes in clothes and activity level only account for roughly half of the variance compared to the PMV Model, found during the work on the Adaptive Model. So what makes up the other 50 % variance?

This chapter briefly discusses the possible influence of architectural aspects upon occupants expectations, based on the book *Forsegling og symbiose* or *Sealing and Symbiosis* (Bjerregaard Jensen, 2005).

5.1 The Relation Between Building and Nature in Modernism

An interesting place to start, when looking at how architecture moved into the real of modernism, is with 18th century English green houses. It is an interesting example since the green house in it's pure form is a passive 3rd space of sorts. The emerge of a heated conditioned climate within a thin, transparent shell marks a milestones in man's ability to control and manipulate nature (Bjerregaard Jensen, 2005).

This is also an early example of the modernistic approach to separating indoors and outdoors, by an almost invisible border. But the border is there - just in the form of energy rather than material. The idea of this almost invisible (but energy-wise expensive) border has affected a large number of modern buildings ever since.

Using this invisible border the glass house acts as a bubble (Bjerregaard Jensen, 2005). But how transparent is this bubble actually? According to Bjerregaard Jensen (2005) modernism has introduced a strict subject/object relationship between the occupant in the building and the nature outside it. In this perception the building is comparable to a picture frame, framing nature without really taking part in it. In the case of the green houses, functions such as rain water drains became hidden along the way. The entrance to the structures transformed from simple doors to climatic air locks that prevented that the artificial (and often exotic) indoor climate was disturbed by nature. In that way the only thing really exchanged with nature was daylight (Bjerregaard Jensen, 2005). So although the structure of an orangery is almost invisible, the world outside is arguably reduced to a back carpet of the fantasy landscape and climate inside.

This is to some extent a similar situation to that of the mechanically conditioned and meretriciously controlled glass structure office building of the 20th and 21st century. In such environments compliance with Fanger (1970) would be expected in terms of comfort evaluation. Universal expectations with little dependency on the outside temperature.

5.2 Alternatives to Modernism

Unlike the world before the oil crisis, the Brundtland Report and general focus on the environmental impact of man, the idea of replacing material borders with energy, has a less than desirable ring to it. There is a demand to utilize natural resources (such as passive heating and cooling means) rather than ignoring nature.

It is therefore meaningful to look at alternatives to strict modernism. The Climate Dynamic Modernism and the Natural Romanticism act as such (Bjerregaard Jensen, 2005) although their approaches are quite different.

Climate Dynamic Modernism

The Climate Dynamic Modernism works with many of the same tectonic elements as modernism, but utilizes advanced building systems that react to nature or strategies based on local climatic conditions (Bjerregaard Jensen, 2005).

Simple examples of building systems that depend on input from the outdoor climate are fx. automatic shading systems or window openers - with a resent term Adaptive Building Skin. Some buildings run indoor temperature set point based on the outdoor temperature, which corresponds very well with the findings related to the Adaptive Model (de Dear and Brager, 1998).

Design strategies linked to a given climate zone could be building designed to use certain often occurring wind directions for an effective natural ventilation. Other design strategies are more generic but still help to create a dynamic transition from outdoor to indoor climate. Such strategies could be zoning or especially the use of buffer zones.

Natural Romanticism

The foundation of natural romanticism is to focus on symbiosis with nature rather than a division from it. This symbiosis is to a large degree based on the connection with the local place and climate of the building site (Bjerregaard Jensen, 2005).

In the view of natural romanticism certain elements can/should be used to connect the occupant with nature. Many elements are connected with the vernacular architecture of the area. More generic elements include the use of untreated materials, visible tectonics (e.g. structural elements) and the use of similar materials and/or patterns both inside and outside to bridge across the building envelope. Such a pattern could for instance consists of similar rhythms in the placement of columns on either side of a window section.

The reason an untreated material links the occupant to nature has to do with the idea of associative design strategies. When the occupant sees the untreated timber structure, the occupant makes an association or imaginative mental process that connects him with the natural environment from where the timber came from originally (Bjerregaard Jensen, 2005). In other words the use of untreated materials would make the occupant perceive a sort of symbiosis with nature.

An interesting thought is whether untreated materials also allow the occupant to connect with the materials natural thermal properties. Looking at an untreated brick wall you would expect it to have a large thermal effect and to feel cold against your hand even if you held it there for a while. If the same brick wall was plastered smooth, you wouldn't, by looking at it, know whether to expect the thermal properties of bricks or a light gypsum wall.

Irregularity is also an important element connecting man with nature, since irregularity is an inherent part of nature (Bjerregaard Jensen, 2005). Finally in contrast to the example above in the modernistic orangery, building systems such as rain water drainage should be visible or even highlighted to make the occupant aware of the changing weather outside.

It can be discussed how much influence natural romanticism has in architecture today, but many of the main ideas is also expressed in ecological architecture that has become apparent since the late 1960's (which coincide with the start of the climate debate mentioned above). Ecological architecture can for instance be seen in a number of projects by the Danish architecture company Vandkunsten.

5.3 Partial Conclusion

Trying to answer the question of what might influence occupant expectations in a 3rd space, a few points can be deduced from the different architectural approaches briefly discussed above. But maybe the first question that needs answering is: *How* would architectural/tectonic elements affect climatic comfort in 3rd spaces?.

Based on the underlying knowledge from the Adaptive Model, of how the use and control of natural ventilation affect occupants thermal neutrality, connecting their preference with the outside temperature, it would make sense to suggest that architectural elements connecting occupants even stronger with nature, would result in an increased dependence on the outside conditions. Regarding thermal comfort this would suggest a steeper slope of the plot of neutral temperature vs. outdoor temperature. All in all this would, if the assumption is correct, result in a greater acceptability of variance in temperature in the built space, over the spectrum of outdoor temperatures.

Back to the main question of which elements that might affect the user expectations and thereby comfort. Based on this chapter it would make sense to include the following elements when considering the criteria to evaluate comfort in 3rd spaces from:

- The occurrence or absence of climatic locks. The absence of those might strengthen the connection to the local climate and the feel of the users autonomy over their climate (if replaced by openable doors directly to the outside. Perhaps especially by introducing a relationship between transparency in terms of both view and movement - "if I can see trough it, I can move trough it".
- Related to this a transparency in terms of materials - using the same materials outside and inside, causing a smooth transition and connection trough the envelope. This would also apply to repetitive patterns or elements 'going through' the envelope, such as placement of trees on either side
- Visible tectonic elements related to the division from the outdoor climate, such as rainwater handling systems.
- Irregular items (could be trees or other plants).
- (As an extra thought) Use of materials typically used in outdoor spaces - terrace-like wooden floor structures, etc.

Another interesting thought is whether the use of naturally occurring phenomena for conditioning of spaces might also strengthen the connection with the outside climate? This could for instance be the use of trees or other plants for solar shading in the summer. Would you be more tolerant towards the changing shadow patterns of a swaying tree or wine, than from a automated louvre systems trying to adapt on a day with mixed weather? Or would the moving shadows of the tree even improve the perceived comfort, like the 'noise' from moving water does in certain environments (Yang and Kang, 2005).

Chapter 6

Discussion - Application of the Thermal Models to Alternate Spaces

As mentioned earlier, there are no standardized methods or models for evaluating thermal comfort in spaces such as the EKO Canopy. There are however existing models of thermal comfort, from which principles, knowledge and calculation methods can be deducted. However each of these existing models have formal or informal limitations, as discussed in chapter 3, that makes it doubtful whether they would produce reliable information in the case of the diverse cluster of 'neither indoor, nor outdoors' spaces.

This chapter discusses how suitable these models are in the case of alternate spaces (such as the EKO Canopy), or how they might be combined and/or extended to fit these cases.

The suggestions the chapter produces are can not be validated without extensive emperical studies of actual spaces, but serves more as debate input.

6.1 Applicability of the Different Models in 3rd Spaces

The problem of the UTCI is, as mentioned in chapter 3, that it basically aims to produce a universal unit of outdoor thermal comfort, based only on meteorological data. Consequently it describes one certain case of outdoor activity - walking at 4 km/h. It is very valid for this case (Bröde et al., 2012; Pantavou et al., 2013).

This situation described by the UTCI is relevant for most 3rd spaces, so the model is definitely of use in the evaluation of these types of spaces, albeit to a limited extent. Apart from that certain elements of the model are very interesting - e.g. the clothing model that is discussed later in this chapter.

The Adaptive Model have a similar issue - no control over the key parameters activity and clothing, that are in this case tied to the outdoor temperature.

A second challenge in terms of using this model in a broad spectrum of 3rd spaces, is it's limitations regarding the mean outdoor temperature. As mentioned in chapter 3, the outdoor temperature ranges from 5°C to 33°C[1] (as an influential parameter) in the

[1] According to de Dear and Brager (1998). Other sources limit the range even further.

Adaptive Model. This might be a problem in certain climates - such as the Swedish, where mean outdoor temperatures are below 5°C significant parts of the year.

The final problem using the Adaptive Model as a platform for a framework for evaluating 3rd space climate, has to do with the models empirical origin. This aspect of the model makes it hard to identify the effect of different parameters, and thus hard to make changes in the relationship between them. It is in short difficult to treat an empirical model analytically.

As in the case of UTCI there are however interesting points and principles in the Adaptive Model, that could inform the discussion of a thermal comfort model to fit 3rd spaces - chief among these the point of a measurable impact of psychological/contextual effects correlated with outdoor temperature, which is discussed later in this chapter.

That leaves the final contender - the PMV Model. Where the other models are limited in terms of controllable parameters, the PMV Model allows customization of pretty much everything. Furthermore all internal parameter influences has been tested meretriciously and often. So the model is very valid in terms of physiological reality. Although it's arguable it is also quite universal in terms of inputs[2]. These three factors makes the model ideal as a platform to create a customized evaluation framework from.

There are however some elements of doubts in this respect. A large concern is to which extent the model is valid for alternate spaces, or if it's only applicable to strict indoor spaces.

> In the introductory chapter to *Thermal Comfort Analysis and Applications in Environmental Engineering*, Fanger was quite clear that his book, and by implication, the PMV model at its core, were intended for application by the HVAC industry in the creation of artificial climates in controlled spaces (Fanger 1970). The extrapolation of the model's scope to all spaces intended for human occupancy, including those with natural ventilation, was a much later development that the results in this paper fail to justify.
>
> - de Dear and Brager (1998)

But even if that is true for the plain version of the PMV Model, what would it take to make it (more) applicable to 3rd spaces? Would it be possible to combine it with elements of for example UTCI and the Adaptive Model? The rest of the chapter discussed which parameters that might affect the thermal comfort in 3rd spaces.

6.2 Effect of Different Degrees of User Freedom

An important parameter, or cluster of parameters, to discuss is the degree of user freedom in the space. It makes sense to discuss this first of all parameters, since it sets the scene defining the usage context of the space, in terms of what's relevant for the evaluation of the climate.

[2]From the perspective of the original work (Fanger, 1970), rather than later standards based on it - e.g. (Dansk Standard/CEN, 2007).

The whole thought of user freedom as an important parameter in evaluation of thermal comfort might seem quite different compared to the mindset in more typical building projects - offices, housing, etc. The reason for this that the users in such contexts often, for good reasons, has a limited degree of freedom on many parameters.

When designing and evaluating a less predefined space, such as the EKO Canopy, the flexibility in terms of use rises dramatically, making user freedom a key parameter.

Activity Level

The activity level of occupants is a key parameter in thermal balance and comfort. In typical buildings, such as offices or housing, the freedom in terms of activity is usually limited to the lower end of the scale, and besides often kept at a quite constant level.

This is not necessarily the case in a 3rd space - public or private. Anything from relaxing in the sun or strolling quietly around to climbing or doing heavy garden work is a possibility here. This has a dramatic effect on the range of what is considered thermally comfortable in such a space as whole. While the man in shorts lying on a lounger prefer a warm micro climate with lots of solar radiation, very different preferences may apply to the running couple or the teenager writing an essay on her computer.

The large span in activity level should however not be seen as a carte blanche to create a climate that 'always accommodate some activity'. There are limitations when you view the issue from a user perspective. If your plan going to a certain place was to sit down and read a book, what good is it to you, that the conditions there are excellent for playing basketball. In other cases adjusting your metabolic rate to counter thermal imbalance, might be an option.

This illustrates the need for the people designing the space and the ones predicting the comfort there to identify the links between space and activity. The importance of good conditions for cross disciplinary collaboration and the connection to the choice of tools is shortly discussed in chapter 7. It also highlights the need of usage examples as inputs to the evaluation.

When evaluating spaces with multiple possible activities, focus should be on determining the percentage of time that is comfortable for certain activities in the relevant spaces.

Clothing

In typical buildings such as office buildings a combination of social conventions and practicality limits the minimum and maximum clothing factors respectively, resulting in a quite narrow range of acceptable clothing. The social conventions may apply to some part of the full range of 3rd spaces - the fully public ones. I the case of semi-private spaces however, the range of possible/acceptable clothing spans significantly wider than the office dress code. Depending on personal preference, anything from a bikini to a full on winter outfit could work there.

But much like with the activity level, there are of course constraints to the users clothing behaviour. Seasons would for example seem as a very important parameter in terms of dressing preferences. Simple practical issues like how long time you would be willing to spend dressing might have an influence as well. In many cases the clothing level might also be connected to certain activities. Finally in certain areas social conventions could play a huge part for clothing in public and semi public areas. Religious preferences/traditions could for instance limit the range of clothing for some individuals.

A plausible way to define a range of clothing factors in 3rd spaces, would be to use the data from the studies leading to the UTCI clothing model (Havenith et al., 2012). It defines a model for clothing level as a function of ambient temperature. These studies also reveals peoples tendency to underdress compared to the amount of clothing needed for thermal balance in cold conditions. One could speculate whether there might be local differences in this tendency - Sweden is for instance known as a country, where people tend to dress according to the weather. This is however contradicted by the UTCI clothing studies, showing that both male and female Finnish nationals follow the underdressing tendency (Havenith et al., 2012).

Freedom of Movement

Again using office or housing building as an opposite, the location of an individual in a 3rd space is not linked to a certain position and micro climate. Where occupants in offices are usually bound by their work station and occupants in both offices and housing by the fact that the climatic conditions are roughly identical all over the place, 3rd space occupants might have both freedom of movement and several micro climates to move to. If the current spot is a bit chilly, there is often a possibility to move yourself and your activity to another part of the space.

Creating the prerequisites for this by offering different micro climates is the responsibility of the designers. Climatic zoning would be a design ??? for this approach.

The flexibility in location is closely connected with, and thus limited by, the links between space and activity mentioned earlier. Certain spots might also have constraints in terms of how many people they can accommodate. Another possible limitation in cases of 3rd spaces connected with housing such as the EKO Canopy, has to to with how far an individual would be willing to move away from their front door before the lacking feeling of security, indolence or the feeling of their habits being broken would compromise their comfort. This is however a quite complex problem, that will not be fully addressed in this thesis.

Ability to Change the Zone's Climate

A fourth element related to user freedom is the possibility to manipulate the climate of the zone. The importance of this can for instance be seen in the Adaptive Model, where personal control over natural ventilation is a prerequisite for the model (de Dear and Brager, 1998).

Individual control over the climate is obviously not easy if even possible to facilitate in 3rd spaces as a whole, because of the shared nature of such spaces.

As an example, individual control over the openings of the EKO Caonpy isn't possible - at least not for all occupants. But are there other possibilities? A parasol would definitely change the micro climate for one or more occupants if opened in the EKO Canopy, as would a moveable windbreak. But even though such features evidently changes the physical conditions for the occupant, it is hard to say whether they would create the same effect of tolerance towards climatic changes as the control of an openable window. In other words it's hard to say whether the 50 % of context and psychological adaptation (de Dear and Brager, 1998) would apply in this case.

The effects of the physical aspects of increased possibilities of controlling the local climate, would probably be possible to include in a climate simulation set-up, like the the ability to control window openings and shading is in most current set-ups.

6.3 Effect of Outdoor Climate

Looking at the whole range of 3rd spaces, from very open ones - actual canopies - to spaces that are more enclosed such as the EKO Canopy, it's hard to imagine a general conclusion on the effect of the outdoor climate on the comfort of the occupants.

In spaces that are closer to being outdoor than indoor spaces, the effect of outdoor climate is undeniable. People would make adjustments to their clothing at the very least, probably to their choice of activity and maybe to their expectations. But even in the very down to earth parameter of clothing level, it's not necessarily an obvious correlation. As shown in the studies of the UTCI clothing model (Havenith et al., 2012), people tend to underdress compared to the clothing level necessary to achieve thermal neutrality in an outdoor climate.

Some of the reviewed sources have suggested a relationship between the outdoor climate[3] and thermal preference of indoor occupants. This might very well be a relevant issue to spaces that lie in the end of the 3rd space spectrum closer to indoor conditions.

But how would the effect of the outdoor climate concretely affect the perception of thermal comport in an occupant in a 3rd space canopy for instance? Would it be possible to just extend the trend line of the Adaptive Model to fit a climate with lower temperatures. Would the effect of adaptation based on outdoor climate be more dramatic, given the closer relation of the space to the outdoors?

Figure 6.1 shows a plot of neutral temperatures in 'free running' and 'other' buildings, meaning naturally ventilated and centrally conditioned buildings respectively. An interesting thing springs to mind when looking at the neutral temperature of the 'other' buildings. It follows the same logic of increased neutral temperature with higher outdoor temperature as the one for the 'free running' buildings in the range for which the 'free running' tendency is defined. But when the outdoor temperature reaches a certain point the neutral temperature drops. The same thing happens at low temperature except the neutral temperature increases there.

The reason for this effect might be found i a human preference related to compensating for e.g. cold weather by 'getting cozy and warm indoors'. The interesting question is whether

[3] Included as different measures of outdoor temperature

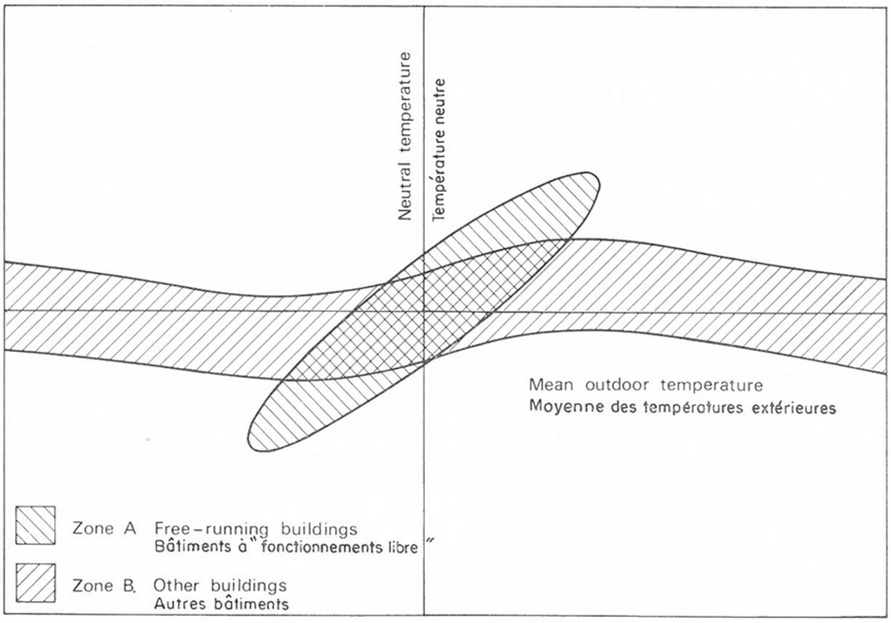

Figure 6.1: "Probable dependence of neutral or "comfortable" temperature upon climate", from Humphreys (1978).

the same effect would occur in naturally ventilated buildings if the considered range of outdoor temperatures were expanded? Or would it in a semi outdoor environment?

Regarding the question of whether adaptation based on outdoor climate in a 3rd spaces would be more dramatic (steep), it would be fair to assume a larger degree of adaptation of clothing and activity level because of a less tight social norm compared to an office space, as mentioned earlier.

But what is the ultimate border of adaptation range? At some point the physical responses to the micro climate would start kicking in. At some lower point, you would for instance have a physical reaction to cold in terms of shivering. Other effects would kick in at hot temperatures. It would be fair to assume that because of this it's unlikely that the contextual and psychological adaptation would keep accounting for 50 % over a broader spectrum of outdoor temperatures.

All of the above deals with adaptation and relaxation of expectations based on outdoor *temperature*, but what other characteristics of outdoor climate might affect the expectations of occupants in a 3rd space? Sky colour? Whether it's raining or not? Wind moving the trees around the canopy? It's hard to guess and no data is currently available to support either idea.

6.4 Perception of the Connection with the Outdoors

In the above discussion of the effect of outdoor climate upon expectations of climate in e.g. a canopy structure, it was stated that an increased effect of adaptability might be expected since the connection the outdoors would be stronger. But is the connection stronger and which parameters affect this connection?

As discussed in chapter 5 the use of glass as the primary material of a building envelope does not guarantee a feeling of symbiosis with nature. A completely glazed structure would naturally provide a good visual connection to the outside, but it might also introduce a *supernatural* feeling, creating a subject/object relationship between the occupant and the outside respectively. It might act as a glass bubble where nature somehow feels even further distanced than in a normal building.

It might therefore be important that the design include elements that will connect the occupants with the exterior. Such elements could be untreated materials, visible tectonics, plants or typical elements from the outdoor environment, such as certain materials, furniture etc.

Based on both Bjerregaard Jensen (2005) and de Dear and Brager (1998) it would also seem important to include openings in the building envelope that are operable by the users. It is as earlier mentioned a criteria for using the Adaptive Model that users have access to control natural ventilation.

6.5 Partial Conclusion

This chapter has discussed how applicable the three reviewed thermal comfort models are to 3rd spaces. The UTCI is although it's hard to customise a proven model for evaluation of outdoor climate. It is therefore usable in the range of 3rd spaces that are more outdoor like. A thing that separates the UTCI from the other two models is that it focusses on physical responses to certain conditions, rather than perceived comfort. This does make it a bad indicator of how people *feel* in a given thermal environment, but the responses would be interesting to consider in a tailored thermal comfort analysis framework for 3rd spaces, as the conditions in such spaces might often lead to physical responses. It might for one be interesting to look at when defining limits of adaptability in such a space.

The Adaptive Model is hard to manipulate given it's empirical/statistical nature and lack of input possibilities. This makes it hard to apply to 3rd spaces since the acceptable temperature ranges it deliver, focuses on indoor spaces. In the case of the EKO Canopy a further problem is that its range of outdoor temperatures does not fit a climate like the Swedish.

It was found that the PMV Model, although its range of validity arguably does not fit the conditions expected in a 3rd space, might be most suitable to build on, because of its customisability. The model might however need adjustment to include elements such as dependency on outdoor temperature.

An interesting aspect of thermal comfort in 3rd spaces is the introduction of a higher degree of user freedom in terms of clothing and activity levels, moveablity and the use of local artefacts (such as parasols or wind screens) to adjust the micro climate. This effect would be interesting to incorporate in analysis of thermal comfort in such spaces.

Most of this chapter is however based on logical deduction or 'qualified guessing' and many of the discussed propositions for a more tailored approach to thermal comfort in 3rd spaces, would require further studies for the validity to be examined.

Chapter 7

Selection of Analysis Tools/Method

Having discussed the comfort framework through which the EKO Canopy case can be examined, the next step is to find a practical way to produce the data needed for such analyses - in other word finding a method and a software suite capable to produce the required information through simulation.

The focus is on finding a method/tool set that works in the early design phase. This focus has to do with both the current standing in the case of the EKO Canopy but is also chosen because of the fact that most 3rd spaces don't fall under the strict regulations and rules that applies to 'standard' buildings. This essentially makes the design process more 'free' and for this reason the method and tools should be suitable for handling projects with fewer constraints.

The value of many 3rd spaces rely on weather they succeed to create a good micro climate for the users (perhaps compared to the outside climate as discussed in chapter 3). This combined with the large degree of design freedom makes the projects very dependent on good design choices. The chosen method and tools should therefore also be able to inform the design process while it's happening.

Even with the best tools, simulation of indoor climate and comfort is never completely aligned with the real world. It is however the opinion of the author that simulating comfort can produce useful inputs to the design project. This approach does of course not exclude inputs from experience, tacit knowledge or supersede measurements and adjustment in the built project.

7.1 Analysis/modelling method

When deciding on a method for this case, it's important to look at the aim of the EKO Canopy project both in short and long term perspective.

On the short term the analysis set-up should be able to produce information that would underline the potential of the project on as many parameters as possible. To produce this it would need to include not only energy concepts and solutions but also the effect of the architectural/programmatic choices, to ensure a result integrated with these choices. To be able to integrate the results in such a way, an integrated approach would be needed in the design team as well. The chosen analysis method therefore shouldn't stand in the way of this collaboration, it should if possible even support it.

In a long term perspective, the EKO Canopy has been described by Elise Grosse from White Architects, as a potential prototype for energy renovation projects at several locations in Sweden. The method should therefore have the potential to smoothly integrate design changes made necessary by local climate, context, etc.

Different Methods for Model Integration

An often used design and analysis approach is based on first doing the design in a geometrical tool such as AutoCAD, Sketchup or Rhino. The geometry is then either exported/imported or remodelled in a Building Performance Simulation (BPS) tool that produces the wanted results in terms of energy use and comfort parameters. This export/import process is a one way, and often quite manual process, that doesn't make direct feedback to the original model possible. The BPS tool would often be one software solution or package, such as IES VE, Ida ICE, etc. These packages include several subtools, such as a geometry tool capable of modelling (and often importing) the geometry used for the performance simulation.

This model integration is what Negendahl (2015) calls a 'Combined Model Method'. There are several disadvantages to such a set-up in terms of multidisciplinary teamwork: 1. The model suites often require skilled technicians (e.g. engineers) to use it. 2. There is as earlier mentioned no direct integration with the geometrical tools used by the designers/architects, making visualization of the results to some degree disconnected from the geometry. 3. Because of the lack of integration with the geometrical design tool, analysing effects of changes in geometry can be very intricately and time consuming. This might result in the designers being unable to wait for results of changes, and instead moving on with the design process, without performance inputs.

Another model integration method is the 'Central Model Method' (Negendahl, 2015). This method allows for independent geometry- and BPS tools to exchange information through standardised formats, making back and forth feedback possible. There is however still some loss of information due to the standardised nature of the shared data scheme. This model is largely assosiated with the BIM (Building Information Modelling) initiatives such as BuildingSmart (Negendahl, 2015).

A third approach is the 'Distributed Model Method' (Negendahl, 2015). This method allows each piece of individual software to communicate directly with the others - giving instant back and forth feedback, without the need of tranfering through a data scheme. Such a set-up often include a 'middleware tool' (Negendahl, 2015) for instance a visual programming language, that facilitates real time translation of properties between the models.

Modelling Method for the EKO Canopy

As earlier mentioned a project as the EKO Canopy is quite sensitive to changes in the early design phase. The modelling/simulation method should therefore be able to facilitate quick performance responses to geometry changes. This encourage the use of a Integrated Dynamic Model.

Such a model might also be more flexible in terms of solving some of the issues that might arise in a 3rd space due to the possibility of incorporating multiple performance tools seamlessly. This aspect is discussed below as part of the choice of BPS software.

Another advantage of the Integrated Dynamic Model is that by integrating all of the design team's tools, it effectively encourages a distribution of control of the design among the team members (Negendahl, 2015). In other words it moves a way from a set-up where the one doing 'the final simulation' seems to have an increased amount of control over design options.

7.2 Tools

Like the overall method framework, the geometry-, middleware- and BPS-tool(s) should be able to work in realation to both the short and long term perspectives of the EKO Canopy project.

In the short term the model should be flexible enough to include certain effects that would not be expected in standard building. Some of these effects are discussed in chapter 8. It should furthermore be able to incorporate evaluation by the thermal comfort models described and discussed in chapters 3 to 6. Thirdly it should be able to achieve the goal of creating distributed and customized comfort results, rather than just single standard values **HUSK I INDLEDNING**. Finally it should like the overall method be able to produce performance results in real time based on design changes, with feedback to the original geometrical model.

In the long term the tools should be able to accomodate changes in climatic input and the changes connected to this in a way that works smoothly with different model operators.

Requirements for the different comfort models

In order to meet the requirements of the different comfort models as explained above, the BPS tool should be able to output the required inputs of the different models show in table 7.1.

Chosen Tools Suite

Based on the criteria above, a set-up based on Rhino and the Grasshopper VPL plug-in (Rutten, 2007) have been selected. The set-up especially utilizes the Ladybug+Honeybee package (Sadeghipour Roudsari and Pak, 2013). The Honeybee plug-in makes it possible to prepare geometry for, and run energy/climate simulations trough EnergyPlus, via Grasshopper. This set-up is an instance of a Integrated Dynamic Model. It will react immediately to changes made in the geometrical model.

Apart from that, it is interesting to the case of 3rd spaces because of its module structure. It means that small modules takes care of different tasks and output data that can then

Table 7.1: Input parameters for the three different comfort models described and discussed in chapters 3 to 6.

Adaptive Model	**Fanger**	**UTCI**
Ambient air temperature		
Mean radiant temperature		
Air velocity		Wind Speed (Air velocity)
	Humidity ratio	
(func. of outdoor temp.)	Clothing Factor	(accounted for in guidelines)
	Activity level	Assumed to be constant (2.3 MET)
Prevailing mean outdoor temperature		

be used as input for another module. This makes it possible for the user to examine the data flow between different parts of the preparation, simulation, evaluation and visualization stages. It also (often) makes it possible to alter certain parts of the data or create customized data inputs. All that takes is an understanding of the data structure, which is often explained in each modules comments. It does for example make it possible to include more detailed custom model for ground temperature (as discussed in chapter 8) or factor certain data in between modules.

Implementing such data manipulation in a more 'traditional' BPS tool (such as IES VE) would require both a lot of time and an intimate knowledge of the coding behind the software, that might not even be open source (which the Grasshopper environment is). Alternatively it would result in very long 'work around' processes requiring multiple export/import sessions.

Apart from data and input manipulation the Honeybee is also favoured by the simulation capabilities of EnergyPlus that is able to cope with some advanced thermal properties, such as distribution of direct solar radiation in interior spaces. The EnergyPlus engine also allows for advanced set-up's of Airflow Networks[1].

The Rhino/Grasshopper/Honeybee set-up furthermore contains the possibility to create distributed plots of the comfort results based on the PMV Model, the Adaptive Model or the UTCI, and will produce all of the needed inputs for these comfort models. This makes it ideal in this case, although not all of the inputs for the thermal comfort models are necessarily produced in a high level of detail, which is discussed in chapter 8.

In does also have available settings and input possibilities

Finally it is an interesting set-up with respect to the idea of the EKO Canopy as prototype that can be projected onto many sites, since it is flexible towards changes in climate, and has very good possibilities to quickly asses important characteristics of the local weather

[1] As it turned out, this aspect has still to be included in the Honeybee plug-in. This is discussed in chapters 8 and 9

trough the many Ladybug components meant for weather analysis.

There are other solutions - even in the Grasshopper environment - the could probably boast of the same possibilities or even more. Such a solution could be the Archsim plug-in for Grasshopper that works much like Honeybee and has the possibility to work with both EnergyPlus and TRNSYS. The reason for choosing the Ladybug+Honeybee suite rather than other similar products is definitely influenced by the authors amount of experience with this tool compared to the other.

7.3 Concrete Model Set-up

The concrete model in this thesis consist of: 1. Rhino geometry in terms of quite simple volumes and surfaces, that are linked (or referenced) into the Grasshopper script. 2. An section in grasshopper focused on turning the linked geometry into honeybee zones, e.g. by adding window geometry and material properties. 3. A lump of modules concerned with prepping the zone(s) with loads and conditioning systems, for example natural ventilation. 4. A simulation section that sets up the parameters for EnergyPlus, runs the simulation and extract the data from it. 5. Finally a section that analyses the data from the simulation turning it to visual result of comfort, surface temperatures, etc. A screen shot of the overall script is shown in figure REF.

Cature af overordnet grasshopper set up

7.4 Partial Conclusion

A analysis set-up in Rhino/Grasshopper using the Ladybug+Honeybee suite in connection with ENergyPlus was chosen. The reasons for choosing this set-up is that it complies with the criteria set for the analysis, which are summed up below:

- Handling of certain effects important to the analysis of 3rd spaces (further discussed in chapter 8.
- Ability to be included in an early design phase and produce instantaneous inputs to the design.
- Posibility to evaluate thermal comfort based on the three frameworks discussed in chapters 3 to 6.
- Flexibility in terms of analysis process and visualisation.

This modelling method is an example of an Integrated Dynamic Model (Negendahl, 2015).

Chapter 8

Special Considerations When Creating Canopy/Atrium Climate Models

In large 3rd spaces such as the EKO Canopy, some effects that are often standardized or neglected when simulating comfort in more standard type indoor environments, may play an important role.

In this chapter the effects of solar gain distribution, air flows and ground temperature in relation to large 3rd spaces are discussed. Furthermore the potentials for dealing with these effects by skillful modelling in the Rhino/Grasshopper/Honeybee/EnergyPlus set-up described in the last chapter are discussed as well.

8.1 Solar Gain Distribution

The first examined effect is solar gain or rather the internal solar distribution simulation. In a typical smaller office space or like it's usually a quite correct approach to divide whatever solar heat that passes through the zone's glazing between surfaces of the zone with certain fixed distribution factors.

This approach would however not be feasible in the case of a large canopy/atrium where the majority of the building envelope is glazed. This has to do with the increased amount of direct sunlight, that both affect the occupants directly and by heat storage in the surface materials.

Another reason why a more detailed approach is needed has to do with this thesis' ambition to create comfort distributions rather than just producing a single comfort measure for large 3rd space zones.

Simulating fairly correct is possible through the EnergyPlus engine, that has the capability to account for the first 'bounce' of thermal radiation. This means that the direct radiation's passage from the outside, through the external (and internal) windows and on to the first surface it hits, is modelled physically correct. After the solar rays have hit a surface, the reflected radiation is diffusely distributed (US Department of Energy, 2010).

But how is the model best set up to handle the detailed solar distribution? To test the effects of different modelling strategies, a simple volume measuring 72 x 24 x 21 meters is used. A large window constitutes most of its eastern façade. The wall, floor and roof material is an inner surface of 20 cm concrete with real properties, connected by 20 cm of rockwool to an idealised outside material that reflect all solar radiation. The reason for the idealized outside material is to neglect the effect of solar gain from the outside, leaving only the interior gains to examine. In the same fashion the entire box was lifted one meter of the ground to leave out the effect of ground temperature, which will be dealt with later.

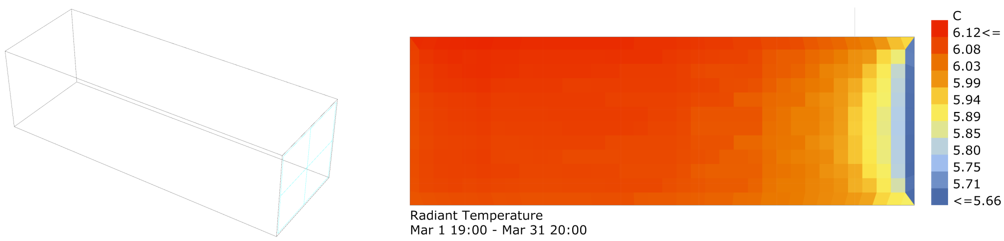

Figure 8.1: Geometry and radiant temp. plot for the 1 zone model

Using this geometry an EnergyPlus simulation has been run, with no internal gains, HVAC systems nor natural ventilation included. The radiant temperature was then visualized for the hour between 19.00 and 20.00 in the month of March. The reason for choosing this hour is that the sun has recently set, making the effects of radiation from the internal surfaces easier to see. The reason for choosing march is that the sun rises approx. due east and sets approx. due west giving an intuitive sense of which areas that would be exposed to solar gain.

The radiant temperature for structure as one large zone, with a floor, a roof and 4 walls is shown in figure 8.1. The plot shows that the radiant temperature for the zone is pretty symmetrical north to south. This would not seem to be the case for the area close to the window, where the northern wall would have absorbed solar radiation during the day and should thus radiate the space closest to it at this hour.

To try to get a more accurate image of the effect of solar radiation storage in the surfaces, two different modelling approaches were tested; virtual zoning and division of surfaces.

*Please note that the legend scales of this chapters figures are **not** identical. Even though that is unfortunate in terms of comparability, it's neccessary to show the often small differences in the results of each model.*

Zoning

The way zoning works in Honeybee/EnergyPlus is that different volumes are merged using a virtual material called 'Air Wall'. This material should be transparent to solar gains, temperatures, airflows etc. To try out this method two new geometrical models were created; one with three zones (see figure 8.2) and one with six zones (see fig. 8.3). Apart from the zoning all properties were the same as the previous model.

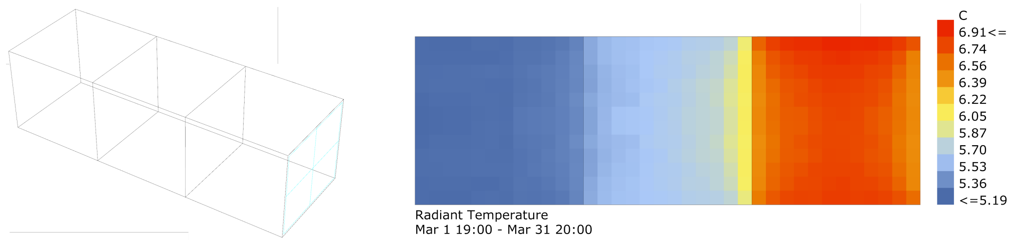

Figure 8.2: Geometry and radiant temp. plot for the 3 zone model.

Figure 8.2 shows the result for the geometry consisting of three zones. Is barely seen but there is a small hint of the expected effect of increased radiant temperature for the northern part of the eastern zone. The middle and western zones are completely north south symmetrical. Apart from that there are very sudden changes in radiant temperatures over the 'Air Walls', which doesn't seem realistic.

Figure 8.3 shows that the radiant temperature for the six zone model is completely north south symmetrical, and that the same effects are seen for the middle and western zone as in the three zone model.

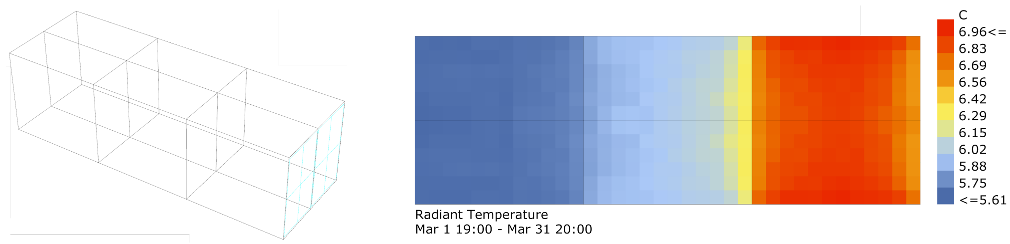

Figure 8.3: Geometry and radiant temp. plot for the 6 zone model

Surface division

A second approach is to keep the space as one zone, but divide the surfaces into smaller elements. In this way it's avoided that the summation over large surface areas render local differences invisible to the radiant temperature distribution. To models were examined with each of the north and south wall and floor surfaces from the original single zone were split up into 3 x 1 and 8 x 3 smaller surfaces (see fig. 8.4 and 8.5).

Figure 8.4 shows the result from the model with 3 x 1 surface split. It's seen that the effect of radiation of stored thermal energy from the eastern part of the north wall is now

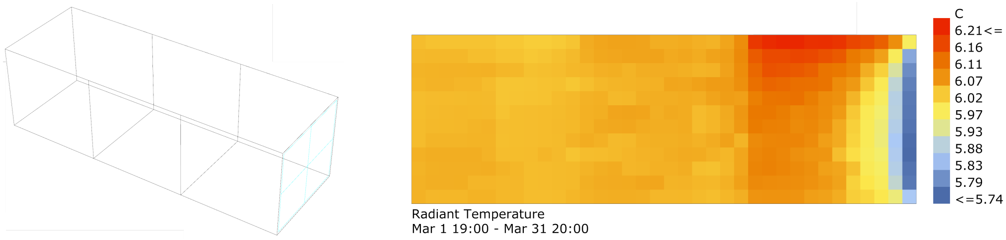

Figure 8.4: Geometry and radiant temp. plot for the model with 3 x 1 surface divisions.

visible on the plot. There are however still some noticeable discontinuities where there smaller surfaces are joined.

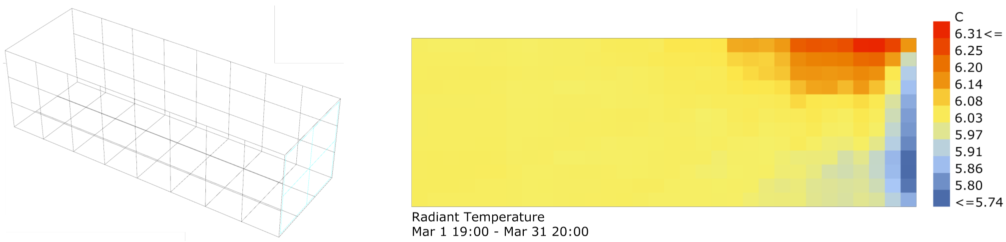

Figure 8.5: Geometry and radiant temp. plot for the model with 8 x 3 surface divisions.

The results from the 8 x 3 surface split model shown in figure 8.5 reveals that this model results in an even more noticeable/concentrated effect of radiation from the eastern part of the north wall. It also shows a much higher degree of continuity in radiant temperature over the entire grid.

Sum Up

Based on the analyses which the above results come from, the temperatures of the hottest and coldest wall of each model can be compared. These data are shown in fig. 8.6. The plot shows that the zoned models have the greatest difference in surface temperature. It also shows that higher detail levels (in terms of surface division) in the one-zone-models, result in bigger temperature differences.

Another thing that is interesting to compare is where these extrema occur in each model. In the three single zone models minimum surface temperatures (apart from the window) occur at the eastern wall, which seems logical, given that it is the surface that would be expected to receive only diffuse internal solar radiation. For the zoned models, the roofs have the minimum surface temperature. In the three single zone models maximum surface temperature occur at the northern wall, the north-eastern wall and the bottom of the most north-eastern wall for the simple, the 3 x 1 and the 8 x 3 models respectively. Again this is in line with what's expected. In the three-zone-model the maximum temperature also

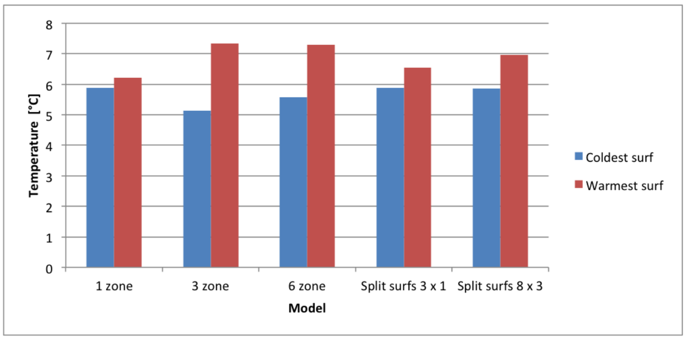

Figure 8.6: Differences in highest and lowest surface temperatures for the different models.

occurs at the north-eastern wall, but in the six-zone-model, the warmest surface is the southern side[1] of the 'Air Wall' between the two eastern zones.

The reason that the zoned models does not seem to display a realistic solar distribution might have to do with the way the 'Air Walls' are transparent to the solar radiation. Looking at the earlier result and the symmetry issues especially in the six-zone-model, it seems that the solar radiation can only pass through the 'Air Walls' as diffuse radiation.

Based on these points as well as the previous results in this chapter it seems that a one-zone-model best models a realistic solar distribution in this type of space. The accuracy is apparently closely connected to the degree of surface division in the zone. Although the effects of the solar distribution has little effect in these example simulations, it will have a much large effect as the glazing ratio of the canopy/atrium is increased.

The results shown here does however not mean that the use of a single zone model with surface division takes every aspect of solar distribution into account. For instance it does not model the heat transfer between each of the subsurface, which in some materials might be considerable. The surface temperatures in a large space would furthermore be closely connected to the airflows along them.

8.2 Airflows

Another issue when working with large - and especially tall - spaces is air flows. In such spaces buoyancy/stacking effects come in to play as well as local effects due to different surface temperatures. Apart from that the relation between the outside wind and indoor airflow would have to be considered in case of natural ventilation.

There are no current standard energy/comfort tools that will simulate these effects realistically. To model a realistic situation including these effects would take an iterative loop including an energy simulation tool and a CFD tool delivering inputs to one another until an equilibrium is reached. Apart from the facts that such a simulation would require a more than normally skilled model operator, it would be extremely time consuming.

[1] For some reason the thermal transparent 'Air Wall' has different surface temperatures on each side.

In this example the air flows are modelled through the Honeybee 'Set EP Airflow' module. This module estimates the airflow through windows based on openable area, outdoor wind speed, wind cardinal direction, etc. This means that it does to some extent include weather dependent variables when calculating the airflows. It is however not close to being a CFD tool, and does for example not consider mass balance, as it will be discussed below.

To examine whether it's possible to create a model that does to some degree display the effects of the airflows, three models were created based on the model from the previous section just with a western window added for possible cross ventilation. The three tested models have one and three either horizontal or vertical zones.

Figure 8.7 shows the air temperature of the one zone model. It's easy to see that it does not contain any distribution of the air temperatures. This fits the aim of distributed comfort poorly.

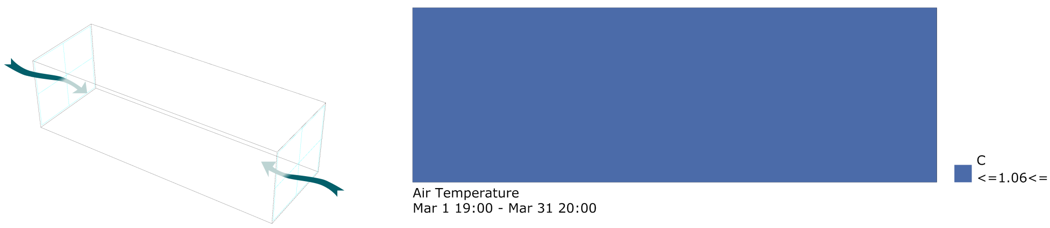

Figure 8.7: Air temperature for 1 zone model with cross ventilation.

An idea for producing distributed distributed results of air temperature is to make virtual zones in the analyses space, using the air wall function mentioned earlier. This is tested using a three zone model. The result of a simulation based on this model is shown in figure 8.8.

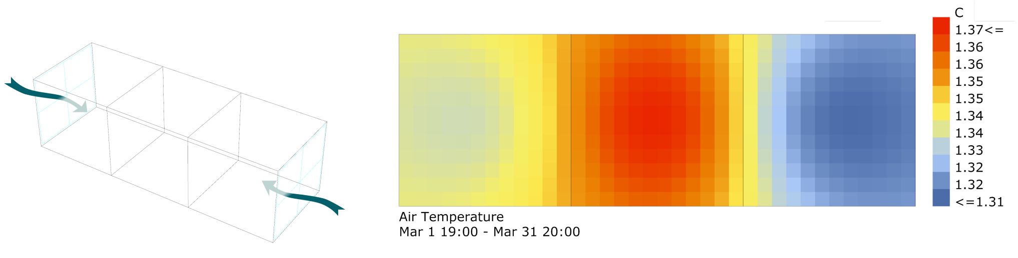

Figure 8.8: Air temperature for a 3 zone model with cross ventilation.

The results show that the air temperature is now distributed, so that the areas closer to the windows are cooler. The difference in temperature is however very small.

The problem with the zoned model arises when looking at the zone air flows, in the Grasshopper script. There is apparently no air exchange through the air walls - the total airflow of the center zone is zero. The same picture is seen for the vertically zoned model. This renders the idea of zoning in terms of the airflows unusable.

Why this apparent error in the air flow trough air walls happen is hard to say. Maybe some effect of transfer is considered and just don't show up as an airflow?.

The modules for creating the MicroclimateMap that visualizes the distributed results, does include some stratification effect, when used for PMV analysis, but the resulting difference in air temperature in the modelled case is less than 1°C for the room height of 21 meters.

Another problem regarding zone air flows is that the Air Flow Network option from EnergyPlus has not yet been implemented in Honeybee. This makes it impossible to simulate airflows between adjacent zones through internal windows.

The combined problems with airflows mentioned here does definitely make analysis of 3rd spaces, where airflows have a large effect, much less valid.

An interesting option that might do a better job, without the complexity of CFD is the not yet released "LiveStock NatVent" plug-in for Grasshopper developed by Thomas Perkov at DTU. This tool used the hand calculation method for natural ventilation, that takes wind pressure and indoor stratification into account. The plug-in is however not compatible with neither EnergyPlus nor the comfort analysis modules.

8.3 Ground Temperatures

The final issue discussed in this chapter has to do with how the ground temperature below the floor is modelled. In 3rd spaces such as the EKO Canopy it would not be unlikely to have a rather low- or even uninsulated floor slab. Combined with the much less steady - and in the case of the EKO Canopy colder - temperatures in the space, the ground temperature would be expected to have a very different behaviour and influence, compared to a standard office or housing building.

Native Honeybee Model

Honeybee/EnergyPlus' model of the ground temperature is quite simple[2]. If the undisturbed ground temperature of the used weather file is below 18°C then a ground temperature of 18°C is assumed. If the undisturbed ground temperature of the used weather file is between 18°C and 24°C, this value is used. If it's above 24°C, 24°C is assumed.

This seem oversimplified in the case of a third space for the reasons mentioned earlier. Furthermore it would seem very high in Nordic climates. It should be noted that this temperature is applied directly to the bottom of the floor construction.

Using the 8 x 3 single zone model from earlier with two windows, including the airflow from both windows described above, and now in contact with the ground, figure 8.9 shows the resulting mean radiant temperature for the 19.00 to 20.00 interval in march as an example, using the native Honeybee model for ground temperature. It's seen that the floor has a very large effect on the overall radiant temperature of the space.

[2] The model is explained by Chris Mackie at: http://www.grasshopper3d.com/group/ladybug/forum/topics/problem-setting-energy-plus-fields-in-honeybee

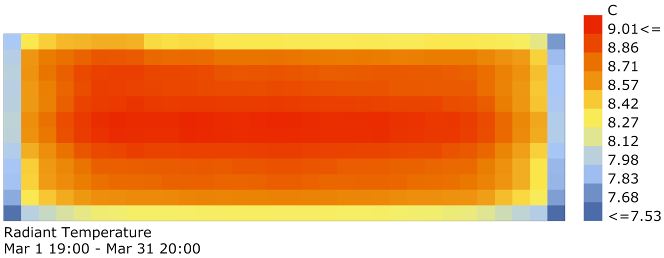

Figure 8.9: Geometry and radiant temp. plot for

Constant Adjusted Value

In his ongoing thesis Alexander Carneiro studies ground temperatures below atrium buildings, using the EKO Canopy as case. This work suggest that the average temperature 3 meters below this type of structure can be considered as equal to the yearly average operative temperature of the space.

Using this knowledge a new model was set up, altering the floor construction to include 2,5 meters[3] of ground beneath the 0,2 meter thick concrete slab used with the native ground temperature model. Through an iterative process[4] of adjusting the ground temperature below this construction to fit the yearly average operative temperature output from Honeybee/EnergyPlus.

The ground temperature was found to be 8.35 degrees for this set-up. Figure 8.10 show the radiant temperature for the space using this ground temperature. It's seen that this ground temperature model has a very different (and less dramatic) effect on the radiant temperature than the native honeybee model.

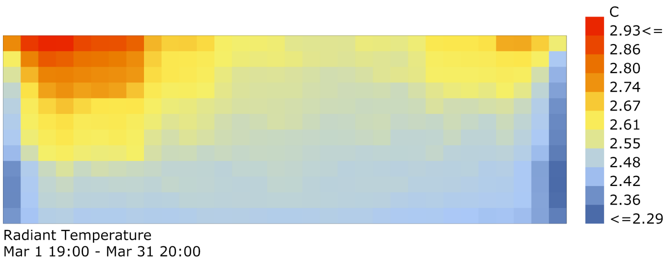

Figure 8.10: Geometry and radiant temp. plot for

[3] The ground was modelled based on the thermal properties of ground given in DS 418 (Dansk Standard, 2011). The raeson for the ground layer only being 2,5 meters thick is that Honeybee will not accept a thicker layer. The reason for this is probably that the engine has a maximum allowed heat storage capacity for a construction.

[4] Meaning that changing the ground temperature also affects the average operative temperature of the space.

Modulating Adjusted Values

Another finding in Carneiro (2016) was that the ground temperature under the center of the atrium structure, was not constant over the year such as modelled above, but could rather be expressed by a sine function with a 2-3 month phase change. The amplitude of the sine function was found to be 4°C using Danish weather data.

How the amplitude would change given another climate is hard to say. It would require a detailed analysis like the one in Carneiro (2016) for that particular site. But to see the effect of such a modulating ground temperature, the amplitude of 4°C was used to create a new input to the Honeybee/EP simulation.

This input was created using grasshopper standard components joined together in a cluster. The cluster the cluster corresponds to the following equation[5]:

$$\theta_{soil} = f_1 + f_2 \cdot sin(2 \cdot \pi \frac{(M - M_0)}{12} \tag{8.1}$$

The content of the cluster is shown in figure 8.11

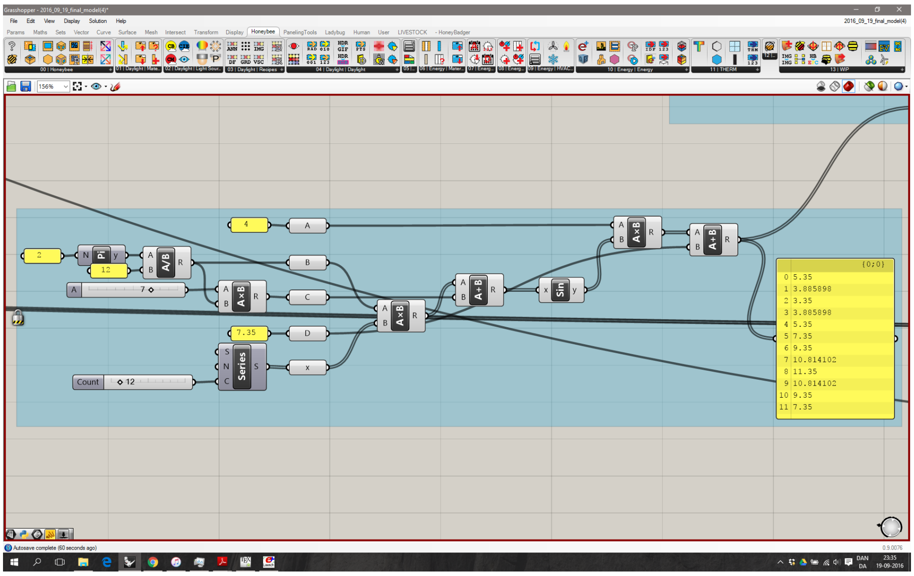

Figure 8.11: The script for a customized ground temperature as seen in Grasshopper. The set-up corresponds to the following for of sine function: f(x) = A sin(Bx + C) + D.

The result of the simulation with the modulating ground temperature is shown in figure 8.12. The overall impression is similar to that of the constant temperature, although the overall temperatures are lower (note the scales).

Figure 8.13 shows the operative temperature of the space over the year for the three different ground temperature models.

[5]Given in Carneiro (2016)

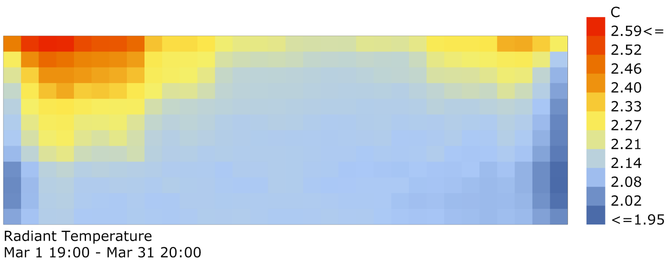

Figure 8.12: Geometry and radiant temp. plot for

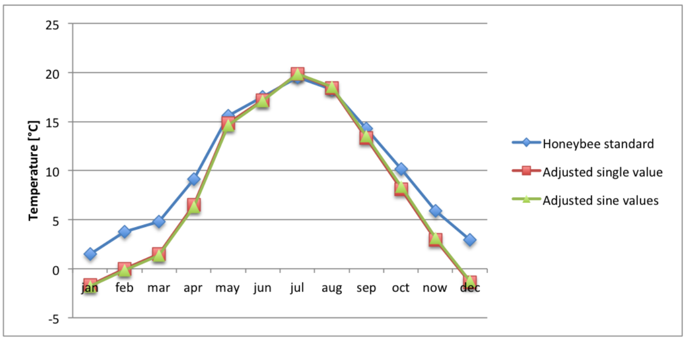

Figure 8.13: Geometry and radiant temp. plot for

The difference between the two adjusted models is hard to see and is therefore elaborated in figure 8.14.

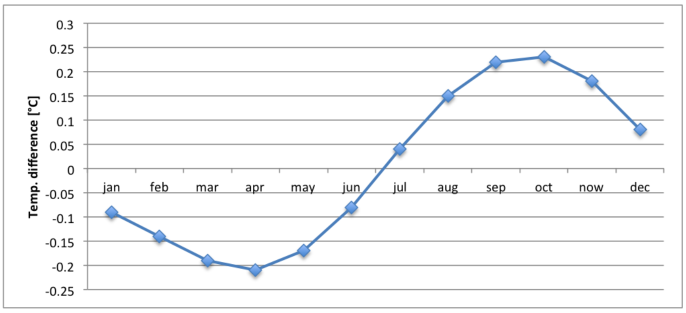

Figure 8.14: Geometry and radiant temp. plot for

As an ending note it should be mentioned that a final finding in Carneiro (2016) was that atrium structures that has adjacent buildings, such as the EKO Canopy, receive some energy trough the ground. This effectively heats up the floor areas close to the adjacent building (< 3 meters approx.). This effect is currently hard to include in the Honebee/EP setup, as it does not allow for more than one set of temperatures, making it impossible to differentiate between different surfaces or zones.

8.4 Partial Conclusion

This chapter has discussed issues that might play an important role in the analysis of third spaces, and how they might be treated in the chosen Rhino/Grasshopper set-up.

Zoning a space using air walls to model internal solar is not a viable solution. Instead splitting zone surfaces into smaller part does improve the validity of the solar distribution calculation.

It was discovered that it is not immediately possible to produce a distributed air temperature by zoning the space. The air walls used for zoning does not seem to allow for air flows through them. Furthermore it is not possible to model inter-zone airflows because of the missing implementation of the EnergyPlus Air Flow Network in honeybee. The problems with air flow modelling is a big issue in terms of the realism and validity of the results.

Finally the influence of ground temperature was examined based on a comparison of the native Honeybee ground temperature model against a model based on the findings by Carneiro (2016).

Chapter 9

Case - Modelling the EKO Canopy

The entire case study of the EKO canopy in this thesis focuses more of showing examples of what sort of information it's possible to the deduce from the results of the chosen set-up and how well different models for thermal comfort might be included, rather than on producing valid results. Even with very careful and complex modelling the issues related to the simulation discussed in chapter 8, would still render the results doubtful.

9.1 Geometry Model

To analyse the thermal comfort of the EKO Canopy the first step is to create a 3D geometry of the canopy that matches the architecture of the project as well as possible without including an unnecessary amount elements with regard to the energy/comfort simulation.

The geometry used in this chapter is based on a mix of the geometry used by Vila (2016), Knudsen et al. (2016) and the original proposal from White Architects (appendix ???).

The basic modelling of zone volumes have been done in Rhino. The created volumes have then been referenced to Grasshopper afterwards.

The model includes individual zones for each of the floor levels of the adjacent buildings. This should allow for some divergence in terms of surface temperatures for the different levels. The reason the apartments have not been modelled individually has to do with the complexity of the resulting energy simulation. The EnergyPlus engine can only handle a certain amount of surfaces for instance[1]. An extra basement floor was added to account for the input of a ground temperature that is fitting the canopy conditions (which is described later).

The EKO Canopy has been modelled as a single zone, as it was found recommendable in chapter 8. The balconies of the adjacent north building was neglected. The reason for this is that although it is possible to include the geometry as a shading within the zone in the Honeybee set-up, it is impossible to give the surface materials thermal properties,

[1] When individual zoning for the apartments was attempted, Rhino simply crashed as soon as it was attempted to run the energy simulation.

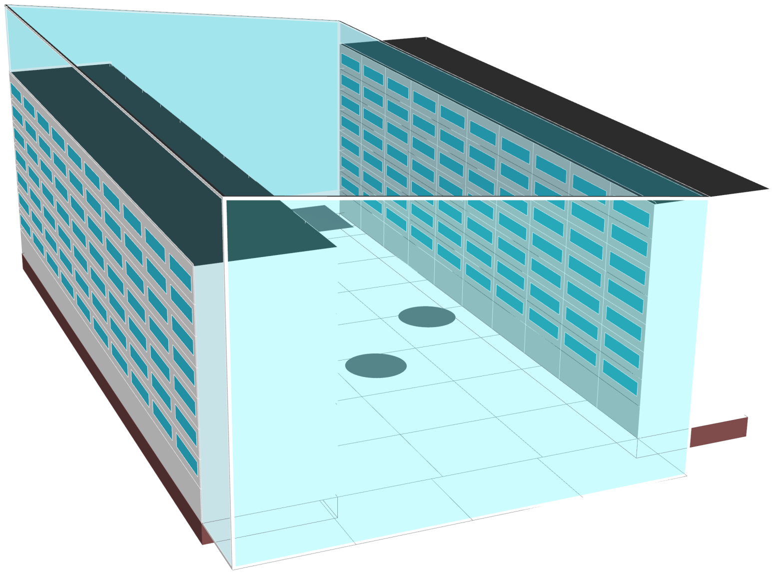

Figure 9.1: Plot of the Rhino/Grasshopper geometry model as seen from south-east.

without defining the balconies as individual zones. The end result if the balconies where modelled as zones would probably be even worse than when neglecting them, and would would increase the simulation time considerably.

To reflect some of the possibilities of in the interior design of the canopy, surfaces imitating the platform structure includes in White's proposal, as well as two parasols have been added to the model.

The created Rhino geometry was processed in Grasshopper turning it into HoneybeeZones. This was done based on import of the wall, floor and ceiling/roof surfaces of each zone. Some geometric actions was carried out by use of Grasshopper functions. The surface of the canopy floor as well as the walls between the canopy and adjacent building was split up into smaller surfaces to allow for better solar distribution calculations (as discussed in chapter 8). Furthermore windows were generated using Grasshopper geometrical functions.

The resulting geometrical model is shown in figures 9.1 and 9.2.

9.2 Materials

The choice of materials is widely based on the description of the existing buildings and the proposed canopy materials in Knudsen et al. (2016). An exception is the floor material of the canopy which was discussed in chapter 8.

For the adjacent buildings the outer walls[2] are constructed of lightweight concrete, insulated on the outside with 400 mm of mineral wool and finished with a metal profile plate

[2]That are assumed to be renovated as part of the project.

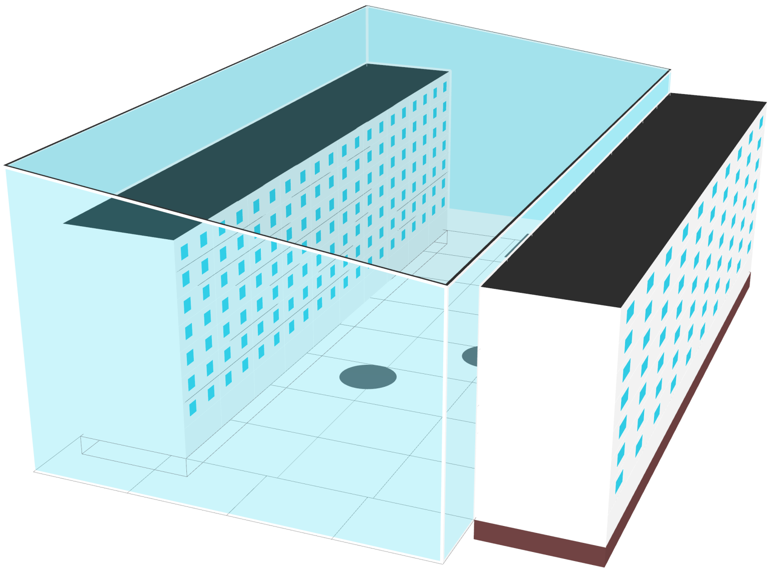

Figure 9.2: Plot of the Rhino/Grasshopper geometry model as seen from north-east.

- resulting in a U-value around 0.08. The windows away from the canopy, have U-values of 0.8 W/m2 K and a visible light transmission and g-value of 0.3 (to account for the neglected balconies). The roofs and floors are essentially constructed of lightweight concrete, 500 mm of mineral wool, again covered with metal plates in the case of the roof.

The canopy envelope is based on the PFTE material proposed by Knudsen et al. (2016), that has a U-value of 1.3 W/m2 K and a visible light transmission and g-value of 0.75. The floor of the canopy uses the same construction as described in chapter 8, consisting of a concrete slab of 200 mm and 2.5 meters of soil beneath it.

To possibly show the potential of using different materials in the canopy to achieve different thermal micro climates, four of the floor sub surfaces have an added upper layer of 20 mm of wood, creating a terrace-like environment.

9.3 Loads and Systems

The loads included in the adjacent buildings is taken directly from the predefined apartment building type included in Honeybee. This includes number of people, equipment and lighting loads.

Natural ventilation have been assigned to occur through half of the windows not facing the canopy. The set point for natural ventilation for cooling is an indoor temperature of 25°C with a threshold of 16°C for the outdoor temperature. The problem of not being able to define an Air Flow Network for inter-zone ventilation makes it impossible to include the effect of ventilation towards the canopy.

Heating and cooling (when the natural ventilation is not enough) is handled by an idealised HVAC system ensuring that the temperature never gets outside a range of 20-27°C.

For the canopy a maximum load of 250 persons have been assigned. This is of course a high number of occupants but actually only 1 per 10 m2 of floor in the canopy. The infiltration for the zone is set high at 0.006 m3/m2 facade per second. This does not reflect that the PFTE envelope is leaky it it self but rather that a constant amount of air can be assumed to be exchanged with the outdoors as people enter or leave the canopy.

Natural ventilation is allowed to take place through 5% of the glazed part of the envelope. This might seem very low, but result in up to 45 air changes per hour for some periods. This value is probably extreme although the canopy is expected to be heavily ventilated at times. This is again a part of the problems related to the very simple way natural ventilation is handled in Honeybee.

As mentioned in the beginning of the chapter, the focus is on is on creating an example analysis rather than one that accurately reflects the climate of EKO Canopy. This shows in the very simple set-up described in this chapter.

Images of the Grasshopper set-up used for this and the next chapter can be seen in appendix ???.

Chapter 10

Case - Analysis of Thermal Comfort in the EKO Canopy

This chapter goes through the result of a thermal comfort analysis based on the model of the EKO Canopy case described in chapter 9. It is important to note that the analysis has primarily been carried out to show the potential of the method used in this study. The results should therefore be considered as examples rather than valid data for the structure.

10.1 Strategies for Analysis of Thermal Comfort

The result have been produced using the three thermal comfort models reviewed and discussed in chapters 3 to 6. All of these models have been used for analysis through their corresponding Honeybee 'recipe' modules (as described in chapter 7).

Considerations Based on the Earlier Discussion of Application of Thermal Comfort Models to 3rd Spaces

The discussion in chapter 6 showed that the parameters that might most likely influence the perceived thermal comfort, had to do with outdoor conditions and architectural/contextual elements. To include these parameters in a quantified way in the analysis of the comfort in a 3rd space without further empirical studies, would however be based purely on guessing.

Even a guess in terms of the magnitude of the impact of these parameters might be interesting though. The reason it has not been possible to do that in this study has to do with both a limited amount of time, and the authors missing skills in the area of programming. The modules that produce the results for all three thermal comfort model, does (unlike many other Grasshopper modules) not output numbers, but instead pieces of IronPython code. This make it impossible to manipulate the output data using native Grasshopper mathematical functions.

In the case of the PMV Model, chapter 6 also discussed the effects of increased user freedom on thermal comfort. The occupants are not as restricted in terms of clothing and activity level as they would be in e.g. an office environment because of practical reasons and social conventions.

It would therefore be interesting to include a certain freedom with regard to these parameters when simulating thermal comfort for a third space. A concrete way to implement these options would be to create the possibility to input ranges for clothing or activity level rather than fixed values. The script should then optimize the comfort within these ranges for each time step resulting in a broader spectrum of acceptable conditions. Once again this is however an approach that require a certain level of programming skill to realise.

Instead the PMV analyses of this study have been carried out using a number of activity level/clothing sets. This is a simple way of including the user freedom on a very low practical level. This approach does not produce the same result as the proposed method above nor results corresponding to real life behaviour of occupants. It's not possible to simple overlay the results of two different sets of activity level and clothing and get a result that include the user having a choice between the two.

The cases from which the PMV results have been produced are shown in table 10.1.

10.2 PMV Results

The main analysis of the thermal comfort is done in periods that correspond to the four seasons. The analysed hours for each day span from 10 am to 6 pm, corresponding to the time where the space is thought to be used the most.

As mentioned above the analyses have been carried out using the PMV Model based on a number of combinations of clothing and activity level. These combinations are shown in table 10.1.

Table 10.1: The combinations of activity level (met) and clothing factor (clo) for which the results based on the PMV Model have been produced.

Season	Relaxing (1 met)	Gardening (2.6 met)	Light Sports (3.5 met)
Winter	1.8	1.3	0.8
Spring/Fall	1.2	0.8	0.6
Summer	0.5	0.4	0.3

The results are shown in terms of percentage of hours that are comfortable. *Please note that the result legends are different for most of the plots in this chapter. The is of course not optimal for comparison of the different plots, but necessary to show the differences in the distributed comfort of each plot.*

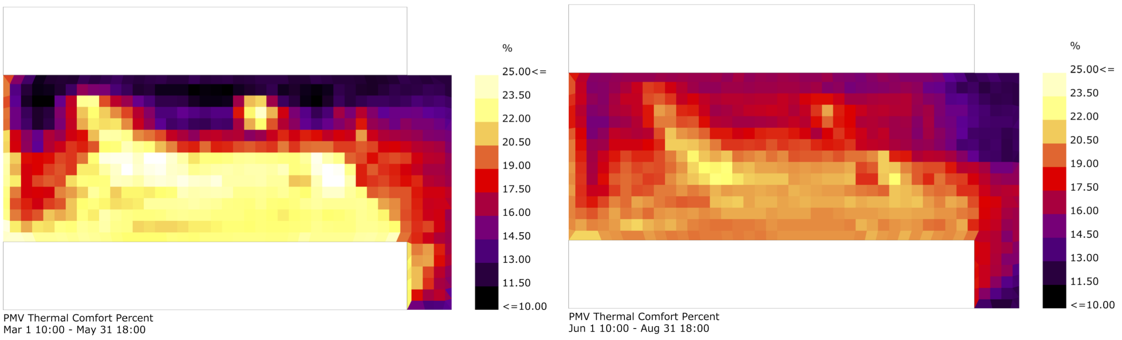

Figure 10.1: Percentage of comfortable hours in **spring (left)** and **summer (right)** for resting occupants. Based on clothing and activity level values stated in table 10.1. Note the different legends.

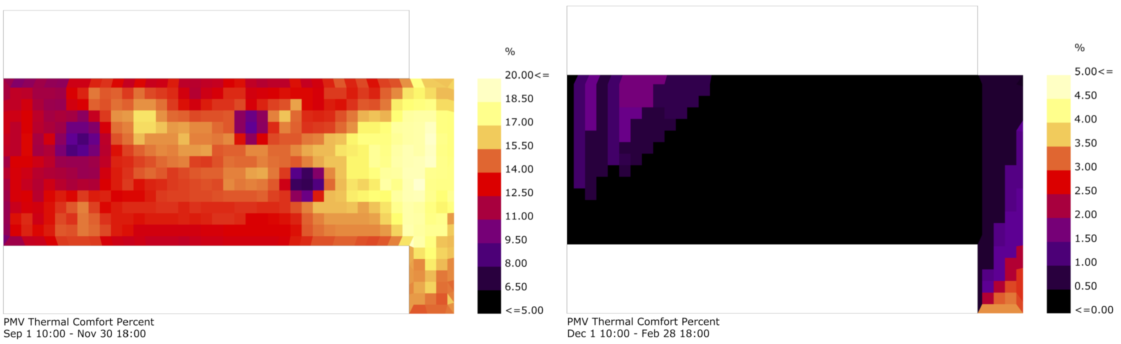

Figure 10.2: Percentage of comfortable hours in **fall (left)** and **winter (right)** for resting occupants. Based on clothing and activity level values stated in table 10.1. Note the different legends.

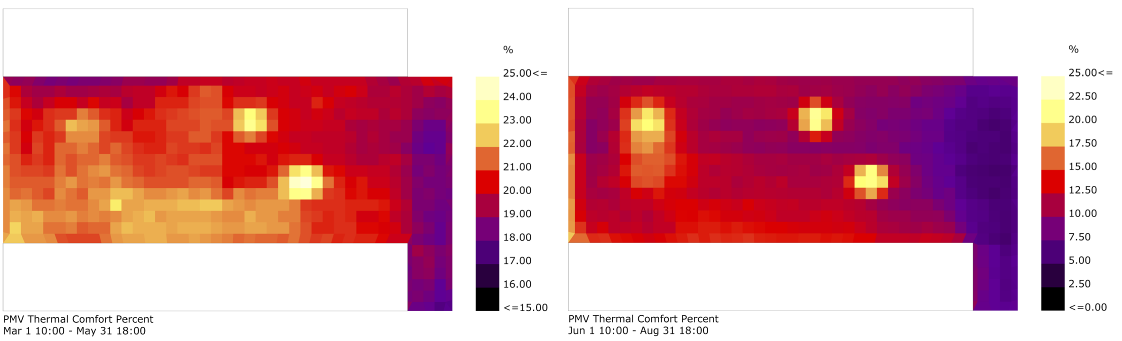

Figure 10.3: Percentage of comfortable hours in **spring (left)** and **summer (right)** for gardening activity. Based on clothing and activity level values stated in table 10.1. Note the different legends.

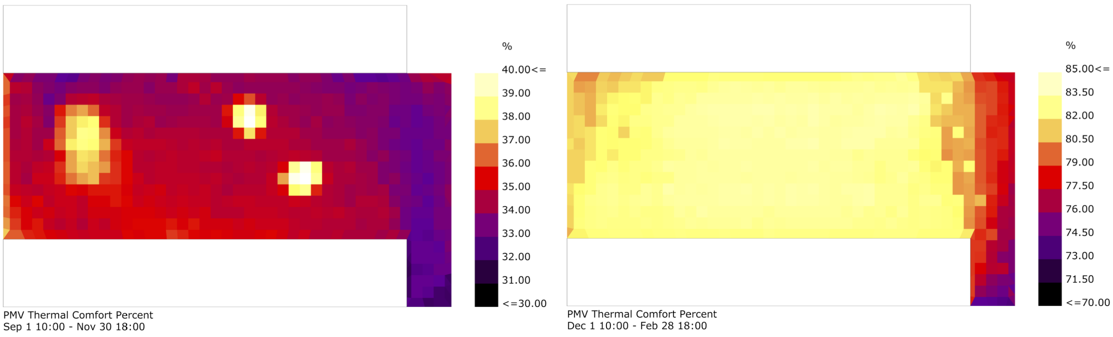

Figure 10.4: Percentage of comfortable hours in **fall (left)** and **winter (right)** for occupants doing gardening. Based on clothing and activity level values stated in table 10.1. Note the different legends.

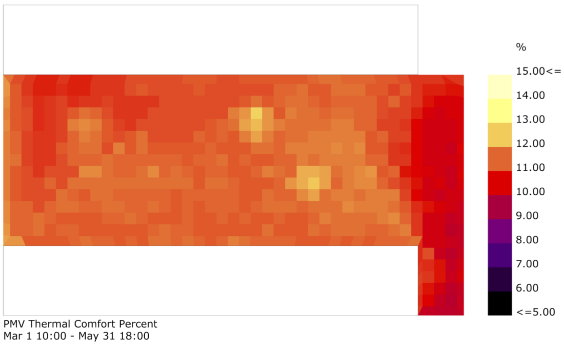

Figure 10.5: Percentage of comfortable hours in the spring for light sport activity. Based on clothing and activity level values stated in table 10.1. Note the different legends.

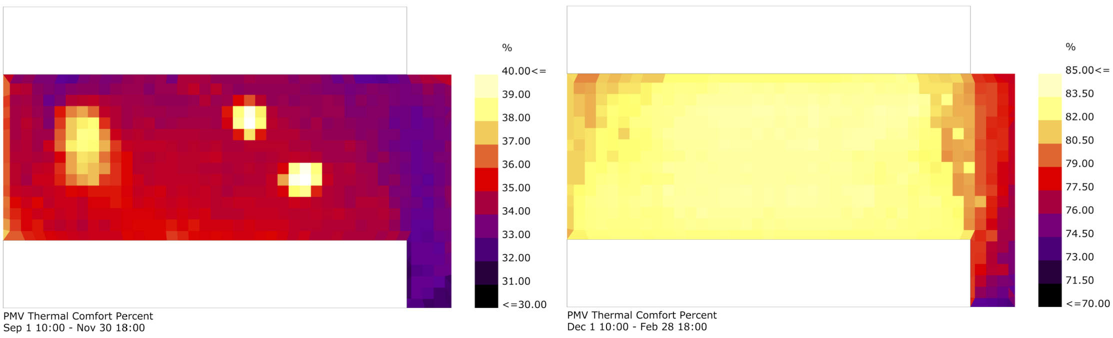

Figure 10.6: Percentage of comfortable hours in **fall (left)** and **winter (right)** for light sport activity. Based on clothing and activity level values stated in table 10.1. Note the different legends.

10.3 Result From The Adaptive Model

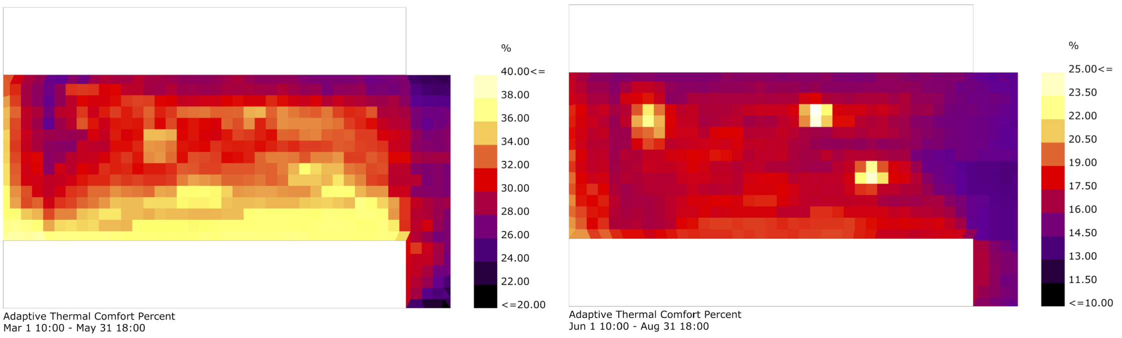

Figure 10.7: Percentage of comfortable hours in **spring (left)** and **summer (right)** according to the Adaptive Model. Note the different legends.

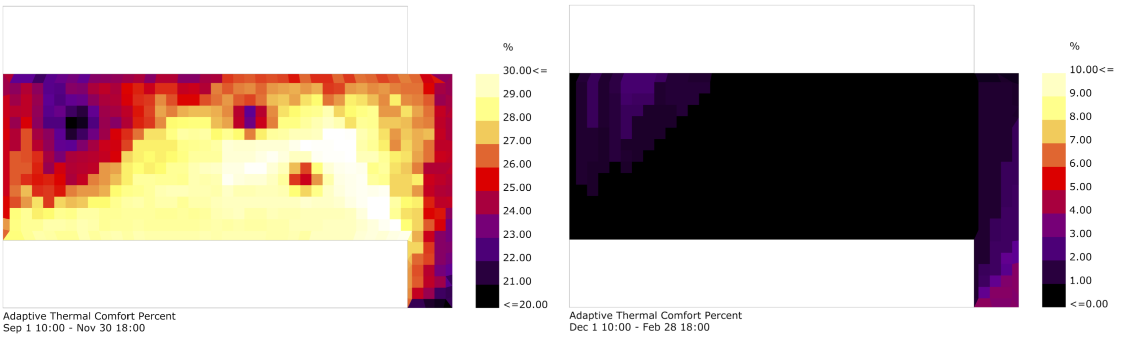

Figure 10.8: Percentage of comfortable hours in **fall (left)** and **winter (right)** according to the Adaptive Model. Note the different legends.

10.4 UTCI results

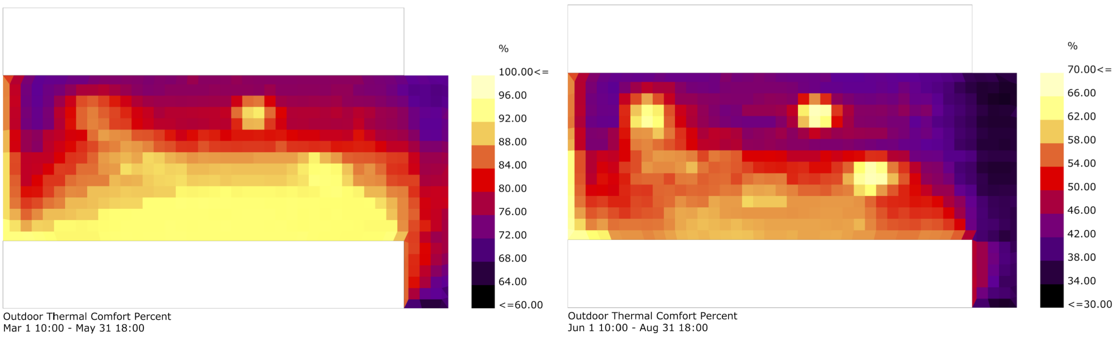

Figure 10.9: Percentage of comfortable hours in **spring (left)** and **summer (right)** according to the Adaptive Model. Note the different legends.

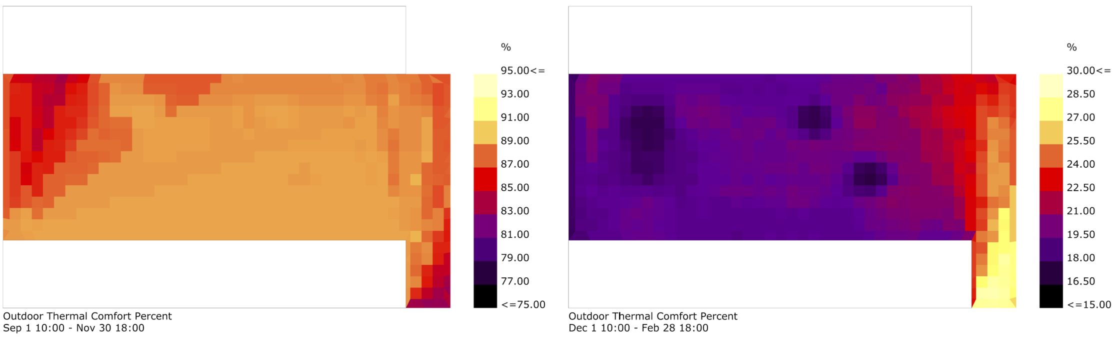

Figure 10.10: Percentage of comfortable hours in **fall (left)** and **winter (right)** according to the Adaptive Model. Note the different legends.

10.5 Partial Conclusion

The PMV plots are showing a spacious distribution of the thermal comfort. By mapping the amount of time where a person feel thermally comfortable the areas in the canopy can be labelled for specific design features. As an example figure 10.2 shows that the eastern part of the canopy is optimal for placing opportunities for relaxing in an autumn situation. The winter situation shows that it can not be recommended to use the canopy for low activity levels during winter with the clothing stated in table 10.1. A much higher clothing insulation is recommended for this. However, by increasing the activity level to gardening suddenly a large part of the canopy reaches a thermal comfort level more than 85 The adaptive model shown in figure 10.7 and 10.8 reveals that the autumn condition is the most optimum thermal comfort condition during a year. This model outputs recommendations in the spacious domain for placing e.g. a playing field, where higher activity levels can unwind in the western part of the canopy.

The UTCI model (figure 10.9 and 10.10) used a fixed activity level and clothing by air temperature. Here, the spring and autumn conditions are the most comfortable. The winter and summer situations result in large differences in terms of comfortable amount of time in the spacious domain in the canopy.

Generally the plots of distributed comfort inform the early design process for mapping special design features.

Chapter 11

How far does the model go? - Alternative strategies for the EKO Canopy

The set-up described in chapter 7 offer the possibility with very few alterations to simulate outdoor climate using the UTCI as well.

This creates possibilities for new and more radical inputs to the early design phase. Using this option it's not only possible to evaluate different designs in an enclosed 3rd space but also whether the space benefits from being enclosed at all.

The EKO Canopy structure might for instance be compared to an open area between the adjacent buildings covered by large shading or transparent parasol structures.

A canopy might not always be the right solution for a certain area or social environment. It may cause isolation a be avoided by outsiders if it feels to private. It would also risk not to be used by the people living there if it has a panopticon atmosphere to it, resulting in feeling watched when using it.

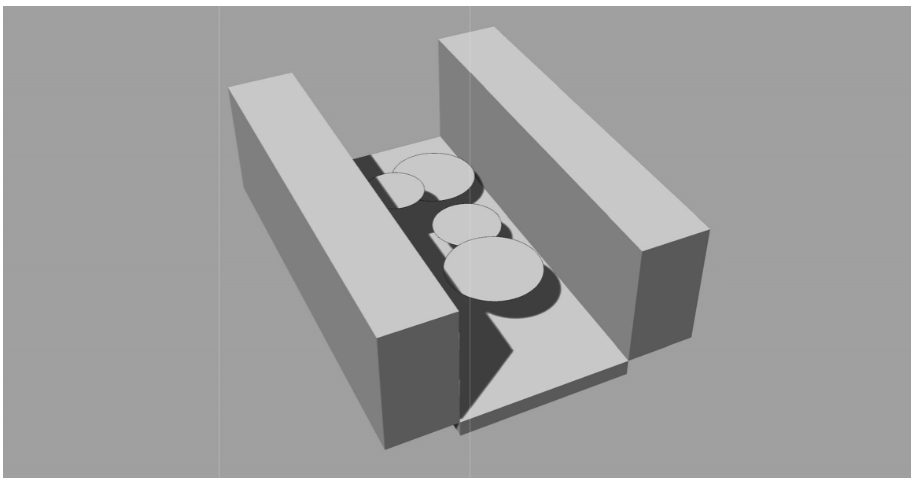

Figure 11.1: A conceptual plot of an alternative strategy for the EKO Canopy

The problem with handling air flows in Honeybee is however an even bigger problem in this case since outdoor wind speeds are much higher than the ones experienced indoors, and therefore plays a much larger role in the human comfort. Apart from this the wind speeds are much less uniform in general in an outdoor space.

Part IV

Conclusions and Discussion

Chapter 12

Conclusions

Chapter 3 reviwed existing models for thermal comfort, especially focusing on their limitations.

Different sources list different limitations of the PMV Model. Fanger (1970) suggest that the model is almost universal in terms of input, whereas e.g. the DS/EN ISO 7730 narrows the input possibilities down. This makes it hard to assess whether the model is suitable for evaluating 3rd space comfort.

The Adaptive Model is interesting because of its focus on the relations between comfort and outdoor climate. The range of outdoor temperatures for which the model has been proven is does however not overlap much, with the weather in the Nordic countries, why the model would need to be expanded, to be applicable in the case of the EKO Canopy. How the relations described in the Adaptive Model can be emphasised even further and how the model might be expanded to cover a wider range of inputs will be discussed later.

Regarding the UTCI, it is (of the three) the model with the widest span of application, which makes sense since it's an outdoor model. The challenge with this model in terms of an 3rd space environment that opts for a variety of activities, is the lack of control/customization that's possible regarding clothing and activity level.

Comparison of the Adaptive Model to the PMV model in terms of reactions to various air speeds showed that the models differ in two ways: 1. At lower air speeds where PMV reacts more dramatically to changes than the Adaptive model, that only reacts to inputs above 0.3 m/s. 2. The bandwidth of acceptable temperatures changes in opposite ways for the two models. In the Adaptive Model the bandwidth widens with higher temperature, in the PMV Model it narrows.

The UTCI and PMV Model display similar reactions to variation of every input except wind speeds. The effect of wind increases with higher wind speeds in the UTCI, whereas it decreases in the PMV Model.

Trying to answer the question of what might influence occupant expectations in a 3rd space, a few points can be deduced from the different architectural approaches briefly discussed in chapter 5. But maybe the first question that needs answering is: *How* would architectural/tectonic elements affect climatic comfort in 3rd spaces?.

Based on the underlying knowledge from the Adaptive Model, of how the use and control of natural ventilation affect occupants thermal neutrality, connecting their preference with the outside temperature, it would make sense to suggest that architectural elements connecting occupants even stronger with nature, would result in an increased dependence on the outside conditions. Regarding thermal comfort this would suggest a steeper slope of the plot of neutral temperature vs. outdoor temperature. All in all this would, if the assumption is correct, result in a greater acceptability of variance in temperature in the built space, over the spectrum of outdoor temperatures.

Back to the main question of which elements that might affect the user expectations and thereby comfort. Based on this chapter it would make sense to include the following elements when considering the criteria to evaluate comfort in 3rd spaces from:

- The occurrence or absence of climatic locks. The absence of those might strengthen the connection to the local climate and the feel of the users autonomy over their climate (if replaced by openable doors directly to the outside. Perhaps especially by introducing a relationship between transparency in terms of both view and movement - "if I can see trough it, I can move trough it".
- Related to this a transparency in terms of materials - using the same materials outside and inside, causing a smooth transition and connection trough the envelope. This would also apply to repetitive patterns or elements 'going through' the envelope, such as placement of trees on either side
- Visible tectonic elements related to the division from the outdoor climate, such as rainwater handling systems.
- Irregular items (could be trees or other plants).
- (As an extra thought) Use of materials typically used in outdoor spaces - terrace-like wooden floor structures, etc.

Another interesting thought is whether the use of naturally occurring phenomena for conditioning of spaces might also strengthen the connection with the outside climate? This could for instance be the use of trees or other plants for solar shading in the summer. Would you be more tolerant towards the changing shadow patterns of a swaying tree or wine, than from a automated louvre systems trying to adapt on a day with mixed weather? Or would the moving shadows of the tree even improve the perceived comfort, like the 'noise' from moving water does in certain environments (Yang and Kang, 2005).

Chapter 6 discussed how applicable the three reviewed thermal comfort models are to 3rd spaces. The UTCI is although it's hard to customise a proven model for evaluation of outdoor climate. It is therefore usable in the range of 3rd spaces that are more outdoor like. A thing that separates the UTCI from the other two models is that it focusses on physical responses to certain conditions, rather than perceived comfort. This does make it a bad indicator of how people *feel* in a given thermal environment, but the responses would be interesting to consider in a tailored thermal comfort analysis framework for 3rd spaces, as the conditions in such spaces might often lead to physical responses. It might for one be interesting to look at when defining limits of adaptability in such a space.

The Adaptive Model is hard to manipulate given it's empirical/statistical nature and lack of input possibilities. This makes it hard to apply to 3rd spaces since the acceptable temperature ranges it deliver, focuses on indoor spaces. In the case of the EKO Canopy a further problem is that its range of outdoor temperatures does not fit a climate like the Swedish.

It was found that the PMV Model, although its range of validity arguably does not fit the conditions expected in a 3rd space, might be most suitable to build on, because of its customisability. The model might however need adjustment to include elements such as dependency on outdoor temperature.

An interesting aspect of thermal comfort in 3rd spaces is the introduction of a higher degree of user freedom in terms of clothing and activity levels, moveablity and the use of local artefacts (such as parasols or wind screens) to adjust the micro climate. This effect would be interesting to incorporate in analysis of thermal comfort in such spaces.

Most of this chapter is however based on logical deduction or 'qualified guessing' and many of the discussed propositions for a more tailored approach to thermal comfort in 3rd spaces, would require further studies for the validity to be examined.

Based on the points discussed in chapter 7 an analysis set-up in Rhino/Grasshopper using the Ladybug+Honeybee suite in connection with ENergyPlus was chosen. The reasons for choosing this set-up is that it complies with the criteria set for the analysis, which are summed up below:

- Handling of certain effects important to the analysis of 3rd spaces (further discussed in chapter 8.
- Ability to be included in an early design phase and produce instantaneous inputs to the design.
- Posibility to evaluate thermal comfort based on the three frameworks discussed in chapters 3 to 6.
- Flexibility in terms of analysis process and visualisation.

Chapter 6 discussed issues that might play an important role in the analysis of third spaces, and how they might be treated in the chosen Rhino/Grasshopper set-up.

Zoning a space using air walls to model internal solar is not a viable solution. Instead splitting zone surfaces into smaller part does improve the validity of the solar distribution calculation.

It was discovered that it is not immediately possible to produce a distributed air temperature by zoning the space. The air walls used for zoning does not seem to allow for air flows through them. Furthermore it is not possible to model inter-zone airflows because of the missing implementation of the EnergyPlus Air Flow Network in honeybee. The problems with air flow modelling is a big issue in terms of the realism and validity of the results.

Finally the influence of ground temperature was examined based on a comparison of the native Honeybee ground temperature model against a model based on the findings by Carneiro (2016).

By mapping the amount of time where a person feel thermally comfortable by using the Adaptive Model or UTCI the areas in the canopy can be labelled for specific design features. The PMV models can recommend activity levels and clothing for a certain time of year. Generally the plots of distributed comfort inform the early design process for mapping special design features.

The set-up described in chapter 7 offer the possibility with very few alterations to simulate outdoor climate using the UTCI as well.

This creates possibilities for new and more radical inputs to the early design phase. Using this option it's not only possible to evaluate different designs in an enclosed 3rd space but also whether the space benefits from being enclosed at all.

Chapter 13

Discussion

Throughout this thesis many approaches and models have been discussed. This discussion summarizes and collects the points of view presented earlier and presents them by putting them into a perspective of future matters.

13.1 Application of Thermal Models to 3rd spaces

13.2 Disadvantages to simulating comfort

As mentioned in earlier chapters, the overall approach of this study, suggesting that simulation of thermal comfort has the potential to inform the design process and direct design choices, is disputable. Are the simulated results close enough to real life, to base important design choices on them?

Chapter 8 shows some of the difficulties in terms of modelling a 3rd space atrium in a valid manner. As an example physically correct simulations of air velocities, air temperatures and surface temperatures would require a very advanced CFD coupled thermal/energy model as discussed earlier. Another example is the effect of the outdoor wind speed and direction upon the natural ventilation flow in a zone. Although some Building Performance Simulation (BPS) tools include semi analytical models to deal with this effect, they are not likely to be accurate in cases of high ventilation rates.

Some of the same difficulties exist in 'standard buildings' as well. But the vast amount of measured data for this type of buildings, and the massive focus on especially indoor climate in office environments have made it possible to approximate some of these effects in a very precise way.

Virtually no data is available for spaces like the EKO Canopy. Likewise none of the reviewed thermal comfort models accurately fit a situation such as the EKO Canopy. More knowledge in this area is therefore required, as discussed in the future work section in this chapter.

The big question is if the simulation results achieved with standard[1] tools, as EnergyPlus

[1] Meaning currently available thermal/energy simulation tools.

in this study, produce so misleading results that they might hurt the design process. This is difficult to say without comparing results from 3rd space simulations with real life measurements. Again more real life data is needed.

13.3 Choice of Analysis Method and Tools

The reasons for selecting the Rhino/Grasshopper set-up for analysing the EKO Canopy case, included the ability to link the simulation to a geometrical model easily, making it more convenient to remodel parts of the geometry as well. Other reasons were: Speed and the possibility of quick feedback to the design process, along with amount of options that stems from Grasshoppers' possibilities to link different data streams and components. After the analysis of the EKO Canopy case it would seem reasonable to discuss whether these projected benefits were actually achieved.

In terms of remodelling in it self, the benefit of the set-up was seen. The model offers all the design possibilities of Rhino and Grasshopper. Once the part of the script associated with turning the Rhino geometry into Honeybee Zones was done, *parametric* changes, such as the size of windows, splitting surfaces into smaller pieces, etc, didn't require manual remodelling. Radical changes in the way the geometric model was set up such as changes in the amount of zones, did require some manual adaptation of the script.

Model size is always a key parameter when talking about simulation speed. In tools such as IES VE increased model size and/or complexity result in much longer calculation times once you hit the simulate button. But apart from that the tool works at normal speed, when e.g. examining results. In the case of the Honeybee simulation and analysis set-up of this study, model size and complexity has a dramatic effect on the general speed and responsiveness of the tool. In the case of the analysis of EKO Canopy in chapter **??** the number of zones was 19, and the surface count approx. 700. At this point the whole tool handled like a 400 meter oil tanker - slowly (!). Especially actions involving Honeybee Zone components took a long time. The analysis was even performed on a computer that is far more powerful than the standard office pc. During work on visualisation of results the tool's use of RAM when not performing any calculations was 10 GB (!).

The total calculation time from import of geometry to the final visualisation of comfort was slightly more than one hour. This means that the desired quick feedback on design changes is not really an option. In light of these facts, the set-up does not really deliver on the speed parameters unless a very powerful computer is used.

Regarding the amount of options offered in the Grasshopper tool, some features such as the MicroclimateMap component that allowed the calculation and visualisation of distributed comfort, proved the point of options. The ability to manipulate data to look at certain parts of the simulated geometry was a benefit as well. The possibility to alter most inputs allowed for changing the ground temperature model, into a more appropriate one.

However there were also missing options that other tools offer. The lack of an inter-zone airflow model was critical in the case studied in this report.

The problem of a proper model for air flow in this set-up would all things being equal make the analysis results less valid. The question is whether other tools would produce more valid results in the case of a naturally conditioned canopy. The natural ventilation and inter-zone airflow models used by all Building Performance Simulation tools is based on a hand calculation method that does not resemble a CFD calculation in any way.

The validity of the open source Grasshopper/Honeybee set-up is problematic compared to central model BPS tools. KRIS CITAT

All the current problems and limitations considered, the potential of setting up simulations of 3rd spaces through a Visual Programming Language (VPL), such as Grasshopper, is however hard to deny. The possibility of manipulating data streams makes the set-up ideal as a playground for analysing cases that fall outside the 'standard building' area, and adding customised aspects to these analyses. Some of these possibilities are described later in the future work section.

Another aspect related to this is the speed of the implementations of new aspects in 'The Zoo' (the Grasshopper plug-in suite). Many private and professional contributors work to include new possibilities in terms of modules. A module integrating the EnergyPlus Air Flow Module (that could have been a huge benefit in this study) is for instance being developed currently[2]. The butterfly module for performing CFD calculations in Grasshopper using the OpenFoam engine has recently been released (mostly for testing so far). This might open for possibilities to couple this important aspect to the comfort simulation in the near future.

13.4 Future work

A lot of things in this study have only been dealt with on a superficial level. Thus there is a number of issues that would benefit from more in-depth studies in the future.

More Data on Thermal Comfort in 3rd Spaces

The discussions in this study are to a large extent based on logical deduction (as mentioned in the chapter on methods). Thus the reflections on how current thermal models might be adjusted to fit 3rd space conditions better are difficult to address properly. There is definitely a need of more measures, real life data from spaces that fall between the typical categories of indoor or outdoor spaces.

There is a need for examining the thermal expectations of occupants in 3rd spaces and the influence of certain parameters, spanning from outdoor conditions to the tectonics of the space. Also aspects like the adaptivity of occupants in terms of clothing and activity level adjustments would be interesting to evaluate.

Furthermore there is a need to compare the results of BPS tools in terms of local climate and comfort with measurements from built 3rd spaces, as it has been done for many tools regarding office and residential buildings.

[2] By Anton Szilasi. See https://github.com/mostaphaRoudsari/Honeybee/issues/506

Development of Analysis Methods That Include User Autonomy

Another interesting piece of future work would be to develop analysis methods or tools that would take user autonomy or adaptation in terms of clothing and activity level into account. Such a tool might for example be one that would fit in the Grasshopper/Honeybee suite. The idea would be to input a range of values for comfort analysis components instead of single fixed values.. The comfort rating would then be based on the amount of clothing or the activity level within the ranges that would fit the microclimate best at any time within the analysis period.

In connection to this it would be interesting to examine whether (and how) it could be possible to determine the range of e.g. clothing in general in 3rd spaces, and what parameters that influence such a range.

Another aspect of an analysis that include user freedom has to do with the possible locations for certain activities. Would it for instance be possible to define what areas an occupant is able to go to in pursuit of higher comfort given a certain activity? Maybe even considering if the space would be overfilled by occupants. Or how far the occupant would be *willing* to move to achieve higher comfort.

Ground Temperatures

It would be interesting to further study models for ground temperatures based on the work by Carneiro (2016). Especially a study of the ground temperatures in different climatic zones would be relevant. But apart from this, it would be interesting to see a wider strategy for implementation of the knowledge in simulations or a further implementation in Grasshopper than the very simple one used in this study.

Chapter 14

Bibliography

ASHRAE (2013). ASHRAE/ANSI Standard 55-2013 Thermal environmental conditions for human occupancy.

Bjerregaard Jensen, L. D. o. C. E. (2005). *Forsegling og symbiose*, 1st edn, Arkitektskolens Forlag, Copenhagen.

Błazejczyk, K., Jendritzky, G., Bröde, P., Fiala, D., Havenith, G., Epstein, Y., Psikuta, A. and Kampmann, B. (2013). An introduction to the Universal thermal climate index (UTCI), *Geographia Polonica* **86**(1): 5–10.

Bröde, P., Fiala, D., Blazejczyk, K., Holmér, I., Jendritzky, G., Kampmann, B., Tinz, B. and Havenith, G. (2012). Deriving the operational procedure for the Universal Thermal Climate Index (UTCI), *International Journal of Biometeorology* **56**(3): 481–494.

Carneiro, A. d. C. (2016). Simulation and Atrium Design.

Dansk Standard (2006). DS/EN ISO 7730 - Ergonomics of the thermal environment, *Technical report*.

Dansk Standard (2011). DS 418: Beregning af bygningers varmetab Calculation of heat loss from buildings.

Dansk Standard/CEN (2007). DS/EN 15251:2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.
URL: *http://sd.ds.dk.globalproxy.cvt.dk/Viewer?ProjectNr=M204572&Status=60.61&VariantID=&Page*

de Dear, R. and Brager, G. (1998). Developing an Adaptive Model of Thermal Comfort and Preference, *Ashrae Transactions* **104**: 145–167.
URL: *http://www.worldcat.org/oclc/246005746*

Fanger, P. (1970). *Thermal Comfort*, Danish Technical Press, Copenhagen.

Fiala, D., Havenith, G., Bröde, P., Kampmann, B. and Jendritzky, G. (2012). UTCI-Fiala multi-node model of human heat transfer and temperature regulation, *International Journal of Biometeorology* **56**(3): 429–441.

Havenith, G., Fiala, D., Blazejczyk, K., Richards, M., Bröde, P., Holmér, I., Rintamaki, H., Benshabat, Y. and Jendritzky, G. (2012). The UTCI-clothing model, *International Journal of Biometeorology* **56**(3): 461–470.

Hoyt, T., Stefano, S., Piccioli, A., Moon, D. and Steinfeld, K. (2013). Thermal Comfort Tool.
URL: *http://www.cbe.berkeley.edu/comforttool*

Humphreys, M. A. (1978). Outdoor temperature and comfort indoors, *Building Research and Practice* **6**(2): 92–105.

Humphreys, M. A. and Fergus Nicol, J. (2002). The validity of ISO-PMV for predicting comfort votes in every-day thermal environments, *Energy and Buildings* **34**(6): 667–684.

Knudsen, M. K., Jensen, L. B. and Nielsen, T. R. (2016). Master Thesis - Investigation of EKO-Canopy energy renovation concept for Swedish million program apartment buildings - A case study of Dragonvägen, *Technical report*, DTU, Lyngby, Denmark.
URL: *http://dtu-ftc.cvt.dk/cgi-bin/fulltext/sorbit?pi=%2F37640.802482.pdf&key=469581941*

Negendahl, K. (2015). Building performance simulation in the early design stage: An introduction to integrated dynamic models, *Automation in Construction* **54**: 39–53.
URL: *http://dx.doi.org/10.1016/j.autcon.2015.03.002*

Novak, M. (2013). Use of the UTCI in the Czech Republic, *Geographia Polonica* **86**(1): 21–28.

Pantavou, K., Theoharatos, G., Santamouris, M. and Asimakopoulos, D. (2013). Outdoor thermal sensation of pedestrians in a Mediterranean climate and a comparison with UTCI, *Building and Environment* **66**: 82–95.
URL: *http://dx.doi.org/10.1016/j.buildenv.2013.02.014*

Rutten, D. (2007). Grasshopper3D.
URL: *http://www.grasshopper3d.com/*

Sadeghipour Roudsari, M. and Pak, M. (2013). Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design, *Proceedings of the 13th International IBPSA Conference Held in Lyon, France Aug 25–30th*.
URL: *http://www.ibpsa.org/proceedings/BS2013/p_2499.pdf*

Schweiker, M., Brasche, S., Bischof, W., Hawighorst, M., Voss, K. and Wagner, A. (2012). Development and validation of a methodology to challenge the adaptive comfort model, *Building and Environment* **49**(1): 336–347.
URL: *http://dx.doi.org/10.1016/j.buildenv.2011.08.002*

US Department of Energy (2010). EnergyPlus Engineering Reference: The Reference to EnergyPlus Calculations, *US Department of Energy* pp. 1–847.
URL: *http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:EnergyPlus+Engineering+Refer*

Vila, L. F. (2016). Parametric Structural Design - Integration of Structural Verifications in the Early Design Phases.

Wojtach, B. (n.d.). F77 UTCI source code - based on original F90 UTCI source code of Peter Bröde.
URL: *http://www.utci.org/utcineu/utcineu.php*

Yang, W. and Kang, J. (2005). Acoustic comfort evaluation in urban open public spaces, *Applied Acoustics* **66**(2): 211–229.

Part V

Appendix