A Method for Driving the Solar Control Mechanism Selection

Christopher Nilsson & Vitaliya Mokhava

Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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

Examiner: Maria Wall (Energy and Building Design)
Academic supervisor: Henrik Davidsson (Energy and Building Design)
Industrial supervisor: Harris Poirazis (Inform Design)

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Abstract

Highly glazed spaces are continuously increasing in popularity due to architectural attractiveness. However, increased use of glass often jeopardizes thermal comfort in several ways and problem of overheating is one of them. A way to face this problem is to appropriately use solar control mechanisms. However, a proper selection of solar control mechanisms from an early design stage is a complex task that often can puzzle experienced building physicists, façade designers and architects.

In this project a method was developed, which drives the selection of appropriate solar control mechanisms based on analysis of overheating due to solar heat gains. The aim of the method is to maintain adequate thermal comfort levels in highly glazed spaces. Two thermal comfort models, Predicted Mean Vote and Adaptive Model, were chosen to set the thermal comfort boundaries included in the method. Moreover, in order to make the output of this method more realistic, the effect of direct solar component was considered as an adjustment to the mean radiant temperature. Three different types of solar control mechanisms have been investigated and assessed, those are solar control glass, interior and exterior fabric blinds.

The results present the overheating in annual overheating charts colored after the scaled range of temperatures for every hour of the year. As a result of the analysis, the appropriate solar control mechanisms are defined according to their performance in solving particular overheating problem. By that the method suggests solutions and helps the designer to understand the potential improvements that can be realized by implementing solar control mechanisms. The method aims to assist specialists with the selection process of solar control mechanism that respects the architectural vision without compromising the quality of thermal comfort.

Due to limitations, only three types of solar control mechanisms were included in this study and a future investigation of angular dependent shading devices would be a valuable addition to the method.

Acknowledgement

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Contribution

The development of the method was mainly performed in Excel and both authors contributed as a team during this process. Nevertheless, some parts needed to be divided in more detail between the authors. Vitaliya Mokhava was the main responsible for all dynamic thermal modelling simulations that were performed during the project and also for the preliminary study of solar control mechanisms that were used in the simulations. Christopher Nilsson made the preliminary study of thermal comfort and of appropriate models that were used later in the method. Christopher was also the main responsible for the validation of the method when the steps were defined. All steps and decisions taken during the project were made through discussions and the writing of the report was equally divided between the authors.

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Nomenclature

MRT – mean radiant temperature (ºC)

T_{air} – air temperature (ºC)

T_{op} – operative temperature (ºC)

T_{out} – outdoor temperature (ºC)

T_{rm} – running mean outdoor temperature (ºC)

RH – relative humidity (%)

V_a – air velocity (m/s)

I_{cl} – insulation of clothing (clo)

M – metabolic rate (met)

AD_u – Du Bois area, surface area of the human body

η – external mechanical efficiency of the body

P_a – partial pressure of water vapour in the ambient air

f_{cl} – clothing area factor

h_c – convective heat transfer coefficient

t_{cl} – mean temperature of outer surface of the clothed body

T_{comf} – comfortable operative temperature (ºC)

$T_{ed\text{-}1}$ – daily mean outdoor temperature one day before (ºC)

Ts,dir – direct solar transmittance

Ts, dif – diffused solar transmittance

$Ts, prim$ – primary solar transmittance

Ts, sec – secondary solar transmittance

Tv – visual light transmittance

g-value – solar heat gain coefficient

pp – percent points

Abbreviations

AM – Adaptive comfort Model

GWR – Glazing-to-Wall Ratio

IB – Interior Blind

EB – Exterior Blind

Low-e – Low Emissivity Glass

OF – Openness Factor

PMV – Predicted Mean Vote

PPD – Predicted Percentage of Dissatisfied

SCG – Solar Control Glass

SCM – Solar Control Mechanism

TGU – Triple Glazing Unit

VBA – Visual Basic for Application

1 Introduction

Highly glazed facades are an attractive and modern trend. From the point of view of architects, the use of large proportion of glass on the facades of office buildings contributes to architectural quality, as it creates the image of transparency and openness. At the same time, the users are attracted by the well daylit indoor environment with the increased view out (Poirazis, 2005). Besides the obvious benefits, highly glazed facades also induce numerous challenges to achieving thermal comfort for the occupants of the building.

1.1 Problem motivation

The problem of thermal comfort in highly glazed spaces have been investigated from different angles. Previously a research work was done within Lund University, which subject was climate and energy use in glazed spaces. This research underlined that thermal comfort of the occupant is influenced by a number of parameters and cannot be assessed by the analysis of the air temperature alone. The importance of solar shading use was motivated by the fact that thermal comfort in glazed spaces cannot be achieved solely by the use of ventilation or reduction of air temperature. It was also stated that it is necessary to study thermal comfort at the design stage, as that can help to define the best position of the occupant in the space (Wall, 1996).

A recent study was made of thermal comfort in transitory and semi-external spaces. Within this study a method was developed, which aims to assist the building designers in defining the measures to avoid the problem of overheating (Deliahmedova, 2016). Another study was made within the field of thermal comfort in highly glazed spaces, which suggested a method for the solar heat gains control by means of selective application of frit on the glazed facade (Stefanowicz & O’Donnell, 2016). Both methods have resulted in the development of the tools, which intended to be used during the preliminary design stage.

Even though it is clearly defined that solar shading is a necessary measure to provide thermal comfort in highly glazed spaces, the selection of the shading type is a complex task that often can puzzle experienced building physicists, façade designers and architects. Therefore, a method needs to be developed, which will combine the preliminary assessment of thermal comfort with the suggestion of the efficient solar control mechanism. The method should be formed as a “hands-on” design tool which is intended to be used by specialists and can potentially bring in better design solutions and lead to the improved indoor environment in highly glazed spaces.

1.2 Goals and Objectives

The aim of this project is to develop a method which drives the selection of appropriate solar control mechanism to improve thermal comfort in highly glazed spaces. In order to develop the method, a study of the solar control mechanisms is needed, as well as an investigation of thermal comfort models and comfort boundaries. The main questions that require investigation are: What are the parameters of thermal comfort in highly glazed spaces? When can thermal comfort be improved by means of solar control mechanisms? How to define when the problem of overheating can be solved by use of solar control glass alone and when the application of solar control blind is needed?

1.3 Limitations

Development of this method has not been focused on optimization of the use of solar control mechanisms for certain conditions. The number of solar control mechanisms investigated within the study was limited to three types.

The method considers thermal comfort and its parameters as the main topic, although some parameters covered in the standards were not included due to limitations of the study. Those are as follows: a) temperature asymmetry due to fluctuation of surface temperatures, b) draught effect and c) the effect of cooled and warm floors.

The method was not designed to handle the problem of cold discomfort by means of passive measures. Therefore, when performing dynamic thermal simulations heating was used to maintain lowest comfortable temperature. The study was limited to conditioned space types; therefore, the use of natural ventilation was not considered. Air cooling was introduced to cut the peaks of overheating.

As the development of the method was based on the analysis of the hourly data from simulations, some limitations were made to cover the most relevant scenarios. The simulations were performed for one location of the model with unchanged geometry and envelope construction. Only the window parameters were varied. The internal heat gains, as well as the occupancy schedule, remained the same in the performed simulations.

2 Background theory

The following chapter provides an overview of the problem of overheating in highly glazed spaces. The principle of energy transfer through the glazing and its effect on the occupant's thermal sensation is explained, as well as the principle of solar control solutions which can be applied to solve the problem of overheating.

2.1 Thermal comfort

2.1.1 Thermal comfort in highly glazed spaces

A window can affect the thermal sensation of an occupant in several ways, but with increased glazing area the impact of the window becomes even more significant. Large area of the glazing can cause a draught effect and temperature asymmetry due to fluctuation of its surface temperature, which occurs more often compared to the other interior surfaces. In this case, the occupant is also affected by radiant heat exchange with the surface of the window, and can experience discomfort of a different scale depending on the proximity to the glazed area (Lyons et al., 1999).

Except for the long-wave heat exchange, the occupant can experience the effect of the direct solar radiation, which increases the sensation of warmth as it hits the human body. Those two effects are especially crucial when the occupant has a sedentary activity and no possibility for adaptation. Both effects can be slightly reduced by cooling the air and the measures of solar control should be introduced (Lyons et al., 1999).

2.1.2 Principles of energy transfer

For a deeper understanding of the problem of overheating and its origin, the principle of energy transfer through the glazing is explained in this section. Three principles of energy transfer, convection, conduction, and radiation, are playing an active role in how transmitted solar energy affect the thermal conditions in the room. The principles of energy transfer are described beneath and visualized in Figure 1a:

1. Transmitted solar radiation, falling on the interior surfaces, is being absorbed, increasing their temperature.
2. Solar radiation absorbed by the exterior surface of the glass pane is conducted to the interior surface.
3. The heat absorbed by the surfaces is convected by air, increasing its temperature.

Figure 1b describes the processes of the heat exchange between the occupant and the room environment:

1. Long-wave radiation exchange between an occupant's body and the surrounding surfaces.
2. Absorption of short-wave radiation by the body of the occupant.
3. The effect of the room air temperature on the thermal balance of the body (Lyons et al., 1999).

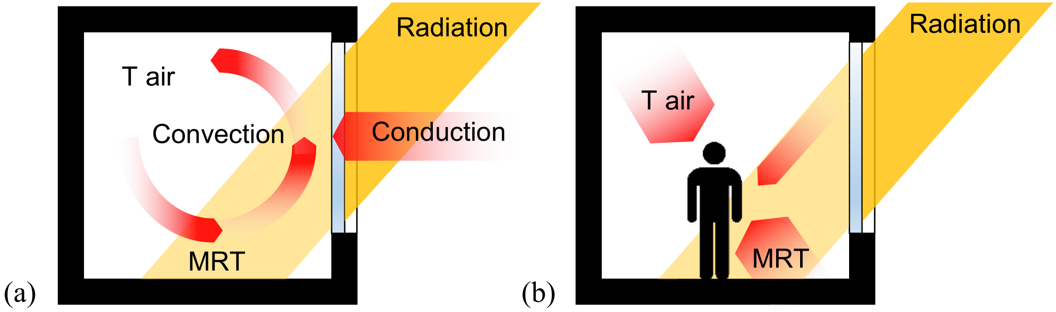


Figure 1. Principle of the solar energy transfer and its effect on thermal environment in the room (a) and on the occupant (b)

2.1.3 Thermal comfort parameters

“Thermal comfort is defined as the feeling of satisfaction with the thermal environment.” (Liébard et al., 2015)
On a physical level the sensation of thermal comfort is determined by a balance in the heat exchange between the human body and its surroundings. Several factors affect this balance.

Individual factors related to the occupant’s body are:

- metabolic rate – heat production by the human body, which is defined by the physical activity;
- clothing level – thermal insulation, which prevents the heat exchange between the surface of the human body and the surrounding atmosphere.

Environmental factors related to the occupant’s surroundings are:

- air temperature (T_{air}), which affects the heat loss from the human body by convection and evaporation;
- mean radiant temperature (*MRT*) of the surrounding surfaces, which affect the occupant by radiant exchange
- relative humidity (RH), which affects the heat loss from the surface of the body by convection and evaporation;
- air velocity (v_{air}), which affect the convection of heat from the surface of the human body.

Specific local conditions, such as draught, radiant asymmetry, direct solar radiation, possibility for adaptation also influence the perception of thermal conditions (Brophy et al., 1999).

2.1.4 Direct solar component and MRT

Direct solar radiation incident on the human body affects the perception of thermal comfort. Due to heat absorbed and accumulated by the human body, a lower air temperature is needed to provide thermal comfort at the presence of the direct solar component. Therefore, in summer as the air temperature and mean radiant temperature are increased, the direct solar radiation falling on the occupant can jeopardize thermal comfort (Lyons et al., 1999). The effect of the direct solar component on the thermal sensation of the occupant is illustrated in Figure 2.

Even though the presence of direct solar component is one of the factors that affect the thermal sensation of the occupant, it is not accounted for by the environmental standards, such as ISO and EN. The calculation of MRT adjusted for the effect of incident solar radiation was described in the method developed by Arens et al (2015). The MRT adjusted is also implemented in Oasys ROOM software (Oasys-software, 2017).

The effect of the direct solar component on the thermal sensation of the occupant is illustrated in Figure 2.

Figure 2. Effect of the direct solar component on the thermal sensation of the occupant

2.1.5 Dynamic thermal modeling

The principle of the dynamic thermal modeling is the simulation of the dynamic changes in the energy flow within the building. This method is used to predict the temperatures, heating and cooling loads, and the thermal comfort conditions accounting for the various conditions throughout the year. Dynamic thermal modeling for the building performance analysis can be done using various software, such as IDA ICE (Equa, 2017), Design Builder (Designbuilder, 2017) and Oasys ROOM.

In this study, Oasys ROOM software was used to assess internal thermal conditions of a single room. This environmental analysis software was developed for calculation of temperatures and comfort conditions for multiple positions of the occupant. MRT in this case represents not only the mean surface temperatures but also includes the effect of the solar radiation incident on the occupant.

The effect of the direct solar component on the MRT can be seen in Figure 3, where the results of simulations with ROOM are presented. The sunpatch falling on the surface of the floor is shown on the picture to the left. The resulted MRT, calculated for the points located 0.6 m above the floor, is shown on the picture to the right. The area with the rapid difference in the MRT represents the area where direct solar radiation is falling on the occupant and increases the sensation of warmth.

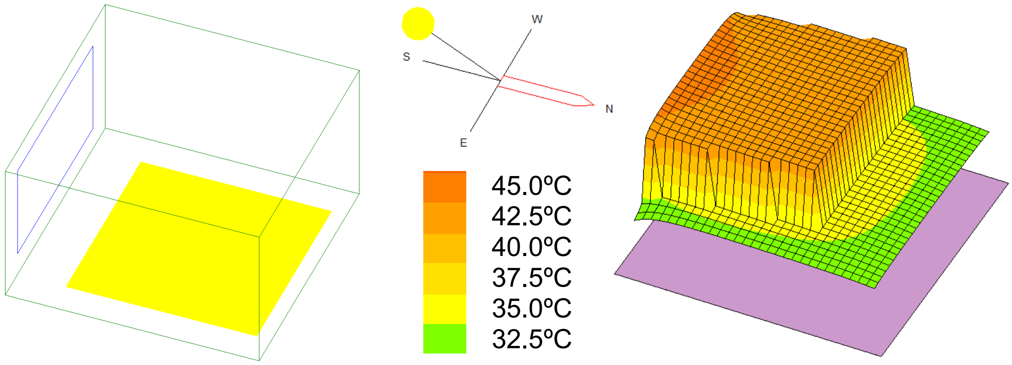


Figure 3. Visualisation of MRT accounting for the effect of the direct solar component

2.2 Thermal comfort models

In today’s practice of thermal comfort evaluation two methods are used, those are PMV (Predicted Mean Vote) index and AM (Adaptive Model). PMV and the connected PPD (Percentage of People Dissatisfied) index were developed by Fanger (1970). They are based on a comfort equation and an experimental evaluation of thermal comfort perception in uniform conditions. The AM is based on field studies and an adaptive approach which assumes that people will adapt to the environment when the possibilities are given (Nicol et al., 2012).

2.2.1 PMV model

The PMV index is taking six variables into account and the formula is developed based on the research with a climate chamber. The model uses a seven-steps scale from -3 to +3 to evaluate the sensation of thermal comfort, where 0 is neutral and -3 is too cold and +3 is too hot, the whole scale is presented in Table 1. Following six variables are included in the PMV formula:

- Air Temperature (T_{air})
- Mean Radiant Temperature (MRT)
- Air Velocity (V_{air})
- Clothing (clo)
- Activity (met)
- Relative Humidity (RH)

The formulas for calculation of PMV and PPD indices are given in the Appendix A.

Table 1. Thermal sensation scale

Index value	-3	-2	-1	0	+1	+2	+3
Thermal sensation	Cold	Cool	Slightly cool	Neutral	Slightly Warm	Warm	Hot

PPD is an index that is developed and based on the PMV index. Table 2 presents how the PMV and PPD indices correspond to each other.

Table 2. Correspondence between PMV and PPD

PMV	± 3	± 2	± 1	0
PPD / %	99	77	26	5

The PMV index was developed to be used in buildings with mechanical heating and/or cooling, thus when the occupants have limited possibilities to control the thermal conditions (Fanger, 1970). Therefore, when assessing thermal comfort in this type of buildings the standards recommend to use PMV-PPD indices (EN 15251, 2007) (CIBSE Guide A, 2006).

2.2.2 Adaptive model

The adaptive approach to thermal comfort is assessing temperatures indoors based on the outdoor temperature conditions. The adaptive model does not require information about the clothing, metabolic rate or relative humidity as the method previously described in the PMV section. Adaptive model (AM) is based on a behavioral approach where occupants of the building have a possibility for adaptation. Occupants tend to make themselves comfortable by adjusting clothing level, activity and posture to adapt to the thermal environment. Even in air-conditioned buildings, clothing level tend to be changed according to the outdoor conditions (Nicol et al., 2012).

The AM is based on field surveys where the occupants have the possibility to adapt when too high temperatures occur. The adaptation was made by adjusting the clothing or opening a window to increase the air velocity.

The AM is mainly supposed to be used in buildings without mechanical heating or/and cooling, but according to Nicol et al there have been no validated reasons that suggest why the adaptive approach cannot be used in mechanically conditioned buildings as well (Nicol et al., 2012).

2.3 Standards

There are three international standards handling thermal comfort and all are based on ISO 7730. This thesis is based on two of those three, which are the European EN 15251 and the British CIBSE Guide A. Both standards are considering PMV and AM as appropriate models to assess thermal comfort in buildings.

2.3.1 EN15251

EN 15251 is the European standard for assessing thermal comfort and it is based on ISO 7730. The demands on thermal comfort are divided into three categories which can be applied for different building types. The categories recommended in the standard can be seen in Table 3 (EN 15251, 2005).

Table 3. Categories within EN 15251

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings

PMV index is recommended to be used for mechanically conditioned buildings and AM for non-conditioned buildings. The three categories within the comfort models are presented in Table 4.

Table 4. Deviation between categories for PMV and AM

Category	I	II	III
PMV	± 0.2	± 0.5	± 0.7
AM / °C	± 2	± 3	± 4

2.3.2 CIBSE Guide A

CIBSE Guide A is the British standard which defines thermal comfort in buildings. As the European standard, CIBSE Guide A suggest that both PMV and AM are valid to assess comfort. However, the CIBSE Guide A differs from the other standards by also accepting the adaptive model for mechanically conditioned buildings. The formulas for AM are presented in Table 5, where the lower one is for conditioned spaces and the one above for non-conditioned spaces.

Compared to the three categories of comfort in EN1525 standard, the CIBSE Guide A has only two categories. For AM the standard recommends a deviation of ± 2 ºC from comfortable operative temperature as sufficient to accommodate the major part of the occupants. When the PMV index is used, it is suggested that for the first category the operative temperature ranges correspond to a PMV of ± 0.25, and for the second category a PMV of ± 0.5 can be accepted. The comfort categories within both standards can be seen in Table 5.

Table 5. Overview of thermal comfort assessment by the standards

	EN 15251	**CIBSE guide A**
Comfort categories	I, II and III	90% and 80% acceptancy
Use of PMV	Conditioned	Conditioned
Use of AM	Non-conditioned	Conditioned and non-conditioned buildings
AM	$T_{comf} = (0.33 \cdot T_{rm}) + 18.8$	$T_{comf} = (0.33 \cdot T_{rm}) + 18.8$ $T_{comf} = (0.09 \cdot T_{rm}) + 22.6$*
*For mechanically conditioned buildings		

2.4 Solar control mechanisms

Solar control mechanisms (SCM), such as solar control glass and shading devices, are an effective measure for the control of overheating. If SCMs are considered from an early design stage, they can help to provide thermal comfort for the occupant by means of passive measures. For effective use of SCMs, it is important to understand the basic principle of their solar energy transmittance. The following chapter presents an overview of the main properties and types of SCMs, which have been used in this study.

2.4.1 Mechanism of solar energy transmittance

Solar energy falling on a glazing surface is transmitted, absorbed and reflected in the proportions which depend mainly on the type of the glass and angle of the incident solar radiation (Liébard et al., 2015). In terms of solar heat gains the absorbed part of the solar radiation is transferred through the glazing unit by convection, conduction and radiation. These main principles of the solar energy transfer are presented in Figure 4.

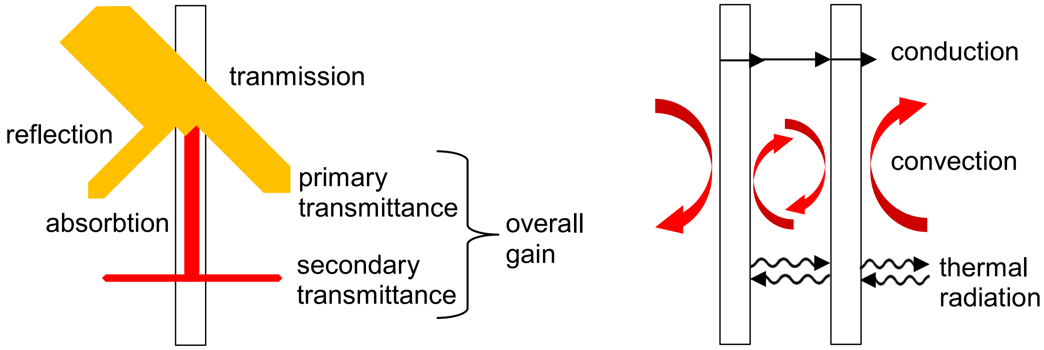


Figure 4. Principles of solar energy transfer through the glazing

The total transmitted solar energy is a compound of the primary and secondary parts. While the primary transmitted energy is the part of the incident energy which is directly transmitted through the glazing or shading, the secondary part represents the absorbed solar radiation which was then reradiated and convected towards the interior.

2.4.2 Solar control glazing

When choosing the glazing type, it is important to find a balance between the thermal performance and the visual transmittance of the system. Three basic methods are used to control the heat losses (Liébard et al., 2015):

a) assembling multiple panes in double and triple glazing units with the air gap in between, which provides an increased thermal resistance;
b) replacing the air in the gap with the low conductive gases, such as argon and krypton;
c) applying a low-e (low emissivity) coating to the glazing surface to reduce the heat loss by re-radiation to the outside and to maintain the comfortable temperature of the inner surface of the glass.

For the improved solar heat gain control, the additional methods can be applied, such as:

a) use of body tinted glass, which reduces the solar transmittance by absorption but blocks the daylight as well;
b) use of reflective coating, which can be applied to a clear or tinted glass to reduce solar gains by increased reflection;
c) use of spectrally selective coating, which reflects infrared solar radiation while transmitting a large portion of visible light.

To secure energy efficiency and to improve thermal comfort the described measures are usually applied in combination. For instance, in double or triple glazing units, a selective coating and one or two low-e coatings can be applied.

Low-e coating alone can be improved to have a broad range of solar control characteristics and at the same time maintain a low thermal transmittance (Commercial windows, 2015). From Figure 5 the positive effect of selective low-e coating on the reduction of the transmitted solar energy can be seen in comparison with low-e coating and clear glass, while almost the same light transmittance can be ensured.

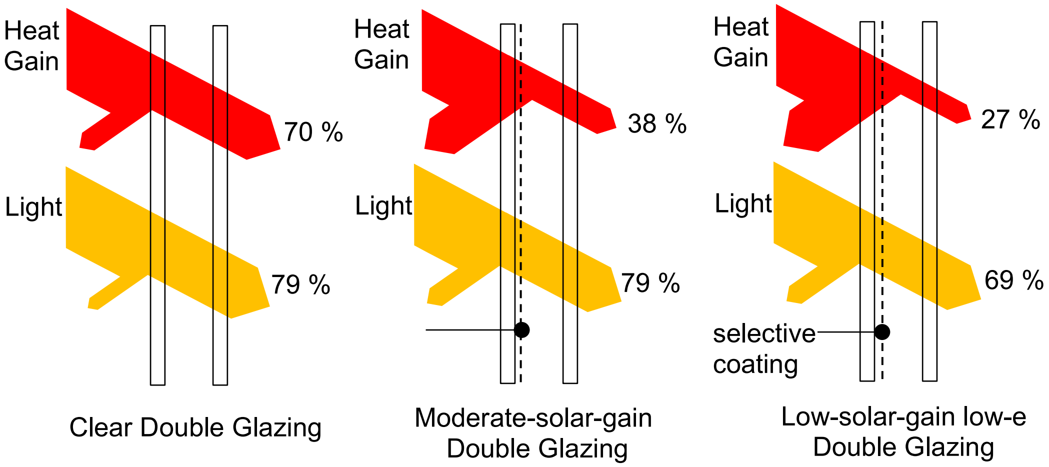
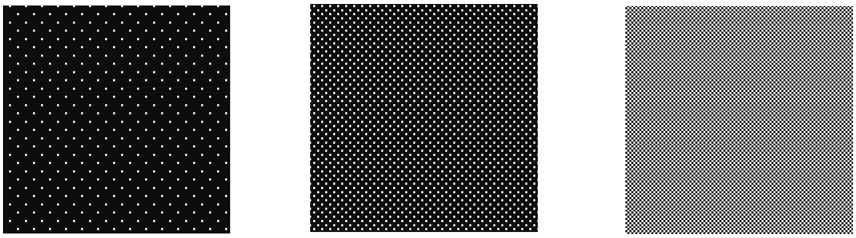


Figure 5. Solar and visual light transmittance of clear glazing, glazing with low-e and spectrally selective low-e coatings

2.4.3 Solar control blinds

While the solar control glazing provides constant effect on the reduction of solar heat gains during the year, the use of movable solar control blind can improve the shading effect when it is needed. In addition, it can protect occupant from the direct solar irradiation, which level is especially high in summer (Kuhn, 2016). Although movable shading devices with low solar transmittance, such as solar control blinds, are an effective measure and can significantly reduce the view out. Therefore, the combination of glazing type and blind type should be carefully selected, so the blind will not be used too often.

The performance of the roller blind in the solar gains control depends on the reflectance of its outer surface (Kuhn, 2016). The openness factor (OF), presented in Figure 6, defines the direct solar transmittance, visual light transmittance and possibility of visual contact with outdoors.



OF = 5 % OF = 20 % OF = 50 %

Figure 6. Openness factor of the fabric solar control blinds

The position of the blind is the matter of aesthetics, durability and thermal comfort. When choosing an exterior position of the blind, its influence on the façade design and possibility for maintenance should be considered. Interior blinds provide easier manual control, maintenance and therefore have lower cost (Liébard et al., 2015). In terms of providing thermal comfort exterior shading is the most effective, as it blocks solar radiation before it reaches the room (Kuhn, 2016). Interior shading in its turn might cause the increase of air temperature, as it absorbs the radiation transferred through the glazing. The surface temperature of interior blind can itself affect MRT and, therefore, thermal comfort of the occupant (Liébard et al., 2015).

3 Methodology

The main task of this study was to develop a design method which drives the solar control mechanism selection for highly glazed spaces. The purpose of the method is to give the user advice on how to choose appropriate SCM to achieve desired thermal comfort in the occupied space without running multiple simulations. The following chapter describes the process of the method development, from collecting and analysing data to setting the comfort boundaries and driving the SCM selection.

3.1 Project structure

In this section, the process of the study is illustrated and described. The project was divided into four phases, as illustrated in Figure 7. The first two phases were needed to gather enough information and knowledge to create the steps and to set the boundaries for the method. Phases 3 and 4 include a description of the method itself and the validation of it.

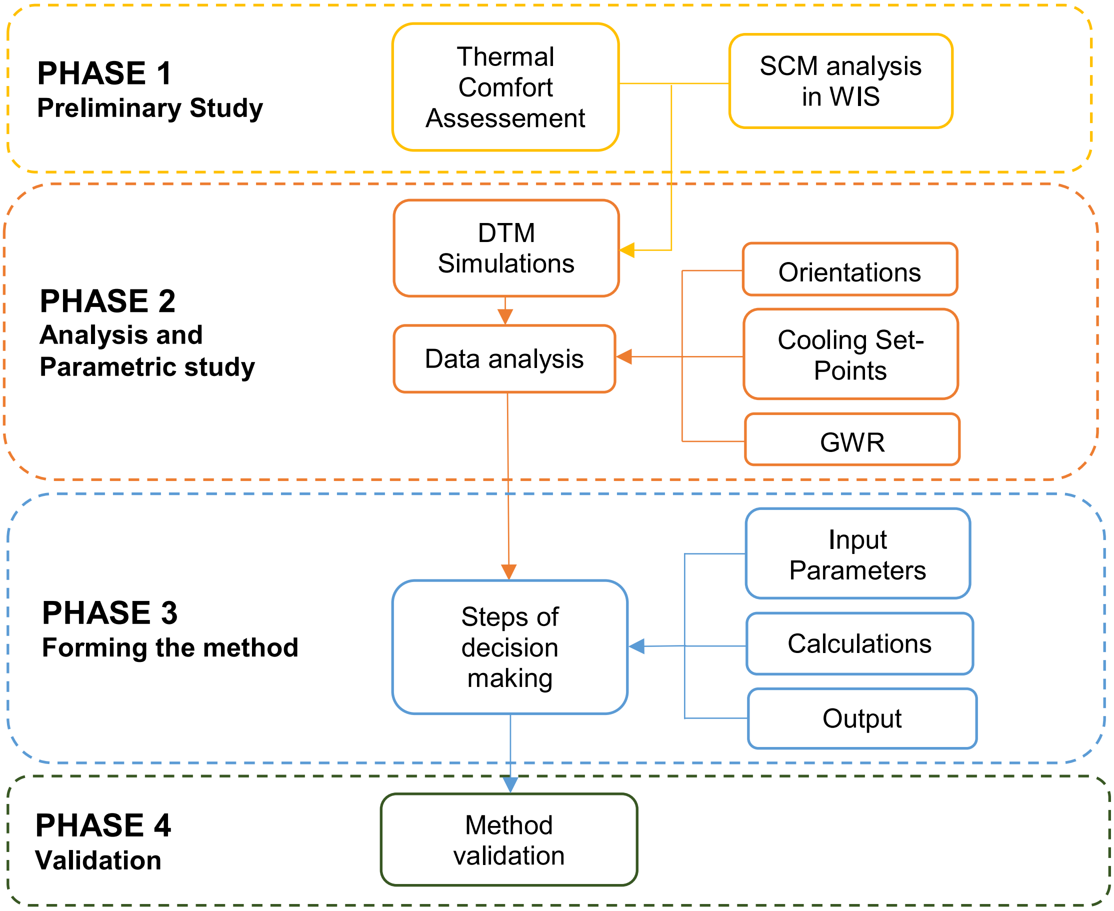


Figure 7. The development of the method divided into processes

Phase 1 “Preliminary study” contains the parts which are the base of the development of the method. The analysis of SCMs and their properties was made with the purpose to build up a database which can be used to drive the SCM selection in the method.

Thermal comfort assessment includes investigation of appropriate thermal comfort models. The aim of this part was to decide on the amount of thermal comfort models to be included and how to choose between them.

Phase 2 contains three parts: DTM simulations, data analysis and parametric study. The DTM simulations are further explained in section 3.3.1. In data analysis, the way of analysing data is described by presenting the parameters that form the method, and introducing the strategy of scaling and weighting the parameters. The parametric study includes variations of three variables that affect the intensity of overheating.

In Phase 3 the method itself is presented and divided into four parts. Input parameters are specified in the first part. Calculations, on which the method was based, are described in the second part. In the output, the third part, graphs are presented to give the user an overview of the results, this is further explained in section 3.4. Steps of decision making are the core of the method, where an advice about the SCM is given.

The final Phase is the validation of the method. Here the data from the simulations was used to check if the suggestions provided in Phase 3 are reasonable and, which is the most important, if the required thermal comfort is achieved.

3.2 Preliminary study

In the preliminary study two parts are included, those are analysis of SCMs and investigation of appropriate thermal comfort models. The purpose of this phase was to gather enough information and knowledge to be able to start the development of the method.

3.2.1 Analysis of solar control mechanisms

The analysis of appropriate SCMs was made in WIS (Window Information System), a steady-state software tool which determines the thermal and solar characteristics of window systems and window components (WIS Software, 2017). WIS was used to assess the physical performance of the glazing units and solar control fabrics by analysing their solar and visual transmittance.

The types of SCMs that have been chosen for the analysis can be generally described as solar control glass, interior and exterior fabric roller blinds. The types of SCMs have been divided into three categories where each category is specialized in solving a certain extent of overheating. Triple glazing units were used in all cases and a glazing unit with low-e coating was set as a reference case to compare the other SCMs with.

Table 6 and Table 7 present the studied SCMs and their parameters. More detailed information about the types of glazing units and solar control blinds can be found in Appendix B, where the specific parameters are given.

Table 6. Solar control glazing units and their properties.

	Solar Control Glass	**Solar Transmittance / %**		**Visual Transmittance / %**
		Primary	**Secondary**	
Reference Case	Iplus top 3 (Low-e)	36	11	70
Solar Control Glass	Ipasol neutral (SCG 1)	23	8	61
	Ipasol ultraselect (SCG 2)	17	6	54

Table 7. Solar control fabric blinds and their properties.

	Solar Control Blind	**OF / %**	**Emissivity indoors / %**	**Solar Transmittance / %**	**Visual Transmittance / %**
Interior Fabric Blind	OHM (IB 1)	10	60	19	18
	Duroscreen (IB 2)	5	60	5	5
Exterior Fabric Blind	Soltice (EB 1)	14	80	22	20
	Sunworker (EB 2)	5	80	5	6

The parameters of the solar control glass are presented as follows: a) the amount of beam solar radiation transmitted into the room, expressed as primary solar transmittance, b) the amount of absorbed solar radiation that is reradiated and convected into the room, expressed as secondary solar transmittance and c) the visual transmittance. Reference case Low-e glazing unit has high transmittance of beam solar radiation, high amount of absorbed energy which is reradiated indoors and high visual transmittance compared to the other two solar control glazings. The main difference between interior and exterior fabric blinds are the emissivity of absorbed energy, as for the interior blind it is lower.

In order to reach a desired solar transmittance of the window system, all glazing units were studied in combination with the interior and exterior fabric blinds. Figure 8 presents the combinations of SCMs that have been simulated and assessed.

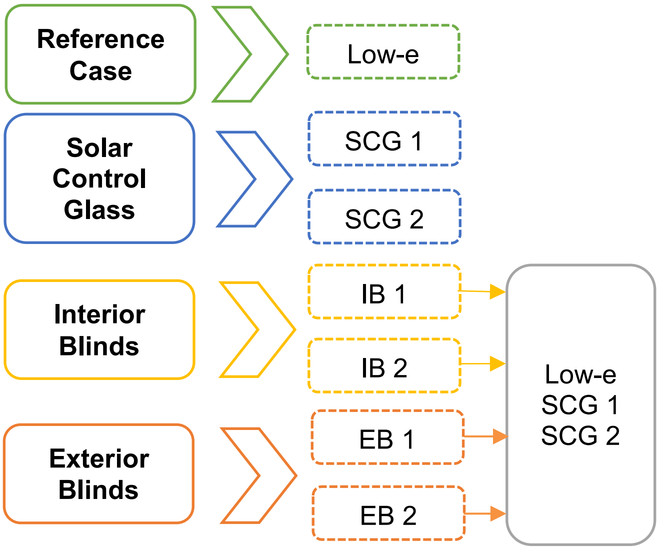
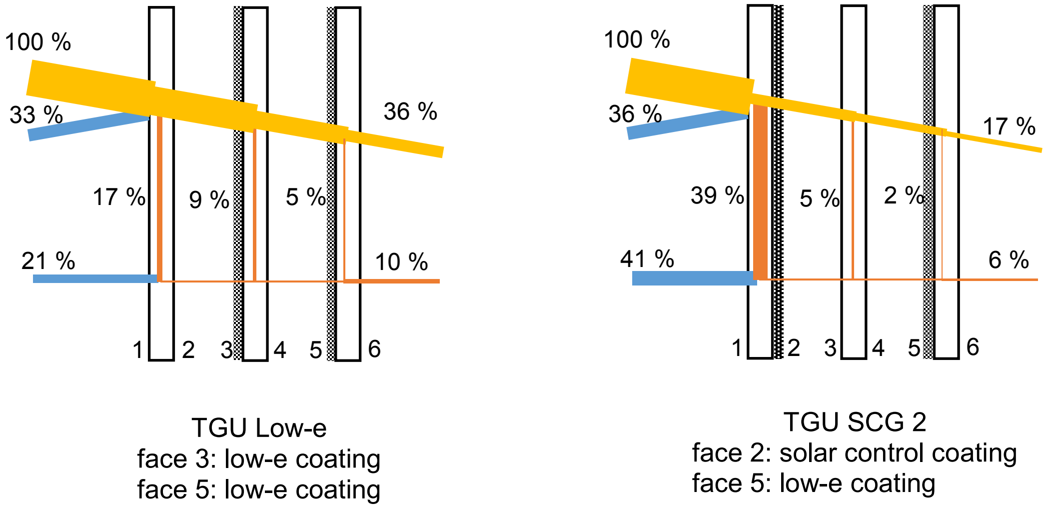


Figure 8. Studied combinations of solar control mechanisms

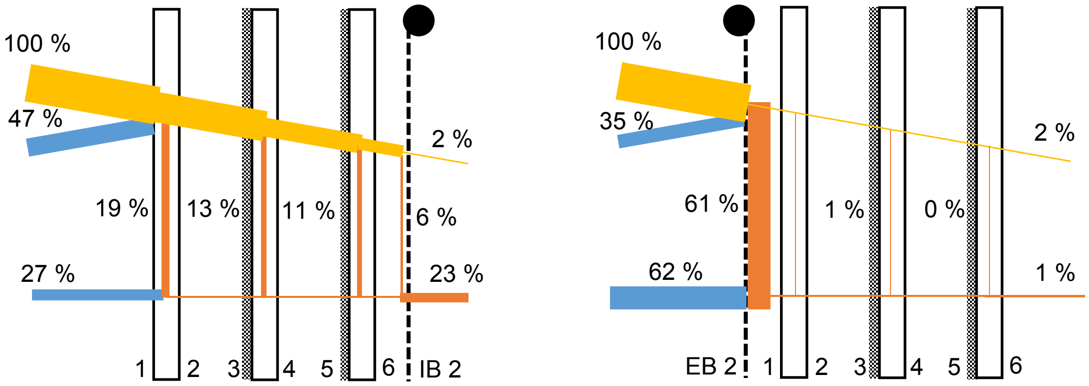
From Figure 9 and Figure 10 the main solar control properties of the studied SCMs can be seen and compared with each other. The low-e triple glazing unit is presented alone and in combination with the most effective interior and exterior solar control blinds. One solar control glazing unit, SCG 2, is presented to illustrate the main difference in handling solar energy compared to the low-e glazing unit. The face of the surface, where the coating is positioned, is indicated. Primary and secondary transmittance are expressed in yellow and orange color respectively. Blue color stands for total reflected and emitted solar energy.



TGU Low-e
face 3: low-e coating
face 5: low-e coating

TGU SCG 2
face 2: solar control coating
face 5: low-e coating

Figure 9. Solar transmittance of the low-e and solar control glazing units



TGU Low-e with Interior blind 2
face 3: low-e coating
face 5: low-e coating

TGU Low-e with Exterior blind 2
face 3: low-e coating
face 5: low-e coating

Figure 10. Solar transmittance of the low-e glazing unit with interior and exterior solar control blinds

3.2.2 Thermal comfort assessment

One adaptive model and one thermal index were used to assess comfort in this method. The EN 15251 standard recommends using PMV index for conditioned and AM for non-conditioned spaces. However, since a second alternative of using AM for conditioned spaces is presented in the CIBSE Guide A, this alternative was included in this study. Figure 11 presents a process chart that describes the thermal comfort models which are included in this study and the conditions when they are recommended to be used. The thermal comfort models are described in detail in the following sections.

Based on the type of the space and the possibility of the occupant for adaptation, calculations for the thermal comfort models have been implemented in Excel for further development of the method and solar control mechanism selection.

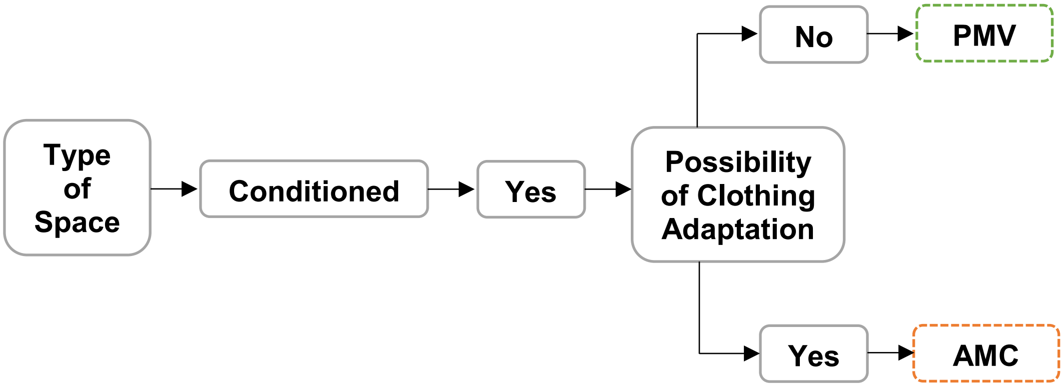


Figure 11. Chart describing recommended conditions for the selection of thermal comfort model

PMV

The EN 15251 standard specifies that the PMV index is only recommended for assessment of thermal comfort in mechanically heated and/or cooled buildings. In this method PMV was used for spaces where a mechanical system controls the maximum and the minimum indoor temperature and the adaptation possibilities are limited.

The six parameters included in the PMV index are represented in this method and can be varied by the user of the method. The hourly values for MRT and T_{air} are needed to be inserted by the user from a DTM simulation of the chosen room. Clothing, activity, v_a and relative humidity can be changed by the user to achieve the desired conditions. However, the EN 15251 standard recommends to use a relative humidity of 50 % and low air velocities. A maximum air velocity of 0.8 *m/s* is allowed.

Results for both PMV and PPD are presented in the method. The calculations for indices were made by using computer code included in ISO 7730 suited for Visual Basic for Application in Excel (ISO 7730 standard).

In Table 8 the boundaries for operative temperature, PPD and PMV for three comfort categories are presented, as recommended by EN 15251. The values are given for single and landscaped office with sedentary activity, corresponding to approximately 1.2 *met*. Recommended clothing level is also given for heating and cooling seasons.

Table 8. Categories of thermal comfort for PMV and PPD indices

Category	**Operative temperature / ºC**		**PPD / %**	**PMV boundaries / -**	
	Minimum for heating season, ~ 1.0 *clo*	**Maximum for cooling season, ~ 0.5 *clo***		**lower**	**upper**
I	21	25.5	<6	-0.2	0.2
II	20	26	<10	-0.5	0.5
III	19	27	<15	-0.7	0.7

Figure 12 shows the comfort ranges of PMV when considering *MRT* and T_{air} for all three categories. The condition of *MRT* and T_{air} to have maximum of 5 ºC difference is used, as recommended by ISO 7730. If a combination of the temperatures is within the yellow field and one of the blue fields at the same time, comfort is reached. For an example if T_{air} is 24 ºC and *MRT* is 25 ºC comfort of category I is reached.

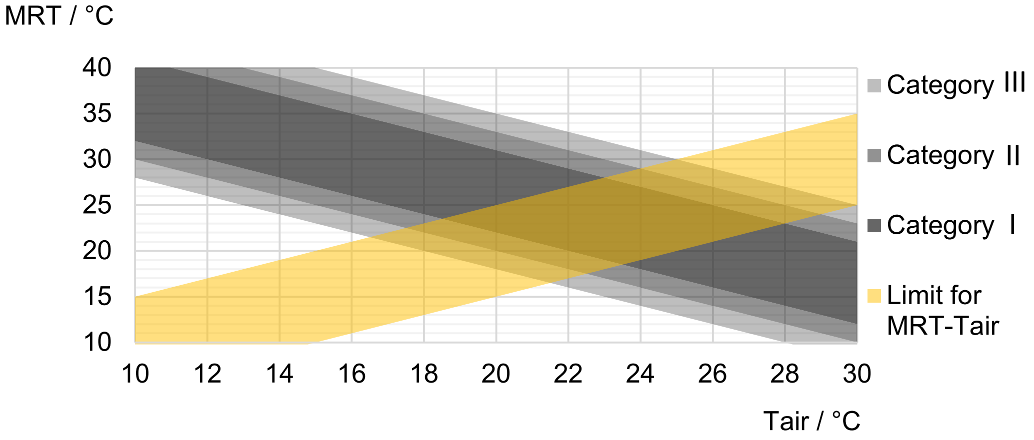


Figure 12. Combination of MRT and Tair for PMV comfort categories I, II and III

AM Conditioned spaces

CIBSE Guide A is the only standard that includes Adaptive Model for conditioned spaces. The AMC is based on the operative temperature (T_{op}) and the running mean outdoor temperature (T_{rm}), which are presented in Equation 1 (ISO 7726, 1998) and 2. The operative temperature is calculated by using the T_{air}, *MRT* and v_{air}, as shown in Equation 1.

$$T_{op} = \frac{MRT + T_{air} \cdot \sqrt{10 \cdot v_{air}}}{1 + \sqrt{10 \cdot v_{air}}} \tag{1}$$

As previously mentioned, T_{rm} is the running mean outdoor temperature, $T_{ed\text{-}1}$ is the daily running outdoor temperature one day before, $T_{ed\text{-}2}$ two days before and so on up to seven days before. The α-value is a constant between 1 and 0, in this case it is equal to 0.8, as recommended by the EN 15251 standard.

$$T_{rm} = (1-\alpha) \cdot (\mathrm{T}_{\mathrm{ed}-1} + \alpha \cdot T_{ed-2} + \alpha^2 \cdot T_{ed-3} + \ldots + \alpha^6 \cdot T_{ed-7}) \tag{2}$$

Figure 13 presents the upper and lower limits for the three comfort categories within AMC, for T_{comf} as a function of T_{rm}. The T_{comf} defines upper and lower comfort levels in the AM formulas and refers to the T_{op}, which makes T_{op} the parameter that defines comfort when AM is used. Even though the CIBSE Guide A does not specify the categories of comfort for AMC, the boundaries have been set in correspondence with AM for non-conditioned spaces, which is described in EN 15251. This is an assumption that was done for the further method development.

The boundaries for the three categories are formed, therefore, by expanding the comfort limits by 1 °C and 2 °C for categories II and III respectively. The T_{rm} have been limited to be within the range of 10 °C to 30 °C for upper limits and 15 °C to 30 °C for lower limits according to EN 15251. The computer code used for AMC upper and lower limits can be seen in Appendix D.

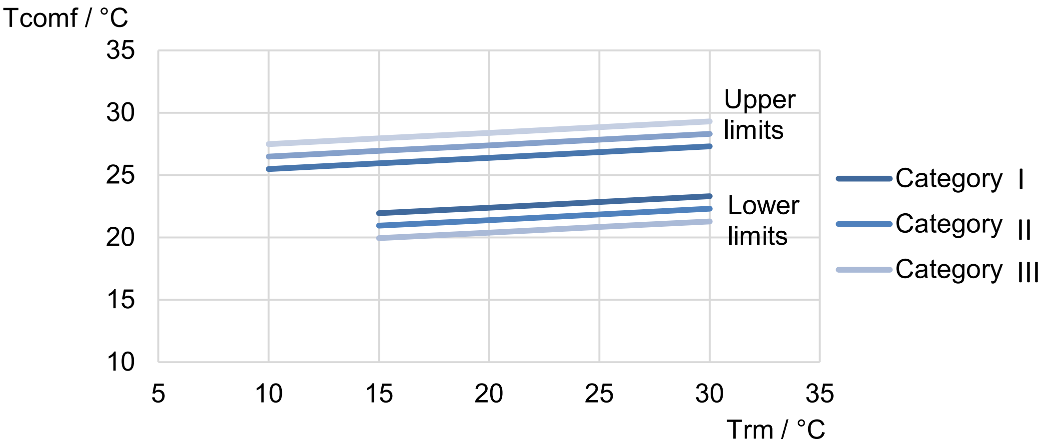


Figure 13. Comfort operative temperature limits for AMC depending on outdoor running mean temperature

Figure 14 shows the *MRT* as a function of T_{air} within the comfort categories of AMC. As it was previously shown in Figure 13, comfort is reached if the combination of the temperatures is within the yellow and any of the blue fields at the same time.

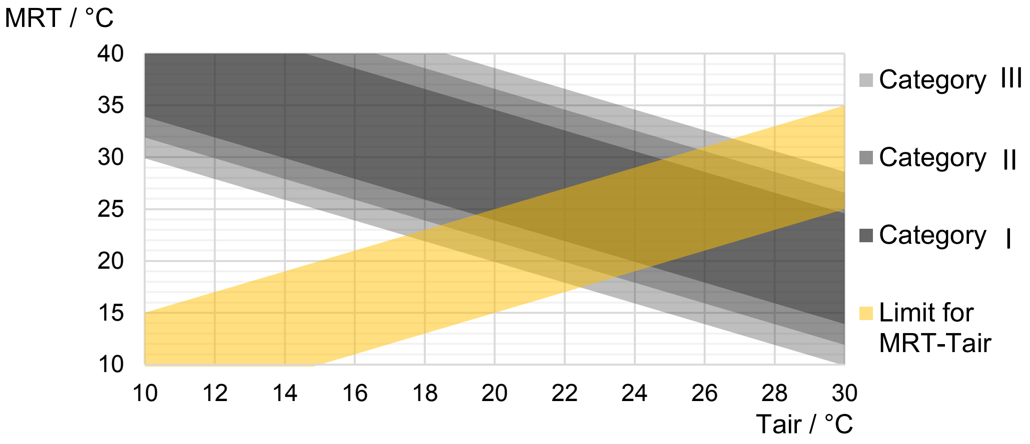


Figure 14. Combination of MRT and T_{air} for AMN comfort categories I, II and III

3.3 Data analysis and Parametric study

This chapter describes the parameters and data, which were used in the process of the method development, and the principle of the data analysis. The input parameters and output data of the DTM simulations are firstly described. Then the principle of the data analysis and the developed comfort scale is presented. The effect of changing the input parameters was studied on the example of several cases, which are included in the parametric study.

3.3.1 Dynamic Thermal Modeling

In order to assess the internal thermal conditions of the reference case throughout the year, dynamic thermal simulations were made using Oasys ROOM software. An office room was used as a reference case for the study. A south facing façade was represented by a low-e triple glazing unit with GWR 100 %. The geometrical parameters of the room model can be seen in Figure 15. Position of the occupant, for which thermal comfort was assessed, is located in the centre of the room at a height 0.6 *m*, as defined by the software, and marked as a dot P_1. Input parameters and output data are described below.

Input parameters:

- Occupancy and internal heat gains for single office according to the CIBSE Guide A standard
- Cooling set point 26 °C
- Heating set point 22 °C
- Weather file: Stockholm Arlanda
- Running period: year

Output data:

- Air temperature, average for the room
- Mean radiant temperature, specified for the occupant position
- Total incident and transmitted solar radiation, measured per area of the glazing
- Dry bulb temperature outdoors

Hourly output data from the simulations was required as an input for the developed method. Detailed input data used for simulations with Oasys ROOM software can be seen in Appendix B.

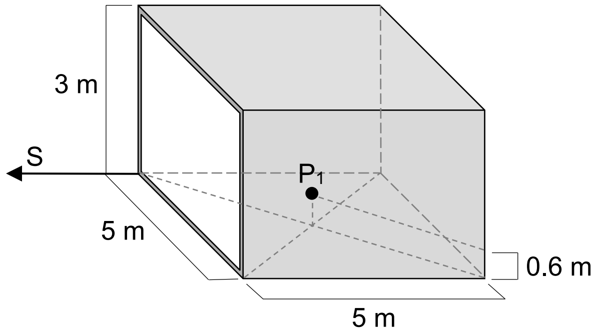


Figure 15. Model of the reference case and the point P_1, representing the occupant position

3.3.2 The principle of data analysis

In the analysis of thermal comfort parameters, every occupied hour was considered. When assessing comfort using the two included comfort models, PMV and AM, there are some differences in what parameters to base the analysis on. The analysed parameters are presented in Table 9.

Table 9. Data analysis to define comfort levels

Parameter	**Comfort Model**
PPD	PMV
$MRT\text{-}T_{air}$	PMV, AM
Direct transmitted radiation	
T_{op}	AM
T_{op}-*Upper limit*	

PPD is simply an expression of PMV, meaning predicted percentage dissatisfied. In this method, PPD is used to express the different levels of overheating to let the user get an overview of the conditions in the room also when overheating occurs.

$MRT\text{-}T_{air}$ is a central parameter of this method. By analysing this parameter, it is possible to make a conclusion about the solar control measures needed to prevent overheating. In the ISO 7730 standard, the tables are presented showing how the parameters within PMV can be varied. It is suggested that a maximum difference between *MRT* and T_{air} to provide comfort is 5 °C. This is used as a guidance in this method during the decision-making part of the method.

The parameter of direct transmitted radiation is important in both comfort models. It is used to find the critical hours when overheating occurs due to excessive amount of solar radiation transmitted through the glazing unit. The direct transmitted radiation can also provide comfort during hours when it is too cold; however, this effect was not accounted for in this method.

T_{op} is the operative temperature for a specific position in the room, and it is depending on the T_{air}, *MRT* and the v_{air} which can be seen in Equation 1 in section 3.2.2. T_{op} is also used to define T_{comf} when AMC is used.

T_{op}-*Upper limit* is the temperature difference between the operative temperature in a certain position of occupant at the certain hour and the AM upper limit. When this variable is positive it indicates an overheating problem.

3.3.3 Scaling and Weighting the parameters

Within this method, a scale was developed to weight the parameters and to define the thermal conditions when temperatures are outside the comfort categories, which are provided by the standard. Except for the three categories of comfort, the developed scale includes four ranges of overheating and one range that is indicating cold discomfort. In Table 10 the scale for each comfort model is presented. The scale was developed to be used together with an overheating chart that is explained further in section 3.4.3. By using the scale, it is possible to get a quick overview of when and of what degree overheating occurs over the year.

Each scale represents itself a range of values for a specific parameter of thermal comfort. The same scale has been used for PMV and AMC, but the ranges for the parameters were defined in different ways.

Table 10. Scale of thermal comfort

Sensation	Cold	Comfort					Slightly warm	Warm		Hot
Scale	0	3	2	1	2	3	4	5	6	7
PMV range / -	- 0.7	- 0.5	- 0.2	0.2	0.5	0.7	1	1.5	2	
AMC, T_{comf} range / °C	*Lower - 2*	*Lower - 1*	*Lower*	*Upper*	*Upper + 1*	*Upper + 2*	*Upper + 3*	*Upper + 4*	*Upper + 5*	

The scale 1, 2 and 3 represents the boundaries of comfort categories I, II and III, which have been described previously in section 3.2.2 for both PMV and AMC. The scale of 0 stands for cold discomfort and contains all the values below the lower limit of comfort category III.

When using PMV, the EN 15251 have been used to define the boundaries for scale of overheating beyond the three comfort categories. This standard connects the thermal sensation with PMV index, as it was presented previously in Table 1, section 2.2.1. The thermal sensation for PMV is defined as follows: 1 is slightly warm, 2 is warm and 3 is hot. PMV of 1 and 2, therefore, have been used in the developed scale as the upper boundaries for scale 4 and 6 respectively. As the step of PMV from 1 to 2 would be too big to define one scale of overheating, the PMV of 1.5 was introduced as an upper boundary for scale 5.

The thermal comfort parameter for AMC, $T_{comf,Upper}$, was used as a base for the scale. The upper boundary for each scale was defined by a gradual increase of the upper comfortable temperature by 1 °C.

3.3.4 Parametric study

The parametric study was performed for the reference case with cooling set point of 26 ° C and south facing glazing with glazing-to-wall ratio (GWR) of 100 %. The parameters have been varied only for the reference case. The effect of the studied SCMs on thermal comfort have been investigated for all cases in the parametric study. An overview of the parametric study is presented in Figure 16.

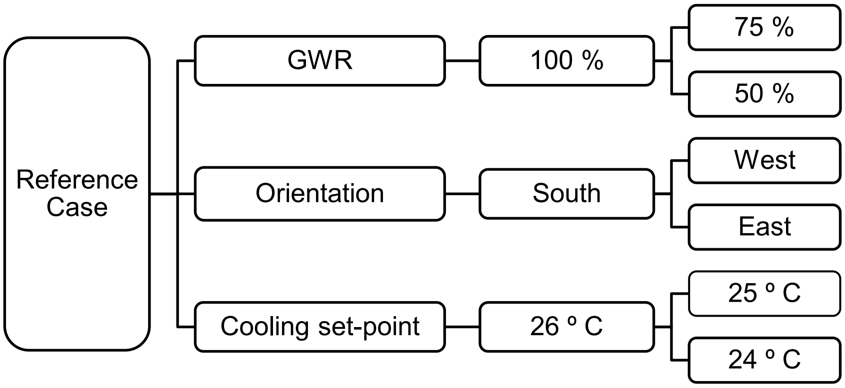


Figure 16. Overview of the parametric study

GWR was chosen to show the relative effect of reduced solar gains on thermal comfort improvement by means of changing the façade design. The reduction of GWR can be a necessary measure when the problem of overheating cannot be solved by means of solar control glazing and blind. GWR of 75 % and 50 % have been considered as reasonable options for the parametric study to make a comparison with fully glazed facade.

South orientation of the façade has the most exposure to direct solar radiation and the highest possibility for overheating problems during noon. Therefore, east and west orientations were chosen to perform the parametric study for to analyse the effect of higher exposure to morning and evening sun.

The analysis of cases with varied cooling set-points was performed to show the effect of reduced T_{air} on thermal comfort. This parameter was studied to analyze the relation between T_{air} and MRT and to distinguish the origin of the overheating problem.

3.4 Forming the method

The method of driving the SCM selection was divided into four stages, which were implemented in Excel spreadsheet and presented in Figure 17. In the first stage the input parameters, on which the analysis is based on, are specified by user of the method. In the second stage the input parameters are used to calculate PMV, AMC and the variables needed for the steps of "Decision making" in stage four. After that, the calculated data is used in the third stage to create informative graphs of the results. The fourth stage "Decision making" presents the three steps which are used by the method to suggest the SCM solutions.

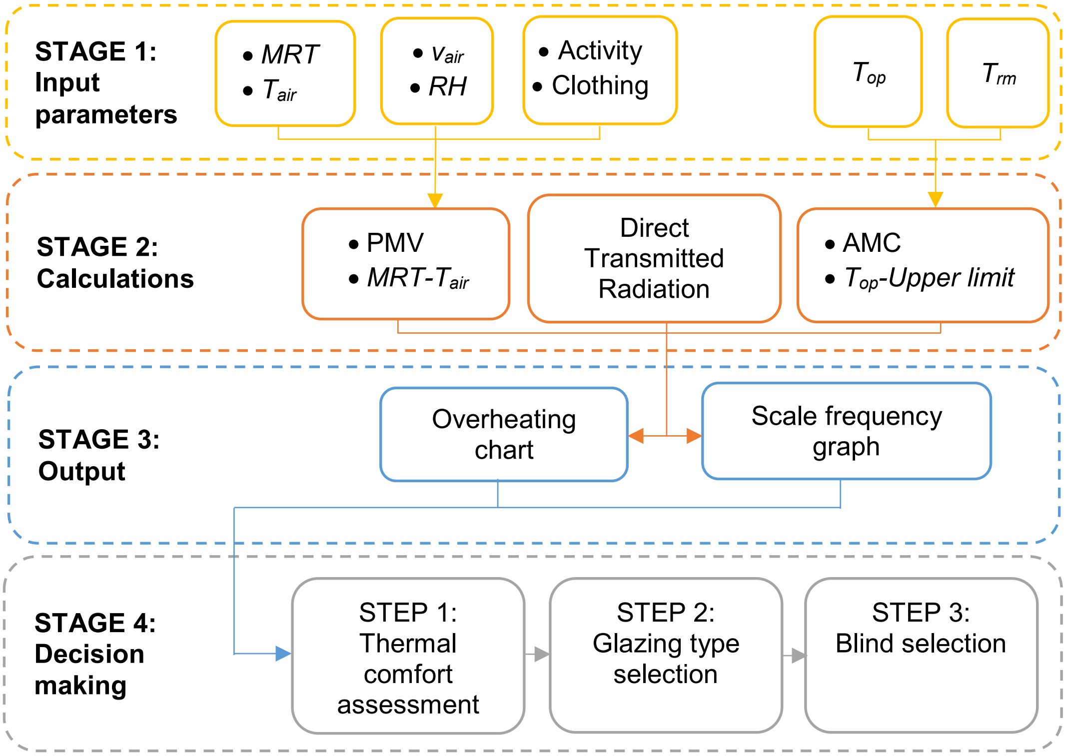


Figure 17. Stages of the method

3.4.1 Stage 1: Input data and parameters

In this stage, the input hourly data and the parameters for the desired comfort model are defined and inserted. For the PMV index there are six parameters to consider, while the AMC requires three parameters, as it shown with dots in Table 11. The hourly values for T_{out} should be provided from the weather data file. The hourly values for T_{air} represent the average air temperature in the room, while *MRT* should be specified for the position in the room where the occupants are expected to be. The limits for the input parameters are defined by the EN 15251 standard and presented in Table 11.

Table 11. Parameters to consider when assessing thermal comfort

Parameter	**PMV**	**AMC**	**Limits**	**Duration period per value**
Relative Humidity / %	●		0 - 100	Yearly
Metabolic rate / met	●		0.8 - 4	Yearly
Clothing / clo	●		0 - 2	Seasonal
Air velocity / m/s	●		0 - 1	Yearly, Hourly
MRT / °C	●	●	10 - 40	Hourly
T_{air} / °C	●	●	10 - 30	Hourly
T_{out} / °C		●	-	Hourly

Note that hourly values are needed for all temperatures and are recommended to be taken from the results from a DTM simulation for the desired case. Therefore, the internal gains are defined in the DTM simulation and already accounted for in the acquired temperatures.

The type of space is indirectly defined while inserting the input data. For the calculation of the PMV index, clothing and metabolic rate are the main parameters that define the type of space that will be assessed. When AMC is chosen as the comfort model, the space type is not important to specify, thus it is dependent on temperatures only.

Both the PMV index and AMC have three comfort categories, which are implemented in the method. For the user of the method it is possible to choose the desired comfort category before all the hourly values are inserted in the tool.

Additionally, hourly values for the transmitted direct solar radiation are needed for the process of selecting an appropriate SCM in the decision-making part of the method. The user of the method can also specify an occupied hours during the day. Further annual assessment, therefore, will be done for the occupied hours only.

3.4.2 Stage 2: Calculations

In Stage 2 all the variables needed to perform Stage 3 and 4 are calculated. Firstly, the PMV and AM limits are calculated to be used in the informative graphs, which are created in Stage 3. Secondly, $MRT\text{-}T_{air}$ and T_{op}-*Upper limit* are calculated to be used for selection of an appropriate blind in Step 3 within the “Decision making” stage.

The last parameter presented in this stage is the direct transmitted solar radiation. This parameter is used to find the day in summer with highest transmitted radiation.

3.4.3 Stage 3: Output

The core of the overheating analysis is an overheating chart, which was developed in this method and shown in Figure 18. This chart is based on the scale, previously described in section 3.3.3, where each color represents the expected human sensation of the indoor temperatures.

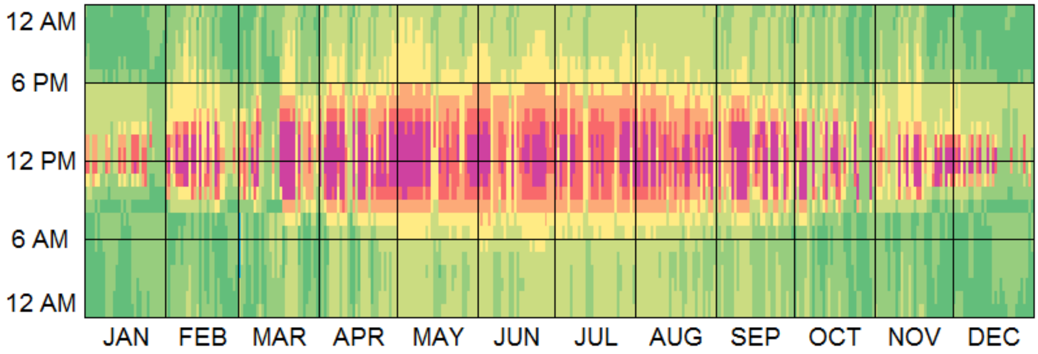


Figure 18. Example of an Overheating chart

The coloured chart makes it possible to see the pattern of overheating and in which season and time of the day it occurs. The method is mainly based on analysis of overheating patterns plotted in this chart when using different SCMs.

In addition to the overheating chart a "Scale frequency graph" was created. An example of this graph is shown in Figure 19. This graph is presenting the percent of occupied hours occurring within each scale throughout the year.

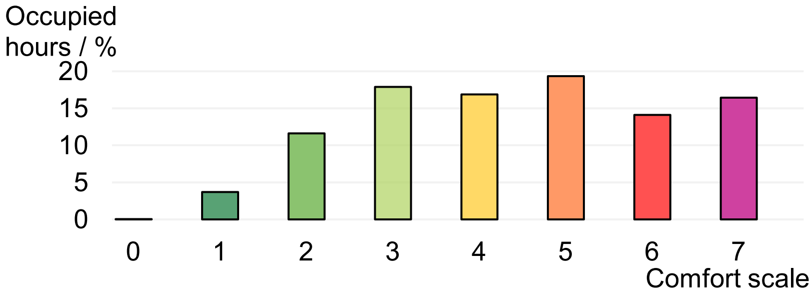


Figure 19. Example of Scale frequency graph

3.4.4 Stage 4: Decision making

The main purpose of this method is to help the user choose an appropriate SCM to prevent overheating. In connection with that an algorithm of decision making is a necessary part of the method.

To develop the decision-making process for SCM selection, the results of DTM simulations for numerous cases, presented in the parametric study, have been analysed. The case with south oriented glazing area was chosen as the most critical, where it was challenging to achieve thermal comfort with the means of SCMs. The percentage of occupied hours when the comfort category III is reached for PMV and AMC was computed in Excel spreadsheet. For that the method of thermal comfort assessment was used, which was previously described in section 3.2.2. The results of the analysis have been used to develop the algorithm of the decision making.

The stage of decision making includes three steps based on the developed rules that suggest how to proceed if the analyzed case does not reach the desired thermal comfort. If the user follows the three steps described below, the final result will be a suggestion that provides comfort in the given space for at least 95 % of the occupied hours, as specified in the EN 15251.

3.4.4.1 Step 1: Thermal Comfort Assessment

The first step checks the comfort level of the analyzed space before the use of any SCMs. The comfort range is compared to the blind use frequency in order to give an overview of how often the fabric blind needs to be used to achieve thermal comfort in 95 % of the occupied hours, see Table 12.

Table 12. Needed blind frequency for a certain comfort range

Comfort range / %	95	85	75	65	55	45	35	..
Blind use frequency / %	-	10	20	30	40	50	60	…
Subjective assessment of the blind use frequency	-	Too rare	Appropriate		Too often			

As a guidance, within this method an assumption was made to keep the blind use above 10 % and below 40 %. The frequency of the blind use within this range was assumed as appropriate to provide sufficient daylight and view out.

The comfort ranges and blind frequencies in Table 12 are used as a base for the development of the rules, which are needed to support the choices of appropriate solutions. The idea was by analyzing data from DTM simulations to find the effectiveness of each SCM in reduction of overheating and then to create the rules, which will advise on appropriate SCM. For instance, if the analyzed space has a comfort in 86 % of the occupied hours, the method suggests a SCG with an appropriate *g*-value to provide comfort in 95 % of the occupied hours.

The method was developed to suggest the most practical and energy-efficient solution first and, if that is not enough, to suggest other more expensive or energy demanding solutions.

The method chooses preferable solutions in the following order: 1) solar control blind; 2) solar control glass; 3) lower cooling set-point; 4) lower glazing to wall ratio.

3.4.4.2 Step 2: Glazing type selection

If the method does not consider changing the cooling set-point or the GWR as necessary solutions, the suggestion will be given to continue to Step 2 for the glazing type selection. The same method, as previously described in Step 1 and Table 12, was used to determine which *g*-value of the glazing to choose.

The recommendations within this step were based on the analysis of data from DTM simulations to determine the effect of the *g*-value on the reduction of overheating. If the user prefers not to use SCG, the recommendation is given to adjust the cooling set-point or the GWR and then to proceed to Step 3.

3.4.4.3 Step 3: Blind selection

When the user reaches Step 3 the method considers fabric blind as an appropriate choice to reduce the overheating to less than 5 %.

For this step, the method finds the day and the hour during summer months when the highest transmitted radiation occurs. With this information, a suggestion based on how the certain solar control blind reduces the $MRT\text{-}T_{air}$ can be made. The assessment of the effectiveness of a certain blind is based on the openness factor (OF) and how much it reduces $MRT\text{-}T_{air}$. Here the position of the blind plays a major role, as for the interior blinds and increase in T_{air} should be accounted for.

3.5 Validation of the method

The validation was made by inserting the values from the simulations in the Excel tool to run it through the steps of the method, described in section 3.4. The validation was made in four steps, which are presented graphically in Figure 20.

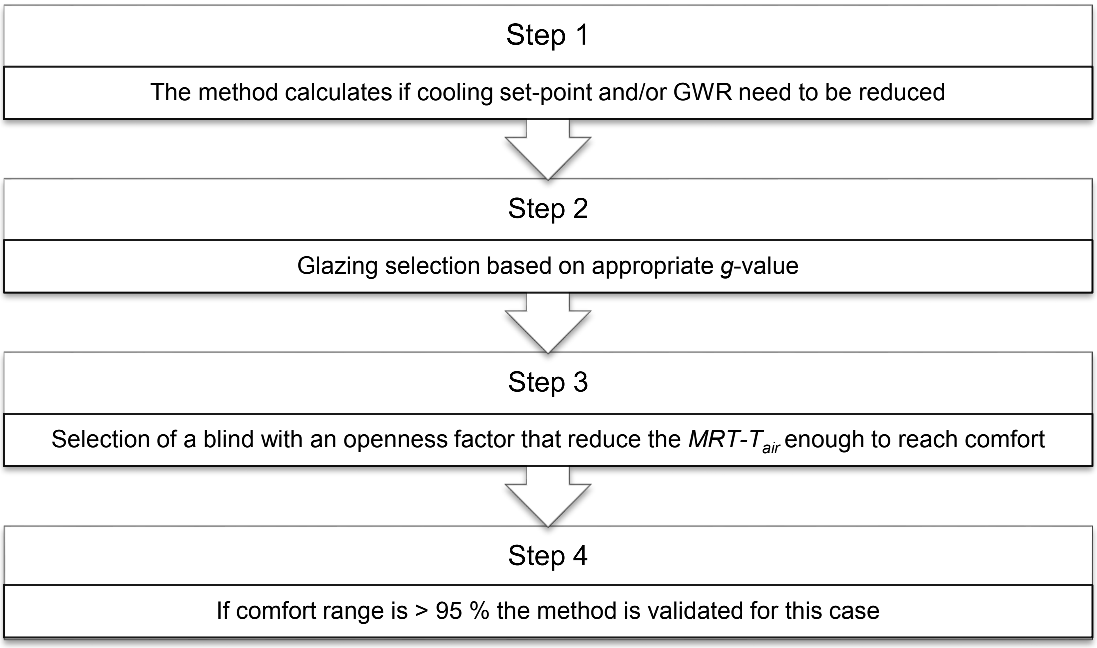


Figure 20. Overview of the steps in validation of the method

Data from DTM simulations with Oasys ROOM software was used to carry out the validation. During the validation process, data from all simulations that have been run during this project was used.

4 Results

The results of the performed study are divided in six parts. First, the analysis of the SCMs performance is presented. In the second part an annual thermal comfort analysis was made on the example of the reference case and the studied SCMs. The results of the parametric study are given in the third part, where the effect of the varied parameters on an annual thermal comfort was analyzed. The sensitivity of PMV and AMC to the varied parameters was shown. The result of the study, which was made for the development of the decision-making step, are explained further. In the last part of the results the validation of the method is presented on the example of three cases.

4.1 Solar control mechanisms assessment

In order to illustrate the static performance of the solar control mechanisms, the data analysis for one node in the middle of the room during one hour with the highest incident radiation of the year was performed. The results are complemented by an analysis of the data for one day.

The transmitted direct solar radiation during one day is presented in Figure 21. The data is given for the reference case with a low-e glazing unit alone and in combination with blinds. The *MRT* for the same cases is presented in Figure 22. The effect of the solar control mechanisms on *MRT* reduction can be seen also outside the hours with solar radiation.

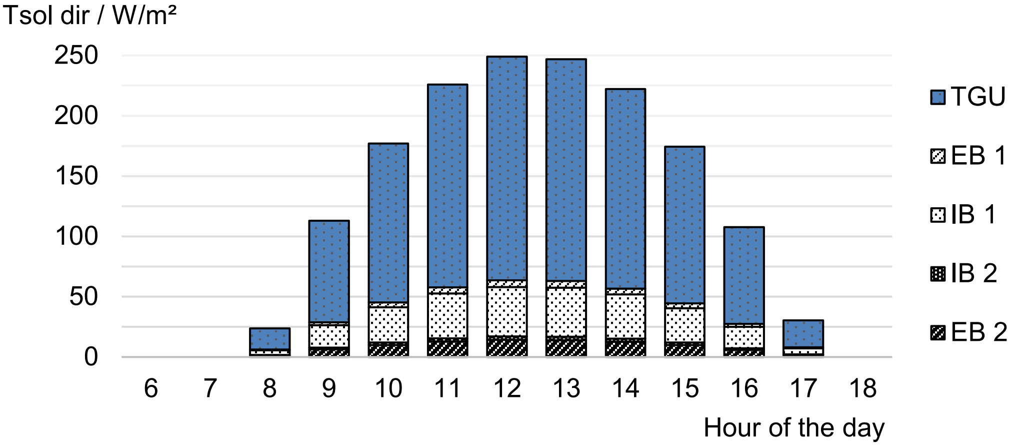


Figure 21. Reduction of the transmitted solar radiation during the day by the application of blinds to the reference case with low-e

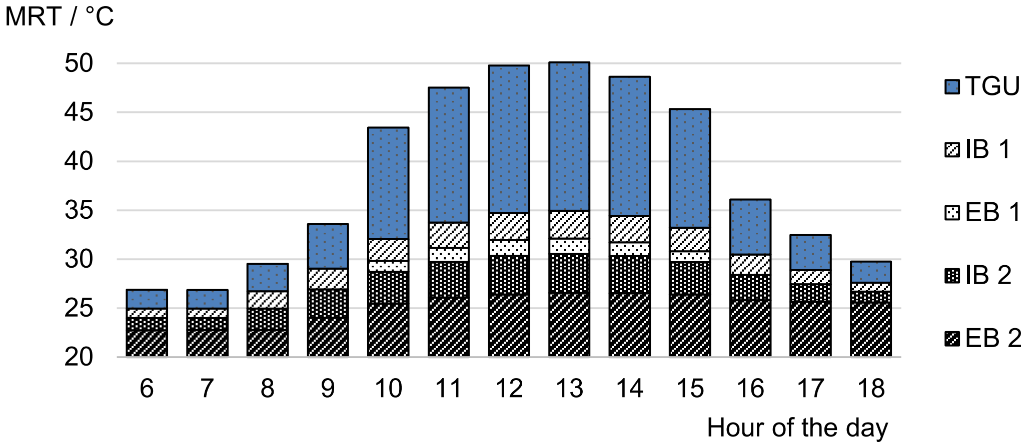


Figure 22. Reduction of MRT during the day by the application of blinds to the case with low-e

A closer look can be given for the transmitted direct radiation at 12:00 of the analysed day, when incident direct solar radiation is at its maximum of 700 *W/m²*, see Figure 23.

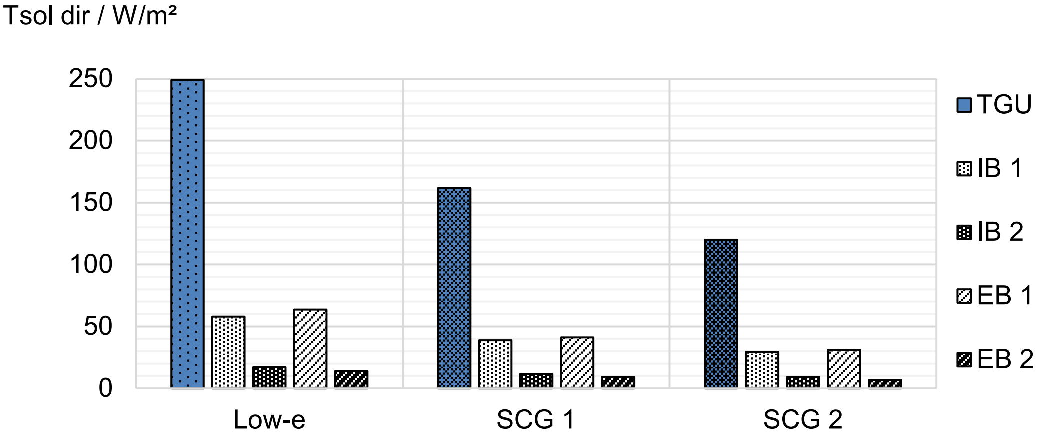


Figure 23. Relative effect of the solar control mechanisms on transmitted radiation

Figure 24 displays the relative effect of the SCMs reduction of *MRT*. The effect on *MRT* can be seen when comparing cases with different glazing units. It can be stated that for the critical hour, the *MRT* reduction of 7 *°C* (14 *%*) can be achieved with SCG 1 and by 12 *°C* (24 *%*) with SCG 2 compared to the reference case with low-e. The application of the interior and exterior roller blinds gives a significant effect on the *MRT* reduction. In the case of combination with low-e glazing unit, the blind gives an improvement of *MRT* from 15 *°C* (30 *%*) to 23 *°C* (47 *%*). However, the difference is not that dramatic when comparing the combination of the blinds with different glazing units.

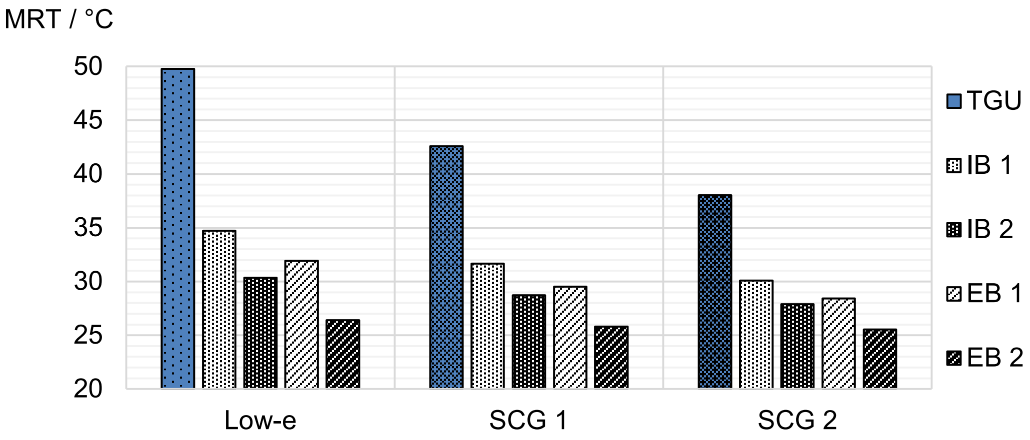


Figure 24. Relative effect of the solar control mechanisms on MRT reduction

Figure 25 is given to correlate the reduction of *MRT* with the reduction of PMV. It can be seen that the effect of the solar control blinds on the *MRT* has direct impact on thermal comfort improvement.

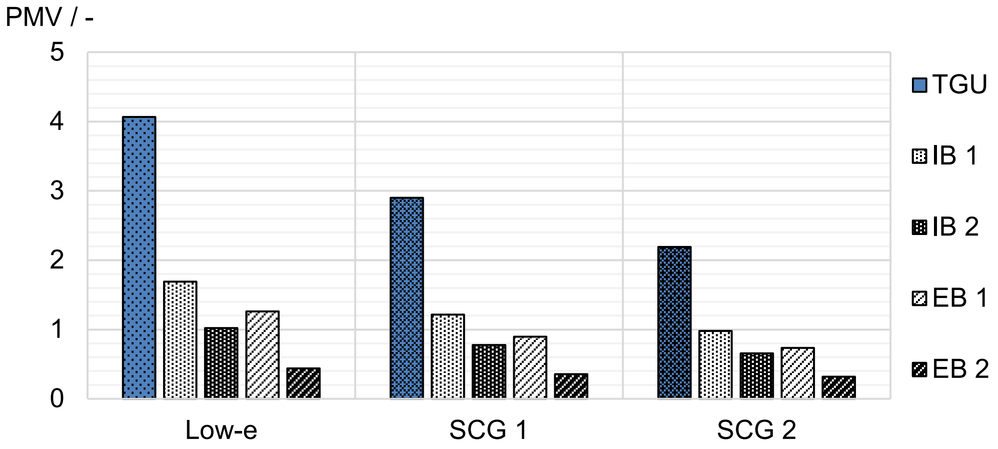


Figure 25. Relative effect of solar control mechanisms on PMV reduction

The effect of the reduction of transmitted radiation was compared to the reduction of *MRT* and the result can be seen in Figure 26. By weighting the percentage of the reduced solar transmittance with the percentage of *MRT* reduction of each solar control mechanism compared to low-e, the Reduction Factor was derived. The Reduction Factor shows the percent of the solar transmittance reduction which results in *MRT* reduction by 1 %. The distribution of the Reduction Factor values is between 2 % and 2.5 % which can be considered as uniform. It can be determined though that the exterior blinds show the same relative effectiveness in *MRT* reduction regardless of the glazing type they are applied with, while the effectiveness of the interior blinds is more related to the type of the gazing unit. It can also be noticed that even though the blinds with the same index have the same openness factor, their contribution to the *MRT* reduction is not the same and has an average difference of 0.3 %. That can be practically read as if the reduction of *MRT* by 10 % is needed, solar transmittance of the applied interior blind should be around 3 % lower than of the exterior blind.

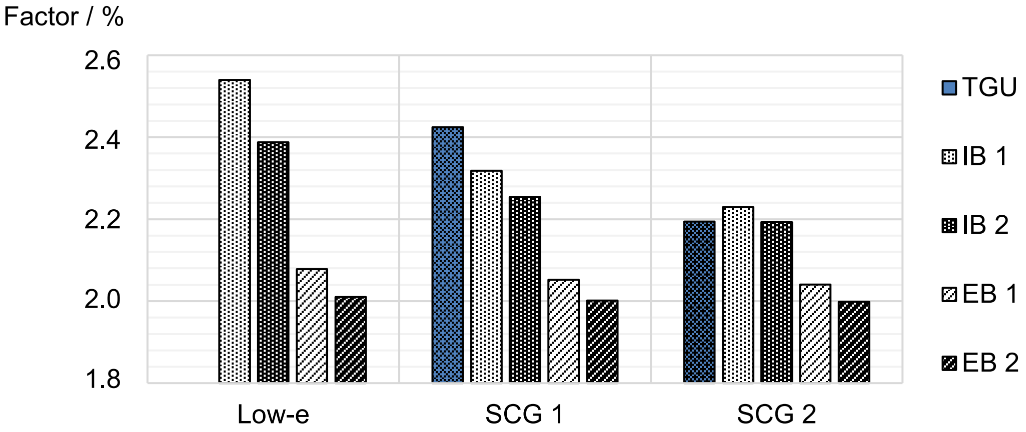


Figure 26. Reduction Factor for the transmitted solar radiation to reduce MRT by 1 %. The effect of reduction is weighted over the case with Low-e glazing unit

4.2 Annual thermal comfort assessment

4.2.1 Reference case

At the figures below the results of the thermal comfort assessment with PMV for the reference case are given. Figure 27 presents an overheating chart with the selected area of the occupied hours from 8 AM to 6 PM, as only they have been accounted for when assessing thermal comfort in this method. In Table 13 an informative scale is given, which explains the range of PMV and thermal sensation for each colour of the chart. The scale was previously explained in chapter 3.3.3 and presented here for the understanding of the results.

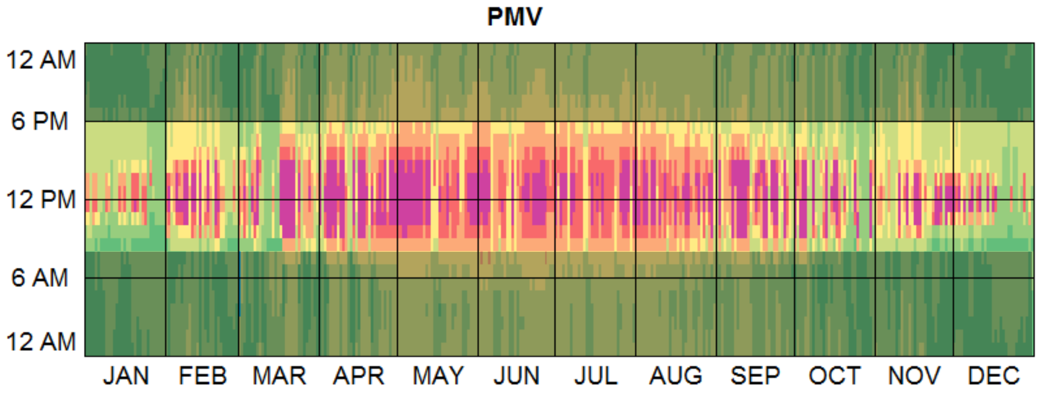


Figure 27. Overheating chart for the reference case with low-e glazing unit

Table 13. Colour index for the comfort and overheating scale

Sensation	Cold	Comfort for categories I, II and III respectively					Slightly warm	Warm		Hot
Scale	0	3	2	1	2	3	4	5	6	7
PMV range	- 0.7	- 0.5	- 0.2	0.2	0.5	0.7	1	1.5	2	

The calculated percent of the occupied hours within the certain scale in the overheating chart can be seen at Figure 28.

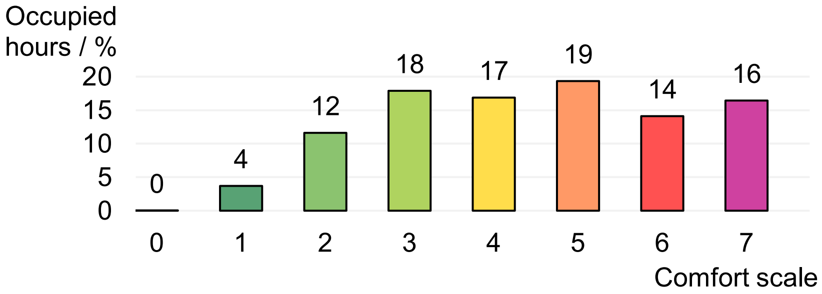


Figure 28. Distribution of the occupied hours within the comfort scale

4.2.2 Comfort models

A comparison of the results of thermal comfort assessment with PMV and AMC was made for the reference case with a low-e glazing unit. Figure 29 shows the percent of occupied hours during the year when a certain comfort scale occurs. A noticeable difference can be seen in the distribution of hours within the comfort scales for two comfort models. Compared to PMV, AMC has a higher percentage of occupied hours with thermal comfort in scales 1 and 2, which indicates that a higher percentage of comfort can be achieved for the same case if AMC is used instead of PMV. The reason for that is more strict comfort boundaries are required when thermal comfort is assessed with PMV.

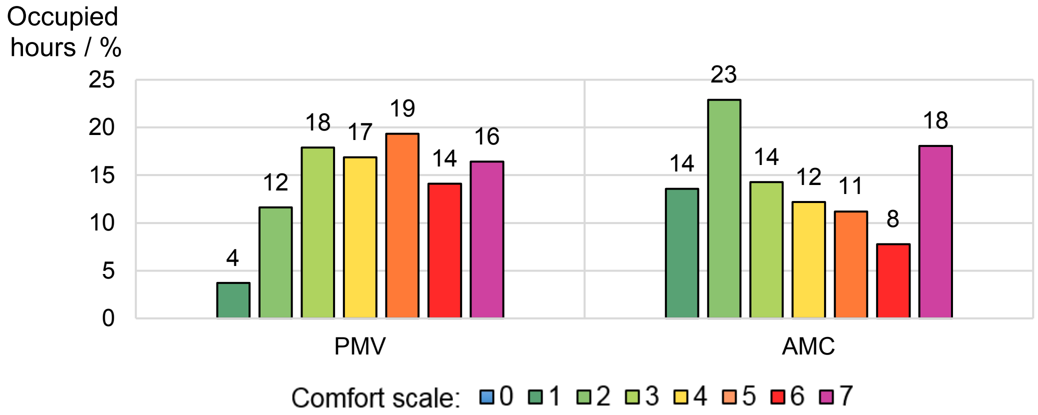


Figure 29. Distribution of occupied hours within the comfort scale when using PMV and AMC for the reference case with low-e glazing unit

4.2.3 Solar control mechanisms

Following analysis of the effect of solar control mechanisms on the annual thermal comfort was made using PMV index first. In order to show the difference in the analysis with AMC the total improvement to thermal comfort of scales from 1 to 3 was analysed for both PMV and AMC.

Figure 30 presents the result of thermal comfort assessment for three cases with different glazing units. The positive effect of SCG, on the improvement of thermal comfort can be seen in comparison with the results for the reference case with low-e glazing. For the SCG 1 and SCG 2 sharp reduction of the percent of occupied hours with extreme overheating in scale seven can be seen, as well as the increase of hours with the comfort in scales from one to three.

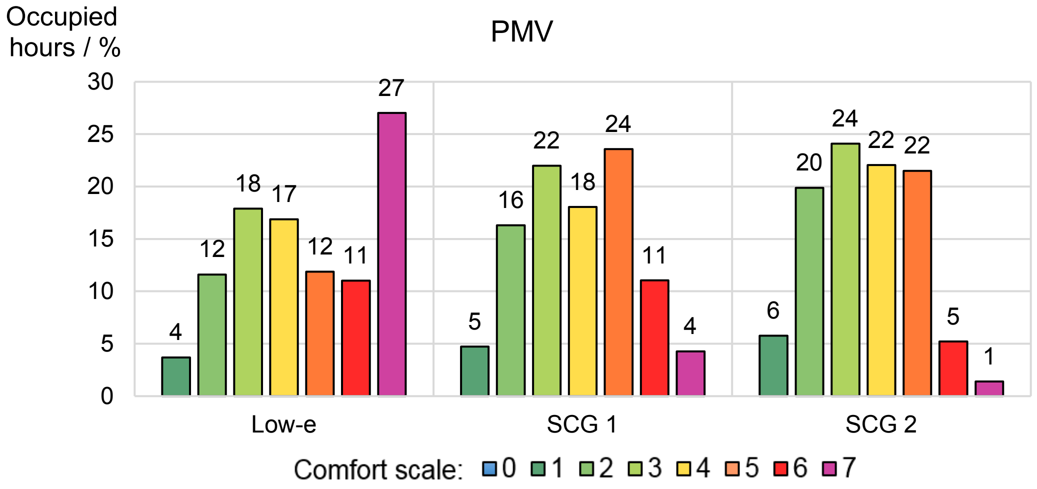


Figure 30. The effect of the solar control glazing type on the thermal comfort

Figure 31 shows the results of the thermal comfort assessment when solar control blinds are used in combination with the low-e glazing unit. A drastic improvement to scale two can be seen in the case with exterior blind 2 (EB2), which represents the most effective solution in control of solar gains. With this solution category III of thermal comfort can be achieved in the studied case, as a total of 98.8 % of occupied hours are within the comfort scales from 1 to 3.

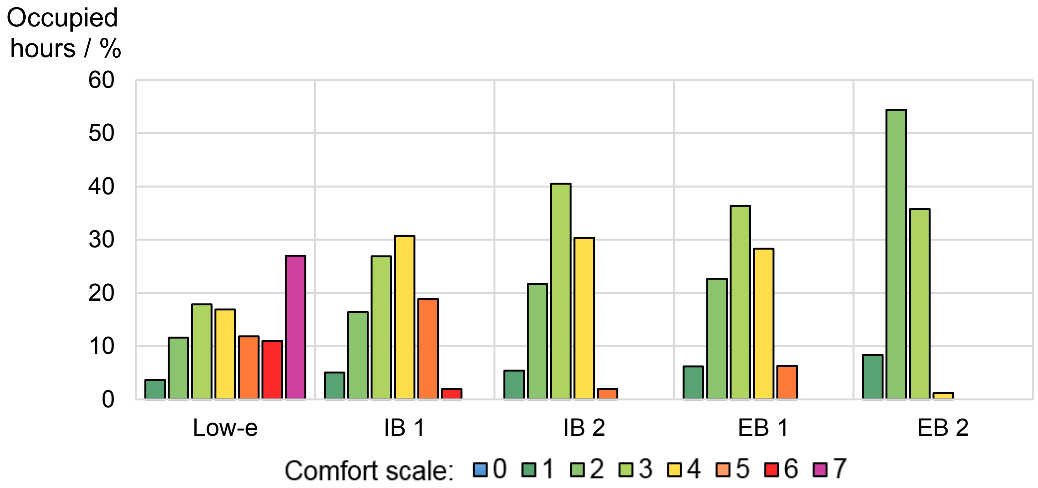


Figure 31. The effect of the solar control blinds applied to the low-e glazing unit on the thermal comfort

Total effect of the thermal comfort improvement by the application of solar control mechanisms is presented at Figure 32 and Figure 33 for both PMV and AMC. The improvement was calculated for the comfort category III, represented by sum of scales 1, 2 and 3.

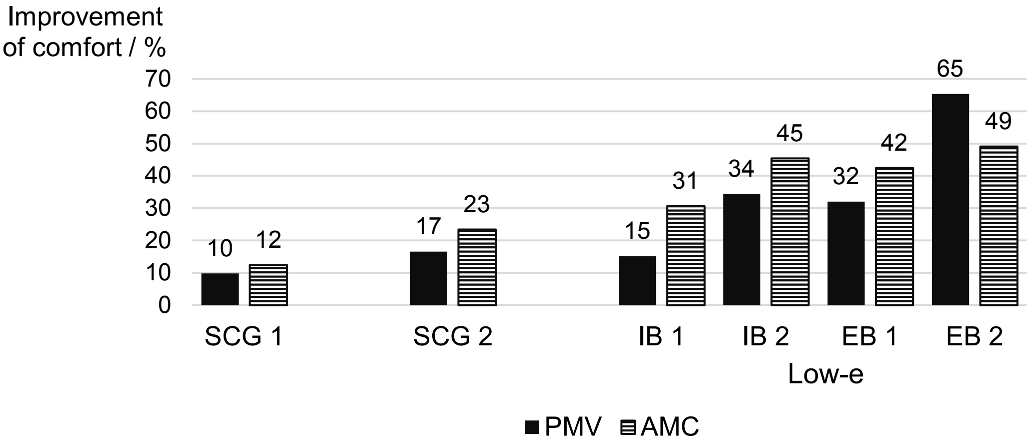


Figure 32. Improvement of the comfort in total for scales 1, 2, 3 for the PMV and AMC in studied cases.

As it can be noted, the effect on the thermal comfort improvement is increasing with the increasing efficiency of the SCM when PMV is used. Meanwhile for AMC application of more effective solutions shows a decreasing trend in the thermal comfort improvement. It can be explained by the fact that for AMC sufficient comfort can be achieved with less efficient SCM.

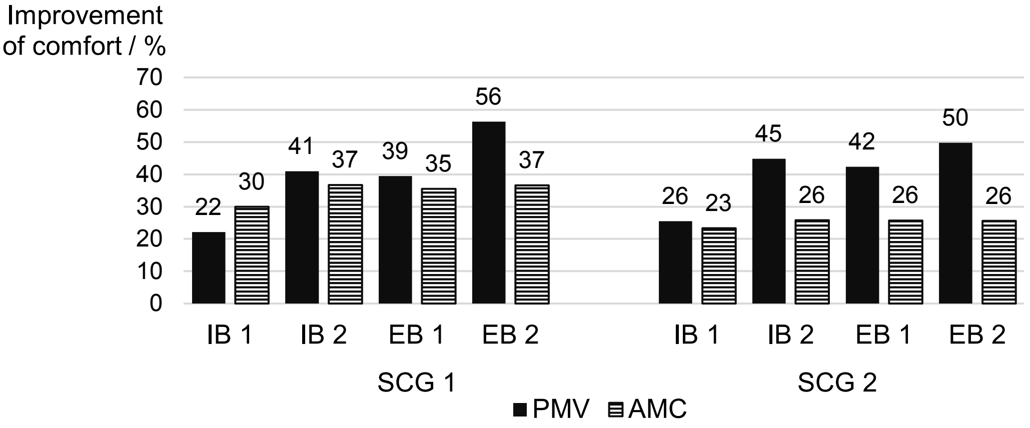


Figure 33. Improvement of the comfort in total for scales 1, 2, 3 for the PMV and AMC in studied cases with different glazing units

4.3 Parametric study

In this part of the Results, the analysis of thermal comfort for the reference case is compared with the studied cases to show the effect when changing the glazing-to-wall ratio, orientation of the window and cooling-set points. As the reference case with low-e glazing unit was set to GWR 100 %, south orientation and cooling set-point of 26 °C. The total improvement of the thermal comfort from overheating to comfort scales one to three for PMV and AMC is presented later in the section as well.

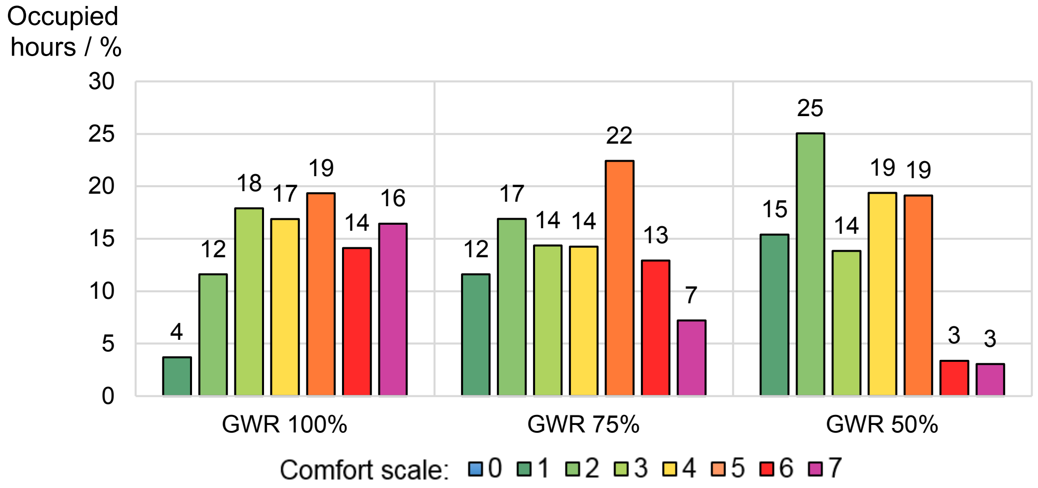


Figure 34. Effect of the decreased glazing-to-wall ratio on thermal comfort of the reference case.

The parametric study with lower GWR shows that reduction of glazing area results in a vivid increase of the hours with comfort scales from 1 to 3 on the account of decrease of hours with scales of overheating 6 and 7, see Figure 34.

The effect of the reduced cooling set-point on the distribution of hours within the scale of thermal comfort can be seen in Figure 35. Decreasing the air temperature gives a positive effect on the reduction of overheating. However, thermal comfort cannot be provided by cooling only as it can be seen in the case with the lowest studied cooling set point of 24 °C, where 38 % of occupied hours still have an overheating of scales from 4 to 7.

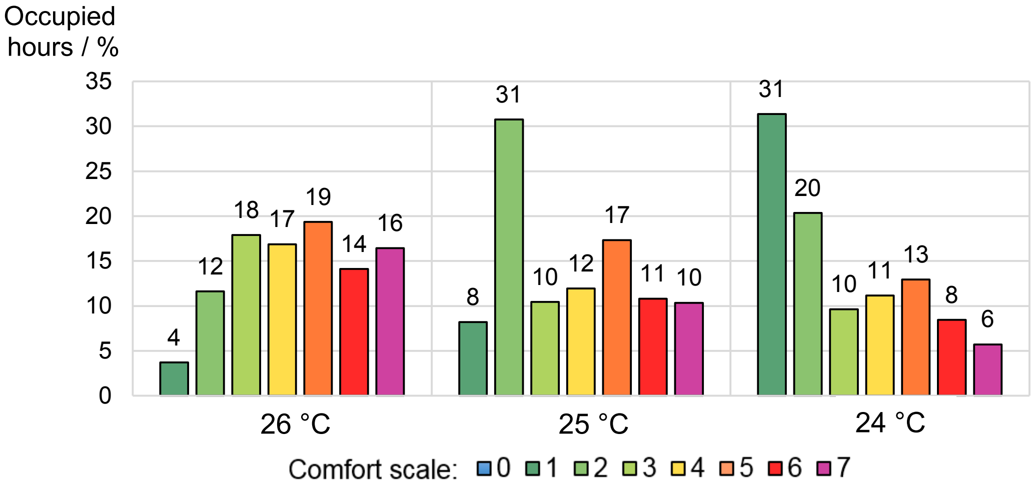


Figure 35. Effect of the decreased cooling set point on thermal comfort of the reference case.

From the comparison of the results for the cases with varied window orientation, it can be seen to which extent the problem of overheating affects the case with south oriented glazing. In the cases with east and west orientation, the total percent of hours within the comfort category III, represented by scales 1, 2 and 3, is higher if compared to the south oriented case, see Figure 36.

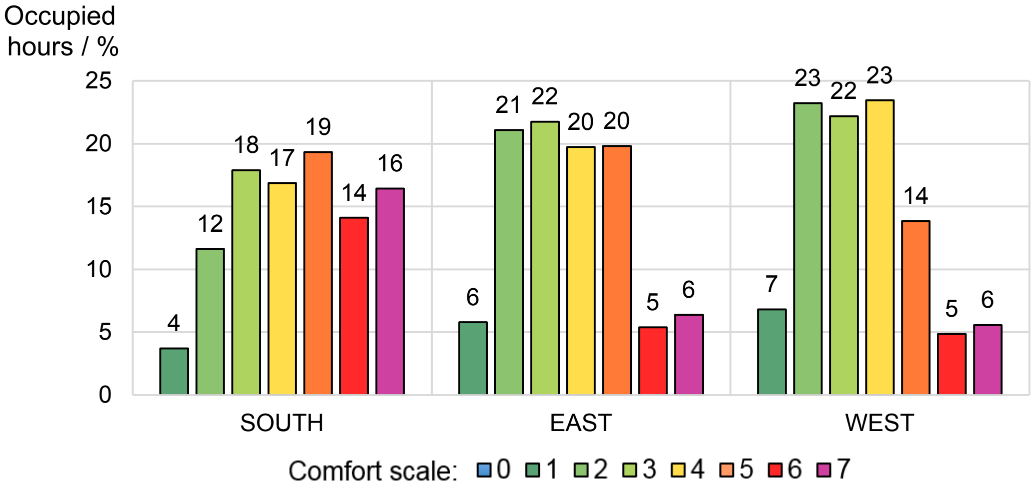


Figure 36. Effect of the orientation of the window on thermal comfort of the reference case

The total effect of thermal comfort improvement in the studied cases is presented in Figure 37. Values are given for thermal comfort assessment with PMV and AMC separately, so it is possible to see that change of the window orientation has a higher impact on the thermal comfort improvement when using AMC, while decreasing cooling set point temperature affected thermal comfort in the case with PMV to a greater extend. Reduction of the GWR had a proportional effect for both PMV and AMC.

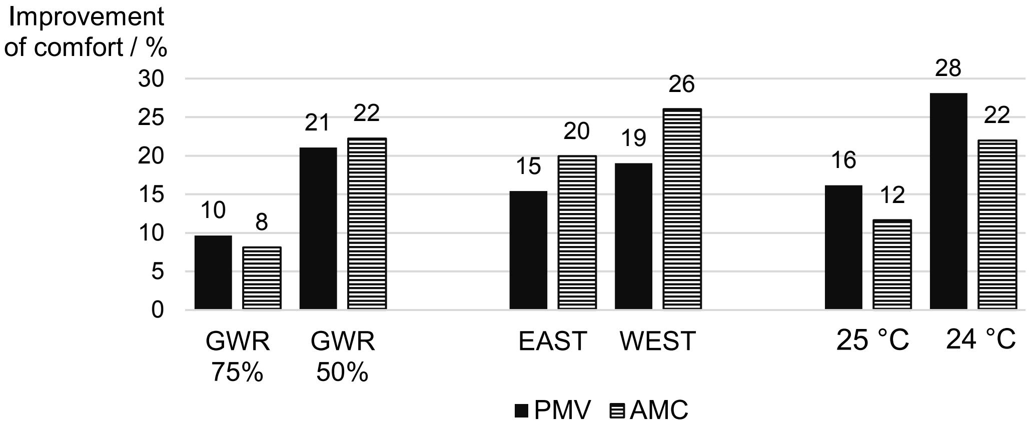


Figure 37. Improvement of the comfort in total for scales 1, 2, 3 for the PMV and AMC in studied cases

4.4 Decision making

The results of the thermal comfort analysis, which was made to base the decision-making process on, are shown in Figures 38 for southern orientation of the facade. Figures for west and east orientation can be found in Appendix F. The results are presented for cases with varied cooling set-points and GWR. Within each studied case the results for three different glazing units, low-e, SCG 1 and SCG 2, are given. The analysis of the thermal comfort was made for both PMV and AMC. The resulted values represent the percentage of occupied hours when comfort in category III is reached.

The green line at 95 % of occupied hours is the comfort level that should be reached to comply with the requirement of the EN 15251 standard. The red line at 65 % of the occupied hours is the minimum level of comfort that should be achieved before applying solar control blind, due to the guideline to not use the blinds more than 30 % of the occupied hours.

For the analysis of the results the case with 26 ºC and GWR of 100 % are used as the reference case. As it can be seen from Figure 38, when thermal comfort is assessed with PMV, more measures are required to reach the comfort level if compared with AMC.

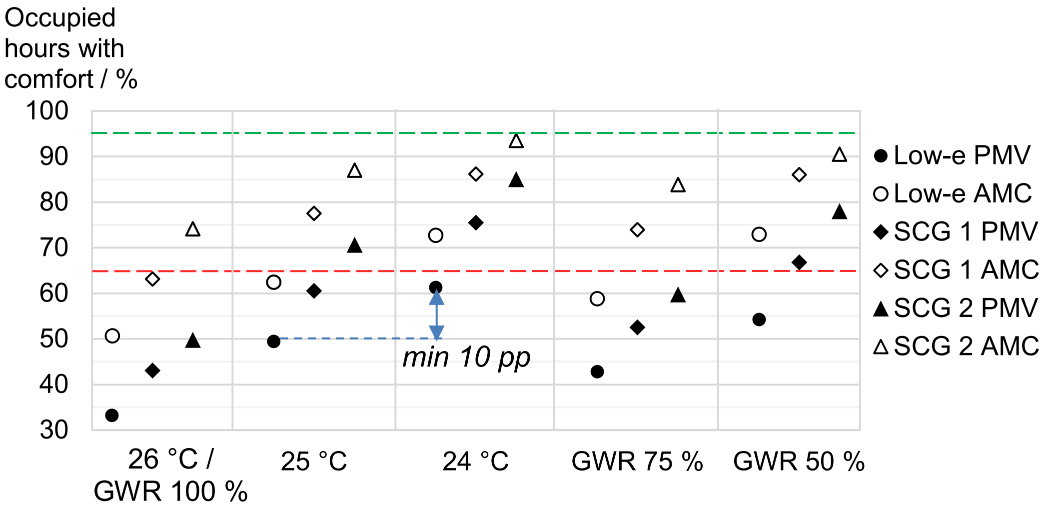


Figure 38. The percentage of occupied hours when thermal comfort in category III is achieved for the cases with south oriented window

From the analysis of the results for cooling set-point reduction it can be seen, that the reduction of 1 °C provides a minimum thermal comfort improvement by 10 percent points (*pp*), which can be seen in the case with low-e for 25 °C and 24 °C. Assuming therefore, that 1 °C reduction of the cooling set-point can improve thermal comfort by 10 *pp*, it can be predicted that the benchmark of 65 % of the occupied hours can be reached for the cases when thermal comfort is 55 % and 45 % of the occupied hours if the cooling set-point reduced by 1 °C and 2 °C respectively.

As in the case with the reduction of GWR, the results vary as well, an approximation was made that the reduction of GWR from 100 % to 75 % and from 75 % to 50 % results in 10 *pp* improvement of thermal comfort in each case.

The results in Figure 38 show that the improvement of thermal comfort by a SCG vary from around 10 *pp* up to 14 *pp*, note that the method only considers SCG as an option when comfort is 45 % of the occupied hours or more. The value of 10 *pp* was used to estimate the possible improvement of thermal comfort by using the SCG 1 with a *g*-value of 0.31, instead of low-e with a *g*-value of 0.47. When using a SCG 2 with a *g*-value of 0.23, the improvement can be measured to 20 *pp* compared to the low-e unit.

Table 14 explains how the choice of SCG is recommended within the method by using the benchmarks motivated above, and in which case the SCG needs to be combined with fabric blinds.

Table 14. Appropriate choice of SCG

Comfort Range / %	45 - 55	55 - 65	65 - 75	75 - 85	85 - 95
SCG *g*-value / -	< 0.23	< 0.31	< 0.31	< 0.23	< 0.31
Blind use (Yes/No)	Yes	Yes	Yes	No	No

When comfort is achieved in 65 % of the occupied hours, the last step is to define an appropriate blind. In Figure 39 an analysis of reduced $MRT\text{-}T_{air}$ while applying the fabric blinds is presented. The dashed line represents the boundary for $MRT\text{-}T_{air}$ of 4.5 ºC, this value was set as benchmark for minimum needed reduction of $MRT\text{-}T_{air}$ by blind to provide thermal comfort. This benchmark was found by analyzing the data presented in Figure 40 and Figure 41, and comparing them with Figure 39.

Figure 40 shows thermal comfort during occupied hours when interior and exterior fabric blinds with different openness factor are applied and PMV index is used as comfort model. The dashed line represents the comfort limit of 95 %, and the line below it shows the comfort limit of 65 %, which needs to be reached before the method considers blinds as an option. Figure 41 is similar to Figure 40 except that AMC is used as comfort model instead.

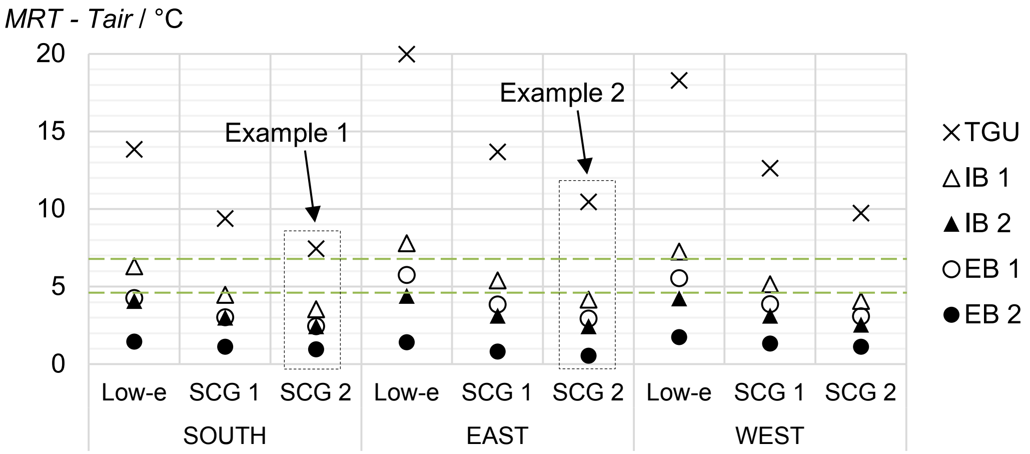


Figure 39. MRT-Tair reduction while applying fabric blinds during the hour and the day of the summer with the highest radiation.

The analysis of those three graphs was made in following steps:

- Find the glazing units in Figure 40 and 41 which have a comfort above 65 % before any blind is applied.
- Then find the blinds which are above the 95 % comfort line in Figure 40 and 41 and at the same time below the 4.5 ºC line in Figure 39.
- If both of those steps can be completed, the blind will be recommended by the method.

$MRT\text{-}T_{air}$ of 4.5 ºC is used due to that it was the maximum value that still provided comfort in all DTM simulations that was made within this study.

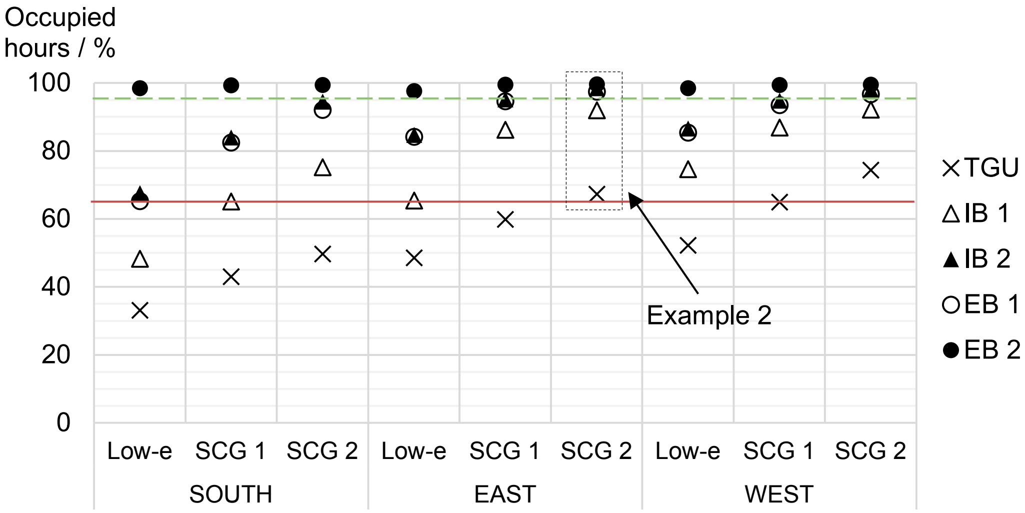


Figure 40. Comfort during occupied hours while applying interior and exterior fabric blinds using PMV index as comfort model

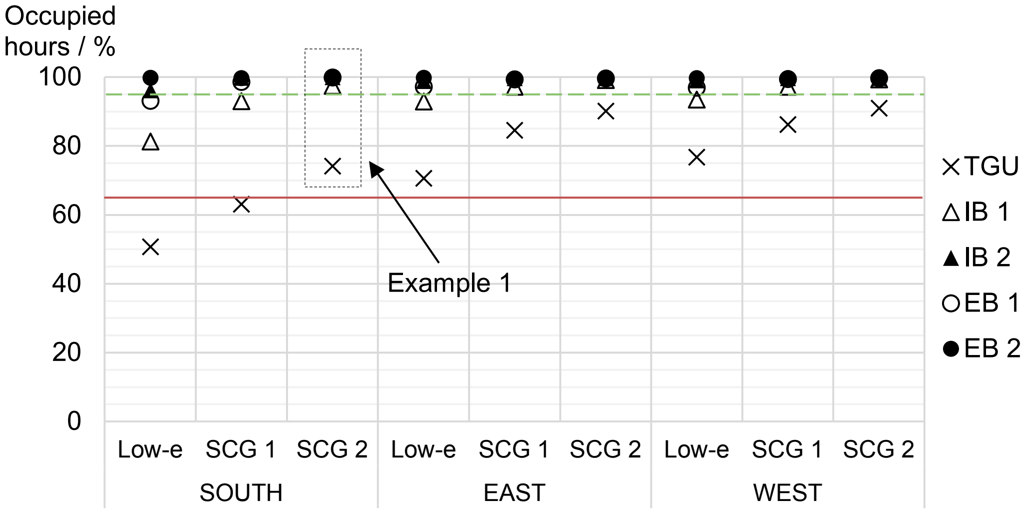


Figure 41. Comfort during occupied hours while applying interior and exterior fabric blinds using AMC as comfort model.

In the following paragraph two examples will be presented that explain how to use the results in Figure 39, 40 and 41 to select an appropriate blind. Follow the rectangles drawn in the figures to understand the process on the examples described below.

Example 1 starts in Figure 41 where AMC is used as comfort model. The glazing unit which is represented by an X is above the 65 % comfort line, which means that the method will consider fabric blind as an option. As can be seen in the same rectangle all four blinds are above the green line which indicates that comfort is achieved at least 95 % of the occupied hours. Next step is to go to Figure 39 and check if the blinds reduces *MRT*-T_{air} to less than 4.5

ºC as maximum during a year. The rectangle named Example 1 in Figure 39 show that all blinds are below the 4.5 ºC line and can therefore be suggested to be used by the method in this case.

Example 2 starts in Figure 40 where PMV is used as comfort model. The glazing unit within the rectangle named Example 2 is just above the 65 % comfort line, therefore the method will consider fabric blind as a possible solution to provide comfort. By analyzing the blind symbols presented above in the rectangle, it can be seen that three blinds provide 95 % comfort while one is not, this blind should not be considered as an option by the method. The three blinds that provide more than 95 % can then be analyzed in Figure 39 if they also achieve the requirement of 4.5 ºC.

Within the rectangle marked as Example 2 in Figure 39, all four blinds are below the 4.5 ºC line, which means that three of the blinds pass the conditions in both graphs and can therefore be suggested to provide comfort by the method.

The previously described steps can be summarized in a process chart, which is shown in Figure 42. Four steps are presented where comfort of at least 95 % should be achieved at Step 4. Step 1-3 also have including rules that need to be fulfilled before continuing to the next step. This can be considered as the core of the study and it can be used as a manual with guidance to reach comfort using the PMV index or the AMC model.

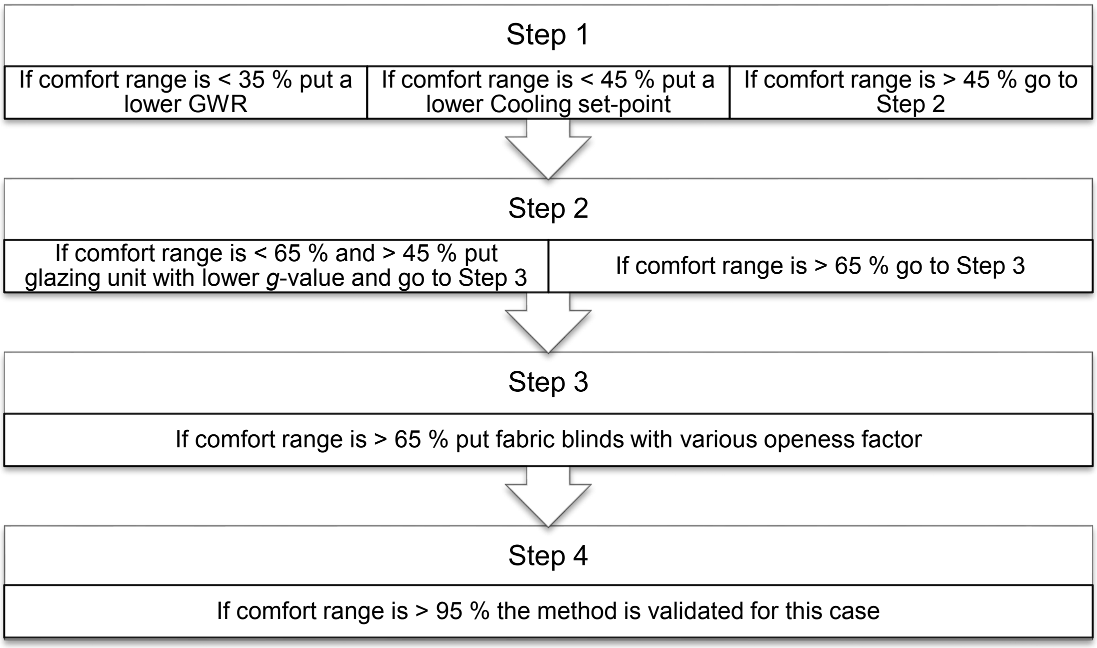


Figure 42. Overview of the steps validate the method

4.5 Validation of the method

The validation of the method was based on the steps described previously in section 3.4.4, by following the guidance in those steps that comfort of 95 % of the occupied hours needs to be achieved after Step 3. Three cases are presented with PMV as comfort model, one for each orientation. The PMV index was used while validating the method, this is due to that PMV is a more sensitive index than AMC and therefore it is also harder to reach comfort when it is used. In all validation cases a low-e glazing unit was used as a reference case and a comfort category III was set as a target to reach.

4.5.1 Case 1: South, low-e and 26 ºC cooling point

The first case with façade orientation to the south is the most exposed to solar radiation and has the most of overheating problems, as shown in the overheating chart in Figure 43. Indicative colors representing comfort scales were used in the bar charts, starting with Figure 44.

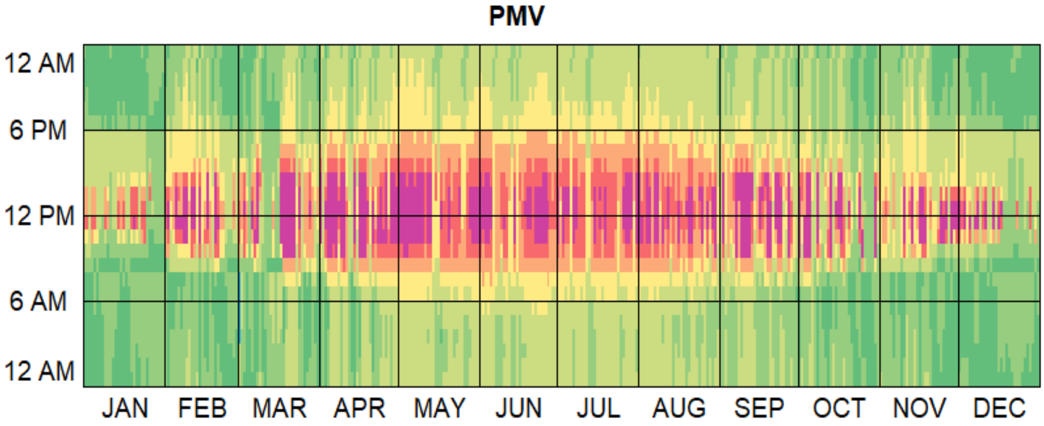


Figure 43. Step 1, overheating chart for the case with south orientated façade, low-e, 26 ºC cooling set-point while using PMV index.

While running this case in the first step of the method, it suggests a solution to change the façade, due to that the comfort during occupied hours is below 35 %. In Figure 44 the percentage of comfort hours within each comfort scale is presented. The occupied hours are spread over all the scales, except for scale 0 which indicates that there are less than 1 % when it is too cold.

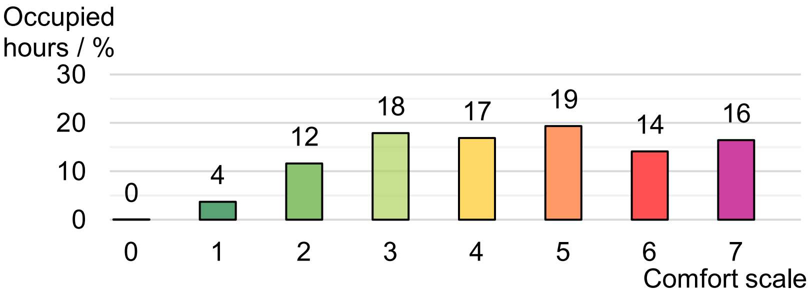


Figure 44. Step 1, overview of the percentage of occupied hours within each comfort scale.

By changing the GWR to 50 % from initial 100 %, the overheating hours are improved to comfort especially during morning and evening, see Figure 45. Note that the overheating chart in Figure 45 does not show the hours that change within the overheating scales, only the hours when comfort is reached in Step 2. The color of white is introduced here and shows the hours which are improved to comfort from Step 1 to Step 2.

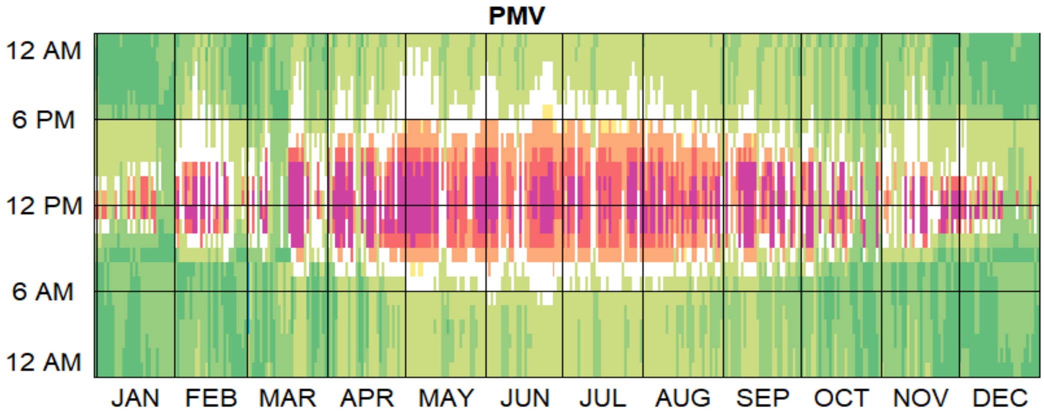


Figure 45. Step 2, overheating chart for the case with south orientated façade with Low-e, 26 ºC cooling set-point and 50 % GWR while using PMV index

In Figure 46 an updated graph over how the hours are divided within the comfort scales are presented. Scale 1 and 2 increased the most within the comfort scales and at the same scale 6 and 7 was reduced the most. Also, the hours when it is too cold increased from 0 % to 1 %.

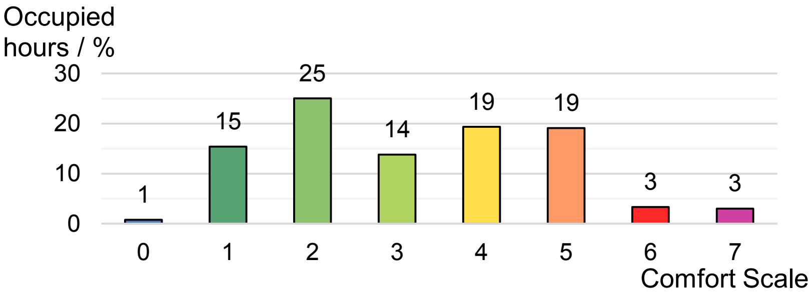


Figure 46. Step 2, overview of the percentage of occupied hours within each comfort scale and percentage of solved hours

The improvements from Step 2 only reach a comfort of 54 % and need further improvements. The method suggests adding a SCG with a g-value of < 0.17, the explanation of the decisions in this part can be found in section 4.4. In Step 3 further improvements can be seen in Figure 47, during the unoccupied hours it starts to occur blue color in the spring and autumn which indicates that it is too cold those hours.

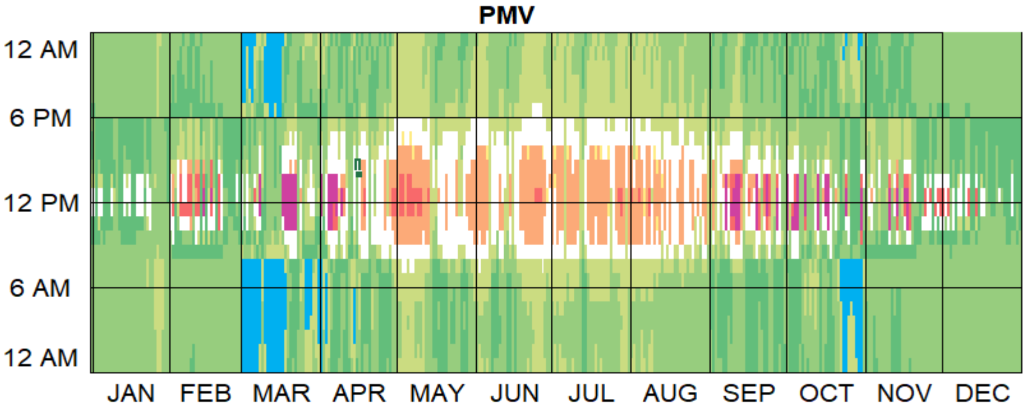


Figure 47. Step 3, overheating chart for the case with south orientated façade with SCG 1, 26 ºC cooling set-point and 50 % GWR while using PMV index

Those blue areas only occur 1 % of the occupied hours which is presented in Figure 48. Further on the hours of scale 5, 6 and 7 are improved except for 4 % left in scale 5. However, together with scale 4 there is 21 % overheating during the occupied hours which still need to be solved.

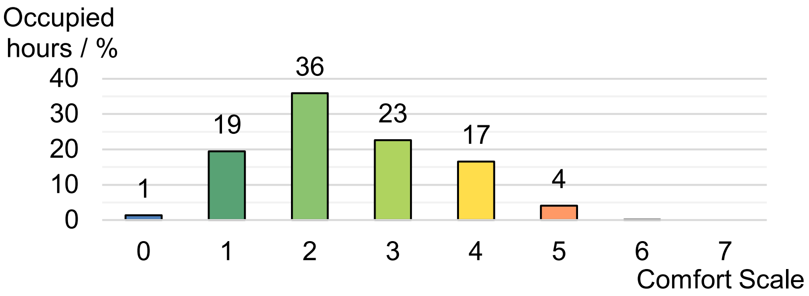


Figure 48. Step 3, overview of the percentage of occupied hours within each comfort scale and percentage of solved hours.

As a Step 4 the method suggested applying a fabric blind with OF 14 % and solar transmittance 22 %. As it can be seen in Figure 49, an application of the selected blind eliminated almost all the overheating problems. More hours with cold discomfort occurred, which can be seen in blue areas of the chart; however, they mostly appeared during unoccupied hours.

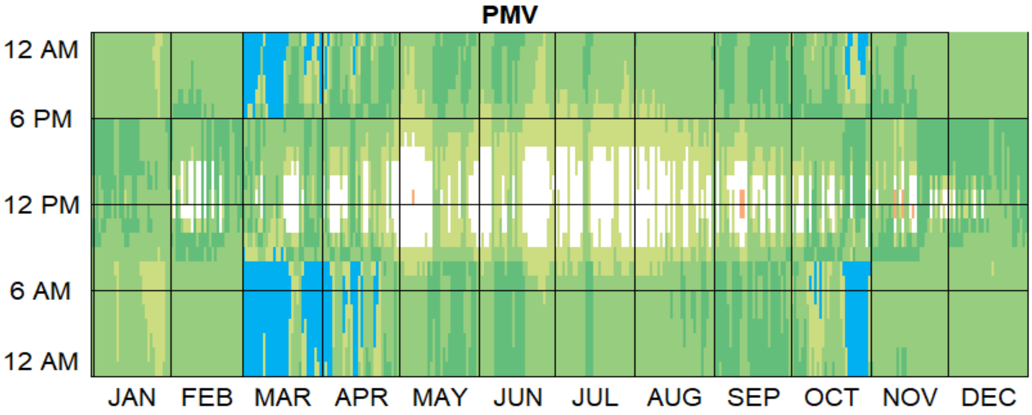


Figure 49. Step 4, overheating chart for the case with south orientated façade with SCG 1, 26 ºC cooling set-point, 50 % GWR and an interior blind with OF 14 % while using PMV index

The percentage of hours with cold discomfort, indicated as scale 0, increased with 1 % but otherwise almost all the overheating hours are improved, as shown in Figure 50. After Step 4 the comfort during occupied hours reached 98 % meaning that the problem of overheating was solved with the recommended solution.

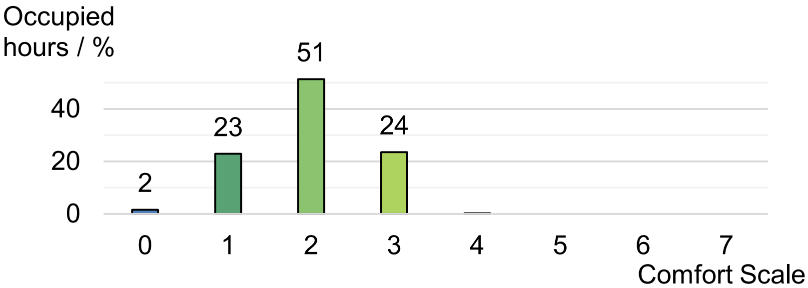


Figure 50. Step 4 overview of the percentage of occupied hours within each comfort scale and percentage of solved hours

4.5.2 Case 2: West, low-e and 26 ºC cooling point

The second case to validate the method is similar to the first case, except that the orientation is to the west instead of the south. By following the steps of the method comfort of > 95 % is reached after three steps.

When the glazed area is oriented to west, the overheating problems occur mostly during the afternoon, as shown in Figure 51. This is due to that the direct solar radiation reaches this part of the façade during this hours. In Step 2 the method suggested using a SCG with the *g*-value of 0.23 which gave the result of improved hours during the morning. However, there were still overheating problems which needed to be solved by going to Step 3. In the next step an exterior fabric blind was applied and comfort was reached except for the period between 3 PM and 6 PM during spring and summer. Also, some hours with cold discomfort, colored in blue, started to occur in the morning hours in March, but not during occupied hours.

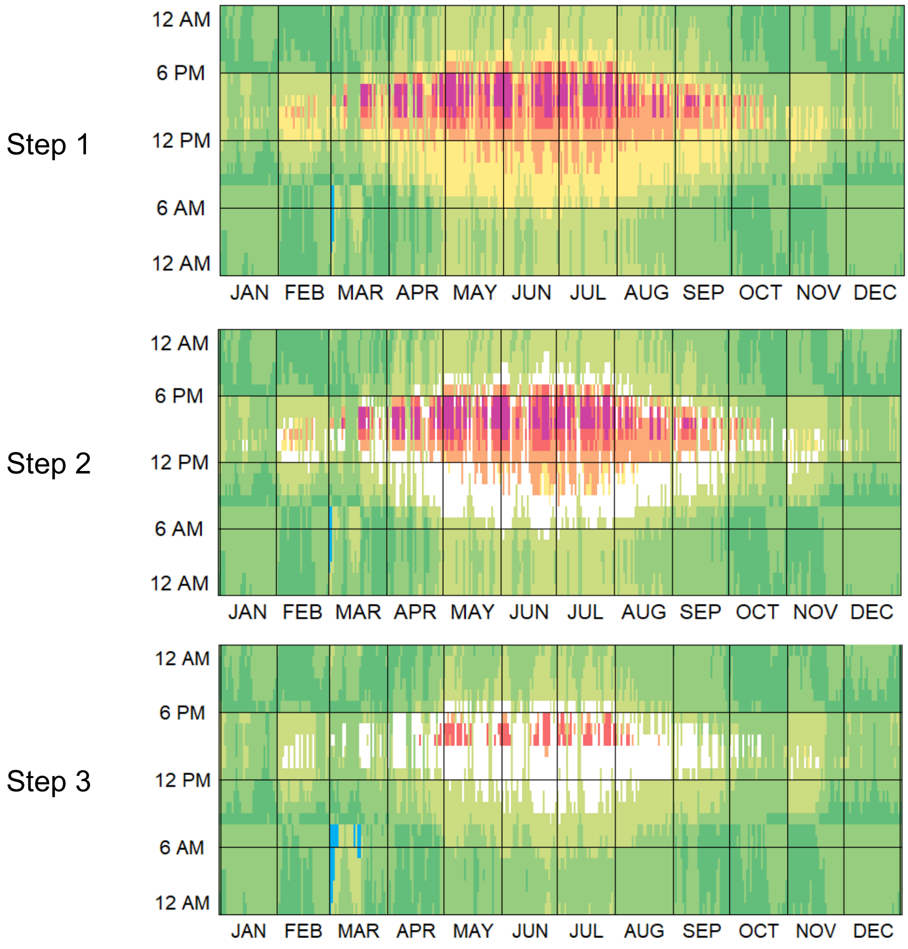


Figure 51. Step 1-3, overheating chart for the case with west orientated façade with Low-e, 26 ºC cooling set-point while using PMV index.

In this case 52 % of the occupied hours are within the comfort limits, 5 % and 6 % represent scale 6 and 7 respectively, see Figure 52. The major part of the overheating, 37 %, that needs to be solved occurs in the mornings and just after noon and is mostly represented by scale 4 and 5.

The SCG in Step 2 improves the comfort during the morning hours which are represented mostly by scale 4, but scale 5, 6, and 7 are almost not affected which can be seen in Figure 52.

By analyzing Step 3 in Figure 52 it can be noted that the overheating hours were improved to comfort except for 3 % in scale 4. The 22 % that were improved compared to Step 2 were divided between scales 2 and 3 with 4 % and 18 % respectively. After Step 3 thermal comfort in 97 % of the occupied hours was achieved due to the proposed design changes.

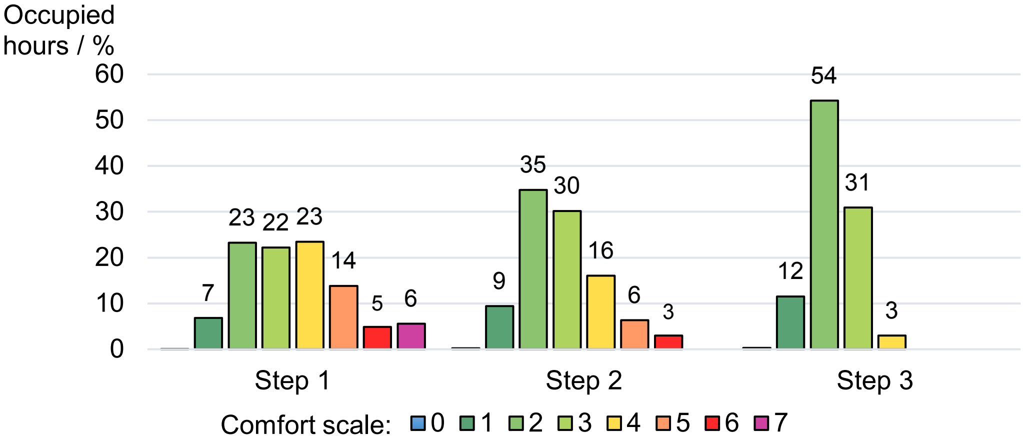


Figure 52. Steps 1-3, overview of the percentage of occupied hours within each comfort scale

4.5.3 Case 3: East, low-e and 25 ºC cooling point

In the third case two parameters were changed if compare to the other two validation cases: orientation was changed to the east and the cooling-set point was set to 25 ºC instead of 26 ºC. In this case only two steps were needed for the method to provide thermal comfort.

This first overheating chart in Figure 53 presents an opposite result comparing to the case 2 oriented to the west. The overheating hours mostly occurs in the morning in this case, this is due to that the direct solar radiation hits the glazing during the morning hours. Some blue areas also occur during mornings in March.

While using 25 ºC as cooling-set point the overheating hours are effectively reduced, which can be understood by analyzing Figure 54. Comfort occurs in 68 % of the occupied hours, which make the method suggest to immediately try an interior fabric blind with an OF 5 %. After applying an interior fabric blind, the remaining overheating hours are spread as small dots occurring around 9 AM, see Figure 53. Those dots have in common that they occur in days with high direct radiation from the sun.

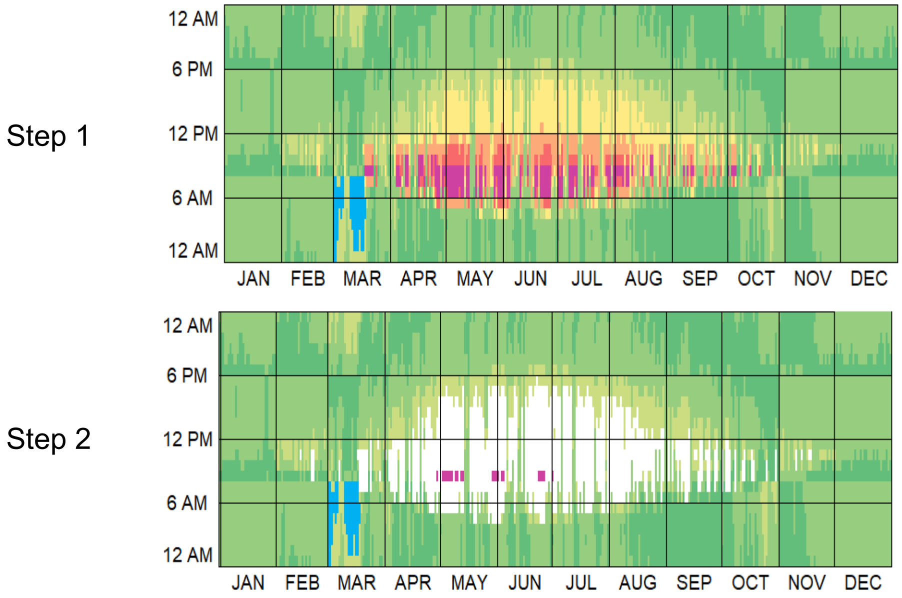


Figure 53. Step 1-2, overheating chart for the case with east orientated façade with low-e, 25 ºC cooling set-point while using PMV index.

In Figure 54 Step 2 shows that the interior fabric blind improves both hours within the comfort categories and the hours from overheating. The blind eliminates all overheating occurring in scale 5, 6, and 7 and just leave 1 % in scale unsolved. According to this result the room achieve comfort 99 % of the occupied hours.

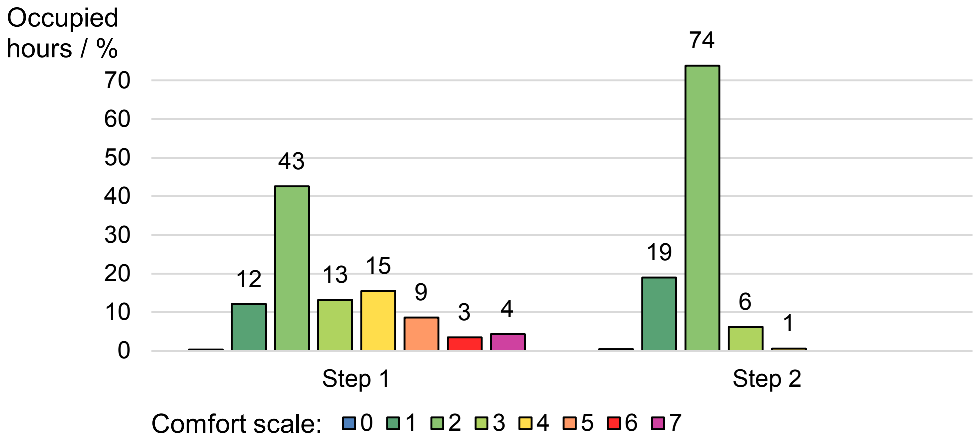


Figure 54. Step 1, overview of the percentage of occupied hours within each comfort scale. Step 2, overheating chart for low-e, 25 ºC cooling set-point and an Interior blind with OF of 5 % to the east while using PMV index

5 Analysis/Discussion

The method in this thesis was developed from the idea that it should be possible to create a design method to advice on the selection of SCM based on the analysis of the overheating and the effectiveness of the chosen SCM. In this chapter three main parts of the study are discussed, as well as the validation of the method; it is divided as:

- Solar Control Mechanisms
- Thermal Comfort Assessment
- Parametric study
- Steps of the method
- Validation

Within those parts both methodology and results are discussed in parallel to give an overview of the project.

5.1 Solar Control Mechanisms

Even though a limited number of SCMs was chosen for the study and implemented in the method, they reflect the main principle of solar control and address the problem of a proper combination of glazing type and solar control blind. In the assessment of the SCMs performance it was important to account for the effect of the blind position, as besides the increase of air temperature, the interior blind can be a source of higher mean radiant temperature itself, especially in the highly glazed spaces. The effect of the direct solar component should be accounted for, as it increases the thermal sensation of the occupant. Therefore, when assessing thermal comfort the adjusted mean radiant temperature is recommended to be used to give a reliable advice on the choice of SCM solutions.

5.2 Thermal comfort assessment

Even though CIBSE guide does not define comfort categories for AMC, they have been adopted from EN 15251 for AM for non-conditioned spaces. This is an assumption that was necessary for the development of the method and for scaling thermal comfort parameters.

Annual thermal comfort assessment, performed with the use of the developed overheating chart and the color index for scaling PMV and AMC, have shown the difference in the calculated comfort hours. The reason for that are the broader comfort limits for the temperatures allowed by AMC. In other words, where the possibility for adaptation is given and the occupant can adjust the clothing level in accordance with the outdoor temperatures and thermal expectations for the indoor conditions, higher temperatures can be perceived as comfortable. The difference in the thermal comfort performance when using PMV or AMC can be partly explained by the assumptions, which were made when developing comfort scale. Due to flexibility of AMC and its dependence on the hourly varied outdoor air temperature, it was not possible to find a correlation between PMV and AMC. Ranges of PMV and AMC for the comfort scale, therefore, were defined in different ways and not connected to each other.

5.3 Parametric study

The main purpose of the parametric study was to demonstrate the relative effect of the varied parameters, such as GWR, orientation and cooling set-points, on thermal comfort. Two of those parameters, GWR and cooling set-point, have been used in the method and advised to change when severe overheating problem cannot be solved by means of SCM. The orientation of the window was used in the validation of the method.

5.4 Steps of the method

To make the method user friendly and flexible, it was developed to provide the user the possibility to follow the advices or make assumptions and try other solutions. The first step of thermal comfort assessment was based on assumptions about how often it is reasonable to use a fabric blind. Fabric blinds are effective in reduction of overheating but they also significantly reduce the transmitted daylight. Although the developed method did not include daylight as a weighting parameter, it is an important parameter to consider when designing office spaces. Within this method an assumption was made which suggests choosing another strategy if the blind is predicted to be used more than 30 % of the occupied hours. The assumption was based on discussions about the reasonable percentage of occupied hours when daylight and view out can be blocked without causing dissatisfaction among the occupants.

The aim of the second step of the method, the glazing type selection, was to predict the effect of the direct solar transmittance on thermal comfort. Questions that needed to be answered were:

- How much can the transmitted direct solar radiation be reduced?
- How will it affect thermal comfort?

By analyzing the effectiveness of SCG units during the day, the affected hours were defined and then connected to the impact of the solar transmittance. The results shown that SCG units are most effective during morning and evening hours. A possible explanation can be that the higher the solar angle of incidence to the glazed area the higher the reflectivity of the glass. By knowing when the SCG is the most effective it was possible to set the boundaries by analyzing the data from DTM simulations. As the method was not verified for other location, there is a possibility that the defined boundaries will be less effective for another location than Stockholm.

When a fabric blind was defined by the method as an appropriate choice, the user was suggested to proceed to the third step of the method. The parameters involved in this step are the OF of the blind and expected percentage to which $MRT\text{-}T_{air}$ can be reduced by its application. To predict the impact of the blinds on $MRT\text{-}T_{air}$ reduction, an investigation was needed for the selected days with a high amount of incident direct radiation. The aim was to find a reference day and the reduced $MRT\text{-}T_{air}$, which can be applied to the rest of the year to achieve at least 95 % of comfort. The value of $MRT\text{-}T_{air}$ was verified with the varied orientation and cooling-set points.

The results of the study showed that a rule for $MRT\text{-}T_{air}$ can be applied if the day in the summer with highest incident direct radiation is used as a reference. It can be stated that the outdoor temperature has an impact on the amount of the overheating that occurs, but a more detailed investigation was not made in this project. The boundary for $MRT\text{-}T_{air}$ was set to 4.5 ºC, as this value was derived through the validation with different types of blinds and with all DTM simulations that were made in this study. Although, as it was stated before, this rule was only investigated with Stockholm Arlanda as location and may not be true if the location is changed.

5.5 Validation

The validation of the method was based on the DTM simulations performed during the parametric study. As it was expected, the most difficult orientation to handle was south, where the most drastic design advice of lower GWR was needed. However, the most effective design suggestion was to use a lower cooling set-point. From the analysis of the results, it may seem that a cooling-set point of 26 ºC is rather high and 25 ºC could be more suitable. The reason for the choice of 26 ºC as the reference case cooling-set point was to get an understanding of how effective the SCMs could be. From an energy-efficient perspective it is better to work with passive strategies to solve overheating, which also was a secondary task while developing this method.

The validation of the method went on smoothly until the west orientation was investigated. In the third step, when an appropriate blind is chosen, the method suggested a blind that did not reach the comfort requirements. The reason to why this mistake occurred was not found, a theory could be that the effect of thermal mass has a higher impact on the west orientation. However, to solve this problem an extra algorithm was added and supposed to be used only when the analyzed case is oriented to the west with a boundary for $MRT\text{-}T_{air}$ set to 3.5 ºC.

In this report, the cases for validation only considered the PMV index as comfort model. The method has also been validated for the use of AMC, the reasons for that are:
1. PMV is more sensitive to the environmental changes in the room;
2. AMC considers the outdoor temperature for the last seven days, while the method considers the temperature and direct radiation for each hour.

A simple explanation is that if the method provides comfort when using the PMV index it will provide it for AMC as well, due to that the PMV index takes more parameters into account and is more sensitive to changes of parameters than AMC.

The validation of the method can be continued in the future to further investigate the boundaries of the method. More rules can be added including more SCG with varied g-values and blinds with varied OF, to give the user a more detailed suggestion. Also, parameters like location, metabolic rate and clothing have not been changed during the validation. According to the EN 15251 standard, it is recommended to be within comfort category I when assessing thermal comfort for offices. This suggestion was not considered during the validation of this method, due to that it is very difficult to reach that category in a highly glazed space. In order to reach this demand more drastic design solutions are needed to be implemented in the parametric study.

6 Conclusion

In this thesis, a design method for driving the solar control mechanism selection was developed with the aim to reduce overheating problems in highly glazed spaces. The method intends to inform façade designers and to assist with the choice of solution in an early stage of the design process.

The method was developed as an Excel based design tool, where the user can insert hourly values from a DTM simulation representing the desired case. The process of developing this method was divided in three steps: Solar Control Mechanism selection, Thermal comfort assessment and Forming the method. The following conclusions can be drawn from the analysis of the results:

- The question of thermal comfort in highly glazed spaces is a complex task where more variables than properties of SCM need to be considered, such as GWR and Cooling set-point.
- Different comfort models acquire different SCM solutions to achieve thermal comfort and the PMV index is more sensitive than AM to changes of variables.
- The position of the blind, interior or exterior, is vital for the effectiveness in the reduction of overheating.
- The frequency of using fabric blinds can successfully be reduced by combination with appropriate SCG.
- It is important not only to consider *MRT* while driving the selection of SCM. A more accurate parameter can be MRT-T_{air}. If T_{air} is too high a SCM is not an appropriate solution as it might not solve the problem of overheating.
- South is the orientation which is the most exposed to solar radiation and, therefore, sensitive to the problem of overheating. If the glazed area is oriented to the south the façade designer need to apply more drastic solutions to reach comfort.
- The effectiveness of the SCM is the lowest when the glazed area is facing the west. This need to be accounted for while suggesting SCM.
- A cooling-set point of 25 ºC is in the most cases more suitable when using PMV index, based on the simulations performed within this study.
- The comfort category I, which is suggested by the EN 15251 standard, is very difficult to achieve when assessing highly glazed spaces, therefore, the validation of the method was based on comfort category III.

7 Future Work

The method leaves a lot of opportunities for further development, some suggestions are as follows:

- The geometry of the studied room can be a flexible parameter which also have a big impact on thermal comfort in different positions of the occupant in the room.
- The method can be expanded to include other comfort models, such as comfort models for transitory and semi-external spaces.
- Daylight is an important parameter to consider while assessing offices, this study did not consider any daylight parameters and that can be a part of a future study.
- View out is one of the main reasons to build with highly glazed facades and it could be an interesting task to optimize the view out while considering thermal comfort inside.
- When solar control blinds are used, the positive effect of daylight and view out is reduced. The detailed study of the frequency of the solar control blinds use without causing dissatisfaction among the occupants can be an interesting topic to study in the future.
- Most of the strategies proposed in this method are passive, therefore, they do not increase the energy demand significantly. However, an analysis of the energy demand could be a part of the validation of the method to see how the suggested solutions affect the energy performance.
- Life Cycle Analysis was not considered in this method, it would be an interesting future study to analyze how the suggestions of the method affect the economy of the project.

8 Summary

An increased use of glazing is architecturally attractive and beneficial in terms of daylight and view out. On the other hand, the problem of overheating due to excessive solar heat gains makes it challenging to provide thermal comfort for the occupants. Temperature control by air conditioning and cooling alone cannot always solve the problem of overheating, as the direct solar radiation falling on the occupant plays an important role in the perception of thermal conditions. Therefore, the use of solar control mechanisms is preferable as a more effective and energy-efficient measure. However, the choice of appropriate combination of solar control mechanisms is a complex task. An efficient control of solar heat gains needs to be provided without compromising the benefits of a highly glazed façade, such as daylight and view out.

To solve this problem, a method for the solar control mechanism selection was developed and formed as an Excel-based tool for an early design stage. Based on the user's input parameters, the method defines the problem of overheating in an examined space and suggests an effective solution to provide thermal comfort. To make the results more visual, an overheating chart was developed and implemented in the tool. This chart shows all hours of the year, colored after the degree of overheating that occurs. The scale was also developed within the method and serves for ranging the perception of thermal comfort. Solar control mechanisms, used in the method, are represented by two types of solar control glass in combination with interior and exterior fabric blinds. When advising on the solar control mechanism, the method ensures that the selected solar control blinds are not used too often.

For the development of the method a single office room was simulated using a dynamic thermal modeling (DTM) tool. A parametric study was performed in order to examine the effect of the reduced cooling set-point, glazing area and façade orientation on how effective the solar control mechanisms are in solving the problem of overheating. The results of the parametric study stood as a base for the decision-making part of the method. Based on the analysis of the results, a lower cooling set-point and a smaller glazing area were chosen as the options which are recommended if the problem of overheating cannot be solved by means of solar control mechanisms. The validation of the method has shown, that the difference between the mean radiant temperature (*MRT*) and the indoor air temperature (T_{air}) is an important control parameter for the solar control mechanism selection. This parameter indicates to which extent the problem of overheating is caused by solar heat gains and, therefore, can be solved by means of solar control mechanisms.

Overall, the results of the study showed that an effective combination of solar control glazing and fabric blind can be chosen to provide the required thermal comfort based on the thermal comfort assessment at an early design stage. To achieve that, it is important to account for the effect of the direct solar component and to control the difference between the mean radiant and the indoor air temperatures. At the same time, the frequency of the blind use can be controlled, potentially providing better conditions for daylight and view out. Providing that the developed method accounts for these parameters, it can be used in an early design stage to advice on the effective combination of the solar control mechanisms. However, a future development of the method is recommended in order to implement other types of solar control mechanisms and thermal comfort models and to validate the method for varied locations, geometry of the room and the position of the occupant.

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Appendix A

A.1. Calculation of thermal comfort

The PMV index is calculated by formula 1, 2 and 3.
PPD index is calculated by formula 4.

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

M – Metabolic rate (activity)
ADui (Du Bois area) – Surface area of the human body
η – External mechanical efficiency of the body
P_a – Partial pressure of vapor in the ambient air
T_a – Air temperature
MRT – Mean Radiant Temperature, mean temperature of all surfaces
f_{cl} – The ratio of the surface area of the clothed body to the surface area of the nude body (clothing area factor)
h_c – Convective heat transfer coefficient
t_{cl} – Mean temperature of outer surface of clothed body
v_a – Relative air velocity

Where:

$$t_{cl} = 35.7 - 0.039\frac{M}{A_{Dui}}(1-\eta)0.18I_{cl}\{3.4 \times 10^{-8} f_{cl}[(t_{cl}+273)^4 - (MRT + 273)^4] + f_{cl}h_{cl}((t_{cl} - T_a)\} \qquad (2)$$

and:

$$h_c = \{2.05(t_{cl} - T_a)^{0.25} \; for \; 2.05(t_{cl} - T_a)^{0.25} > 1.04\sqrt{v} \; 1.04\sqrt{v} \qquad for \; 2.05(t_{cl} - T_a)^{0.25} < 1.04\sqrt{v} \qquad (3)$$

Appendix B

B.1. Input data in Oasys ROOM. Reference case

Table B.1. Site data

Weather file	Stockholm Arlanda
Orientation of the window	180°

Table B.2. Room elements

Element	**Area / m²**	**Orientation / °**	**Thermal boundary**
floor	25		adiabatic
TGU Low-e	15	180	normal
partition	15	90	adiabatic
partition	15	0	adiabatic
partition	15	270	adiabatic
ceiling	25		adiabatic

Table B.3. Construction element layers

Element	**Element layers**	**Thickness / mm**
floor	flooring, timber hardwood	25
	concrete, insitu	250
partition	surface finishes, plasterboard	25
	concrete, block lightweight	150
ceiling	miscellaneous, ceiling tiles	25
	concrete, insitu	250

Table B.4. Glazing unit layers and their properties from WIS

Element	**Element layers**	**Solar transmittance / %**			**Visual transmittance/ %**
		Primary	**Secondary**	**Total**	
TGU Low-e	clear float 6mm	79	11	90	89
	16mm Argon 90%				
	iplus 1.1 6mm	64	1	65	89
	16mm Argon 90%				
	iplus 1.1 6mm	64	1	65	89
TGU SCG 1	clear float 6mm	79	11	90	89
	16mm Argon 90%				
	iplus 1.1 6mm	64	1	65	89
	16mm Argon 90%				
	ipasol 70 39 6mm	40	1	41	77
TGU SCG 2	Clear float 6mm	79	11	90	89
	16mm Argon 90%				
	iplus 1.1 6mm	64	1	65	89
	16mm Argon 90%				
	sunguard 62 29	29	1	30	89

Table B.5. Properties of the window system from Oasys ROOM

Blind position	**SCM, TGU alone and with blind**	**Solar Transmittance / %**			**Visual transmittance/ %**
		T solar Primary	**T solar Secondary**	**T solar Total**	
	Low-e	**36**	**11**	**47**	**70**
interior	OHM	8	26	34	15
	Duroscreen	2	25	27	4
exterior	Soltice	9	3	12	13
	Sunworker	2	1	3	4
	SCG 1	**23**	**8**	**31**	**61**
interior	OHM	6	18	24	13
	Duroscreen	2	18	20	3
exterior	Soltice	6	3	9	12
	Sunworker	1	2	3	3
	SCG 2	**17**	**6**	**23**	**54**
interior	OHM	4	14	18	12
	Duroscreen	1	14	15	3
exterior	Soltice	4	2	6	10
	Sunworker	1	1	2	3

Table B.6. Solar control blind properties

Element	**Name**	**Reflectivity / %**	**Absorptivity / %**	**T sol / %**	**T vis / %**	**Openness factor / %**
IB 1	OHM	56	25	19	18	10
IB 2	Duroscreen	83	12	5	5	5
EB 1	Soltice	42	36	22	20	14
EB 2	Sunworker	35	60	5	6	5

Table B.7. Internal heat gains

Energy source	**Load / Watts**
High pressure discharge lighting	300
2 personal computer	400
2 occupants with light work activity	280

Table B.8. Room environment

	Value	**Profile**
Heating	22 ºC	Constant
Cooling	26 ºC	Constant
Infiltration	0.25 ACH	Constant

Appendix C

C.1. VBA code for calculation of PMV

```
Function PMV(Ta, Tr, Vel, RH, CLO, MET, EW)    'Definition of the Function "PMV" by 7 factors

'  Ta  : Air Temperature,               [deg.C]
'□@Tr□@: Mean Radiant Temperature, □@    [deg.C]
'□@Vel : Relative Air Velocity,         [m/s]
'  RH  : Relative Humidity,             [%]
'  CLO : Clothing,                      [clo]
'  MET : Metabolic Rate,                [met]

'  EW : External Work,                  [met] (=normally around 0)
'  PA  : Water Vapor Pressure,          [Pa]
   PA = RH * 10 * FNPS(Ta)   '[Pa]=(RH/100)*1000*[kPa]

'---METABORIC RATE---
 m = MET * 58.15:    'Metabolic Rate,    [W/m2]
 W = EW * 58.15:     'External Work,     [W/m2]
 MW = m - W          'internal heat production in the human body

'---CLOTHING---
 ICL = 0.155 * CLO:  'thermal insulation of the Clothing, [m2K/W]
 If ICL < 0.078 Then FCL = 1 + 1.29 * ICL Else FCL = 1.05 + 0.645 * ICL  'clothing area factor

'---CONVECTION---
 HCF = 12.1 * Sqr(Vel):  'convective heat transfer coefficient by forced convection
 TaA = Ta + 273:         'Air Temperature in Kelvin [K]
 TrA = Tr + 273:         'Mean Radiant Temperature in Kelvin [K]

'CALCULATE SURFACE TEMPERATURE OF CLOTHING BY ITERATION
 TCLA = TaA + (35.5 - Ta) / (3.5 * (6.45 * ICL + 0.1))
'first guess for surface temperature of clothing
 P1 = ICL * FCL:  'calculation term
 P2 = P1 * 3.96:  'calculation term
 P3 = P1 * 100:   'calculation term
 P4 = P1 * TaA:   'calculation term
 P5 = 308.7 - 0.028 * MW + P2 * (TrA / 100) ^ 4 'calculation term
 XN = TCLA / 100
 XF = XN
 n = 0:           'N: number of iterations
 EPS = 0.00015:   'stop criteria in iteration

Do
XF = (XF + XN) / 2

'convective heat Transf. coeff. by natural convection
 HCN = 2.38 * Abs(100 * XF - TaA) ^ 0.25
 If HCF > HCN Then HC = HCF Else HC = HCN
 XN = (P5 + P4 * HC - P2 * XF ^ 4) / (100 + P3 * HC)
 n = n + 1
```

```
 If n > 150 Then GoTo 50
Loop Until Abs(XN - XF) < EPS

 TCL = 100 * XN - 273:  'surface temperature of the clothing

'---HEAT LOSS COMPONENTS---
'heat loss diff. through skin
 Ediff = 3.05 * 0.001 * (5733 - 6.99 * MW - PA)
'heat loss by sweating (comfort)
 If MW > 58.15 Then Esw = 0.42 * (MW - 58.15) Else Esw = 0!
'latent respiration heat loss
 LRES = 1.7 * 0.00001 * m * (5867 - PA)
'dry respiration heat loss
 DRES = 0.0014 * m * (34 - Ta)
'heat loss by radiation
 R = 3.96 * FCL * (XN ^ 4 - (TrA / 100) ^ 4)
'heat loss by convection
 C = FCL * HC * (TCL - Ta)

'--- CALCULATE PMV AND PPD ---
'Thermal sensation transfer coefficient
 TS = 0.303 * Exp(-0.036 * m) + 0.028

'Predicted Mean Vote
 PMV = TS * (MW - Ediff - Esw - LRES - DRES - R - C)

GoTo 80
50 PMV = 999999!
80 '
End Function
```

C.2. VBA code for calculation of PPD

```
Function PPD(PMV)
   PPD = 100 - 95 * Exp(-0.03353 * PMV ^ 4 - 0.2197 * PMV ^ 2)
End Function
```

Appendix D

D.1. VBA code for calculation of AMC lower limit

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

D.2. VBA code for calculation of AMC upper limit

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

Appendix E

E.1. VBA code for calculation of T_{rm}

```
Sub DM()
Dim myArra(365) As Double
dayAvgTemp = 0
For i = 4 To 8763 Step 24
nrow = i + 23
Sum = 0
For j = i To nrow Step 1
Sum = Sum + Worksheets(2).Range("k" & j).Value
Next j
Worksheets(2).Range("n" & i).Value = Sum / 24
myArra(dayAvgTemp) = Sum / 24
dayAvgTemp = dayAvgTemp + 1
Next i
For k = 0 To 364
tita = 0
alfa = 0.8
alfaPower = 0
For l = k - 1 To k - 7 Step -1
lnew = l
If l < 0 Then lnew = l + 365
tita = tita + alfa ^ alfaPower * myArra(lnew)
alfaPower = alfaPower + 1
Next l
For m = 3 To 26
Worksheets(2).Range("o" & (k * 24) + m).Value = tita * (1 - alfa)
Next m
Next k
End Sub
```

Appendix F

F.1. The results of the thermal comfort analysis for the cases with east and west oriented glazing

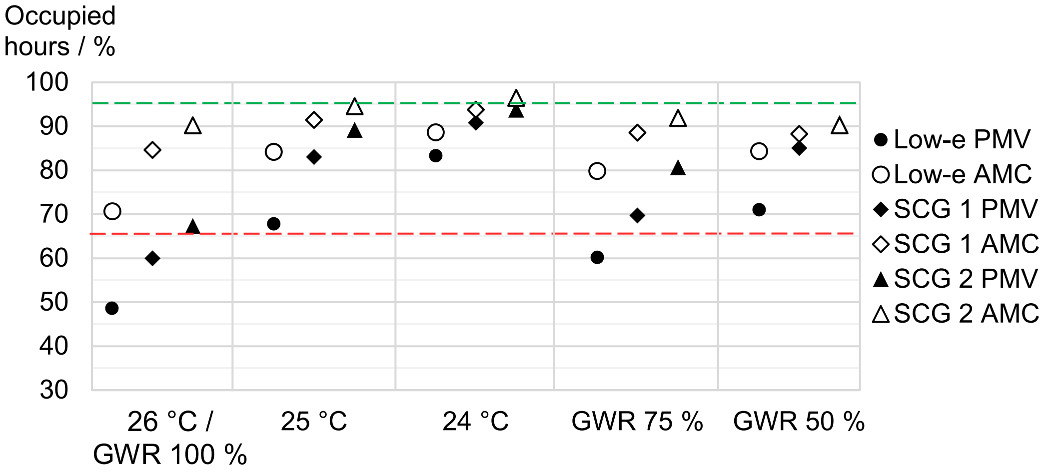

Figure X. The percentage of occupied hours when thermal comfort in category III is achieved for the cases with east oriented window

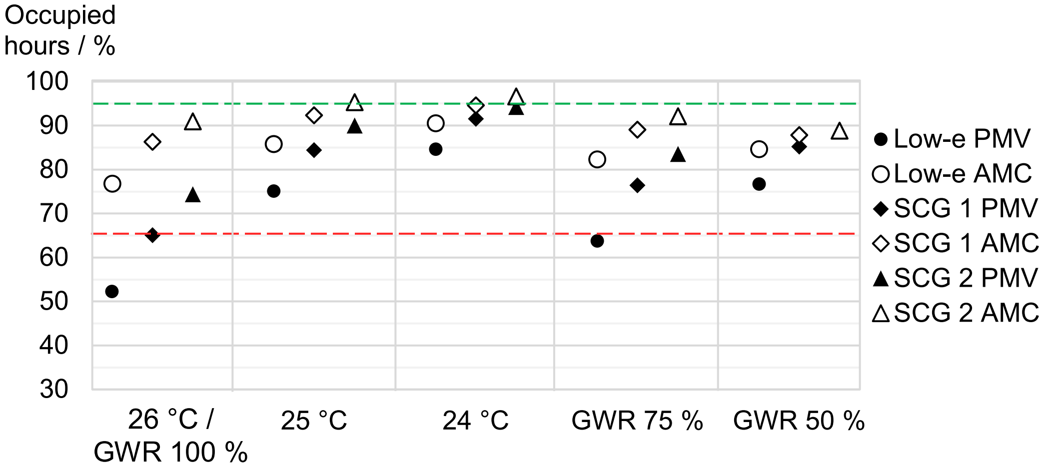

Figure X. The percentage of occupied hours when thermal comfort in category III is achieved for the cases with west oriented window

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Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services