

Refined distribution of frit

Design tool for improvement of thermal comfort
in glazed spaces

Amanda O'Donnell & Magdalena Stefanowicz

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 centers 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.

Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

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

Keywords: Thermal comfort, glazed spaces, g-value, over-heating, solar shading, frit, parametric design

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Abstract

Thermal comfort in highly glazed spaces has long proven to be a troublesome matter due to unwanted passive solar heat gains, and consequent elevated cooling loads.

A methodology was developed to correlate overheating with shading need, informing designers of how to distribute the solar heat transmission (g -value) of glazed façades in order to mitigate local discomfort to the extent possible with passive shading design. A light, reflective ceramic shading device known as frit has been utilized, enabling selective alleviation of solar gains. The methodology has been developed into a design tool, scripted in Rhino/Grasshopper, facilitating parametric applicability.

The results indicate that the methodology is successful in reducing local peak temperatures in a glazed office space (for Swedish climate conditions), achieving up to 9%, 19%, 32% and 87% annual reduction of hours where temperatures exceed 26°C, 28°C, 30°C and 35°C respectively. Other results include; the method being most efficient for local over heating problems, decreasing coherently with increased analysis area. Further, the usability increases notably with reasonable initial overheating problems, indicating that the method could be a beneficial complement to a functioning ventilation system, rather than a substitute. Moreover, by concentrating shading where it is needed most, the average g -value can be increased with as much a 11% for at still maintain initial climate conditions above 35°C, showing potential for the method/tool to contribute to economic and environmental savings for highly glazed spaces in Sweden.

These outcomes prove favorable for further development of the methodology to decipher more complex building geometries and user specifications.

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Abbreviations

Low-e glass – low emissivity	
DGU – double glazing unit	
<i>g</i> -value – shading coefficient	
<i>g_{av}</i> - average <i>g</i> -value of a glazing	
<i>U</i> -value - rate of heat transfer (W/m ² K)	
VT - visual transmittance	
<i>E_R</i> – Solar heat energy reflected to the outside	
<i>E_{DT}</i> – Direct solar heat energy transmitted to the inside	
<i>E_A</i> – Solar heat energy absorbed by the glazing	
<i>E_{AT}</i> – fraction of energy absorbed by the glazing and transferred to the inside	
<i>T_o</i> – operative temperature (°C)	
<i>T_{op,Adj}</i> – solar adjusted operative temperature (°C)	
<i>T_{air}</i> – air temperature (°C)	
<i>MRT</i> – mean radiant temperature (°C)	
<i>MRT_{Adj}</i> – mean radiant temperature adjusted to compensate for the effect of short wave solar radiation on human body (°C)	
<i>ERF</i> – effective radiant field	
<i>f_{eff}</i> - fraction of the body surface exposed to radiation from the environment (0.696 for a seated person)	
<i>h_r</i> - radiation heat transfer coefficient (W/m ² K)	
<i>f_{svv}</i> - fraction of sky vault in occupant's view	
<i>I_{diff}</i> - diffuse sky irradiance received on an upward-facing horizontal surface (W/m ²)	
<i>I_{TH}</i> - total outdoor solar radiation on the horizontal plane (W/m ²)	
<i>R_{floor}</i> - reflectance of the floor	
<i>A_p</i> - projected area of the body	
<i>f_{bes}</i> - fraction of body exposed to sun	
<i>I_{dir}</i> – direct beam (normal) solar radiation (W/m ²)	
<i>A_D</i> - the DuBois surface area of the assumed person (ca. 1.8 m ²)	
<i>T_{sol}</i> – total solar transmittance of a window system	
<i>α_{SW}</i> - short-wave absorptivity (0.67 for white skin and average clothing)	
<i>α_{LW}</i> - long-wave emissivity/absorptivity, typically equal to 0.95	
<i>E+</i> - EnergyPlus, a whole building energy simulation program	
.epw – EnergyPlus weather file format	
<i>GH</i> – Grasshopper, a graphical algorithm editor	
<i>HB and LB</i> - Honeybee and Ladybug, open source environmental plugin for Grasshopper	
<i>g_{av}</i> – average <i>g</i> -value of the facade	
<i>A_{sh}</i> – Total shading frit area need, m ²	
<i>A_{facade}</i> – Total façade area, m ²	
<i>TR_{sh}</i> – Frit transparency	
<i>g_{non-shaded}</i> – Non-shaded glass <i>g</i> -value	
<i>A_{ΔTfactor}</i> – Single frit area relative to <i>ΔT factor</i>	
<i>A_{sh,unit}</i> – Shading area needed for a glazing unit, m ²	
<i>A_{unit}</i> – Area of a glazed unit, m ²	
<i>g_{non-shaded}</i> – Non-shaded glass <i>g</i> -value	
<i>F</i> - Number of frit dots per glazing unit	
<i>A_{frit}</i> - Area of a single frit dot, m ²	
<i>A_{frit,unit}</i> – Total frit area needed for a glazing unit, m ²	

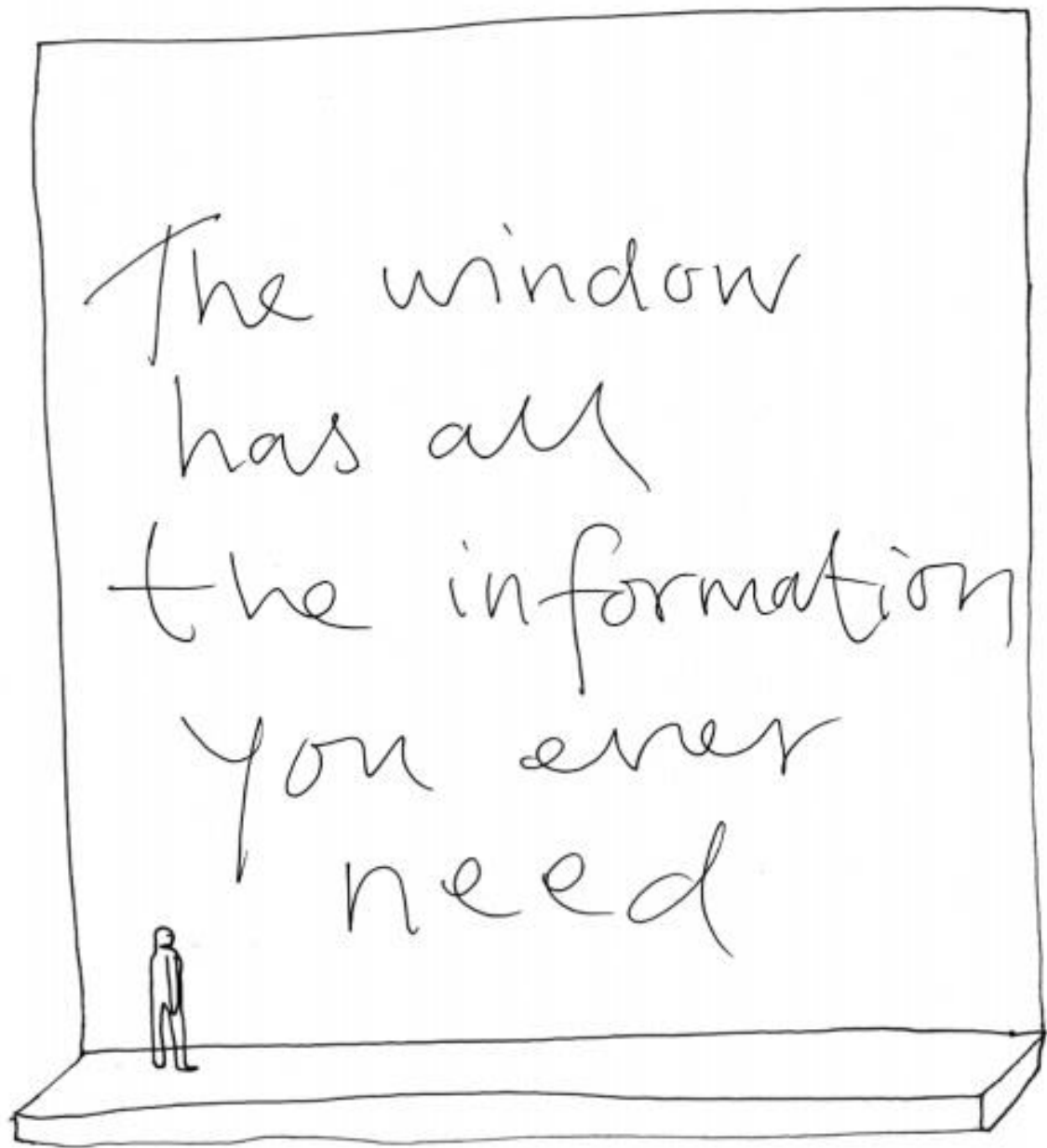


Figure 1: DAYLIGHT & ARCHITECTURE, Issue 22

1 Introduction

The energy required to heat and cool our buildings, and the very way we define the “comfortable” thermal conditions we are trying to maintain, play significant roles in this environmental impact [of buildings]. The use of energy for heating, ventilating and air-conditioning (HVAC) of the indoor environment is already the largest sector in energy consumption in most of the developed world (Griffiths et al 1988). (de Dear, et al., 1997)

Thermal neutrality occurs when the body is in equilibrium with its surroundings. The stability of an indoor climate, enabling thermal neutrality, depends highly upon the thermal resistance of the building envelope, for which glazing is an Achilles heel.

Highly glazed envelopes are prominent in modern architecture for many reasons, including; increased levels of natural light, views to the exterior and, when desired, passive solar gains. However, when not desired, the consequences of passive solar gains on the indoor environment are considerable, for which many buildings must overcompensate with elevated mechanical cooling and additional shading in order to comply with comfort regulations.

Advanced glazing systems, incorporating multiple layers of glass, gases and/or solar control coatings are often introduced to lower the solar energy transmittance of glazing, g -value, and mitigate overheating, but concurrently tend to subside the architect's original ambitions of transparency. This become particularly apparent in multifunctional glazed spaces, where daylight and views may be desired in some places, but in others, not.

Hereby, the purpose of this study is to develop a method which aims to correlate specified overheating problems indoor thermal discomfort with shading need of glazed facades. The method consists of a parametric design tool, which identifies regions of a façade which are source to critical thermal discomfort and hereafter suggest means of distributing the g -value of the façade, in order to lessen these problems locally.

1.1 Problem motivation

A need was expressed by the industry to innovatively connect overheating in glazed spaces with customized shading solutions for quick and informed decision making in the early design phase, a notion which inspired the thesis.

Initial analyses revealed that there is limited availability of multifunctional tools of this sort on the market. There are several advanced simulation software which can produce specific output however, without having substantial experience of these tools and in-depth knowledge of how to interpret their results, their applicability in the early design phase becomes less apparent.

1.2 Objectives and aims

The primary objective was to create a comprehensive methodology to investigate to what extent local thermal comfort can be improved by eliminating specific solar gains in glazed spaces. Secondly, to depict this methodology in design tool able to inform designers of both thermally problematic regions and if/how they could be omitted by applying the method. The tool should provide suggestions for shading distribution as well as enable iterative processing of results and provide designers with knowledge to inform their design. The tool aims to be parametric, enabling applicability on a wide range of geometrical, geographical and behavioral cases.

1.3 Limitations

The method has been run on a simple “box” building geometry, representing a freestanding office with no furniture or obstructing geometries. The results of the method/tool are based on simulations only, for which the conformance to physical measurements is unknown. Regarding the simulation setup, a few limitation have been made. Firstly, the analysis of thermal comfort in the study is restricted to temperature parameters, i.e thermal comfort is measured in adjusted operative temperature. Any secondary effects of the method on other

comfort parameter have been ignored. Secondly, construction materials and schedules from the simulation engine's built in database have been used, for which some deviation to Swedish standards may have occurred. Thirdly, no angular dependent properties of incident solar radiation have been considered. These simplifications are explained further in the methodology section of the report.

1.4 Contribution

The project has inherently been a collaborative process and was developed with equal contribution of Amanda and Magdalena. The methodology was consequentially planned and processed in great detail by both authors. Tool definitions were collectively structured throughout. With regard to scripting, Amanda focused more on thermal module and data module of the tool and Magdalena worked more on solving the ray tracing module. All encountered problems in the scripting were solved together and the definitions were continuously refined in accordance with ambitions of both authors. All output from the separate modules of the tool was analyzed by both parts, with comparative and critical reasoning.

Interpretation of numerical data and translation to graphical results were developed together. Visual communication of results were mainly shaped by Magdalena where as written output was mainly articulated by Amanda, with continuous feedback from both parts.

1.5 Acknowledgement

We would like to thank our supervisor Henrik Davidsson for his rational guidance and selfless support. We would have lost track many times without you. Immense gratitude goes to our mentor Harris Poirazis for his knowledge, encouragement and passion for the project, pushing us and the project beyond our expectations. We would like to thank the Hans Eliasson Foundation for supporting the EEBD Master program.

2 Theory

This chapter includes theoretical aspects which have been considered when deriving the method.

2.1 Thermal comfort

Thermal comfort is defined as “*that state of mind which expresses satisfaction with the thermal environment*” (ANSI/ASHRAE Standard 55, 2010). Since “state of mind” is a highly subjective matter, thermal comfort is a difficult matter to quantify. Nevertheless, there is a common understanding of that the thermal balance of the human body varies with a range of environmental and physical parameters.

The environmental parameters include air temperature, mean radiant temperature, relative air velocity and humidity. The physical parameters include metabolic heat production and clothing level (ISO, 2005)

2.1.1 Thermal comfort in glazed spaces

Understanding the influence of windows on thermal comfort is important not only to help designers create comfortable buildings, it will also help evaluate the benefits of improved windows. (Huizenga, et al., 2006, p. 5)

Heat is transferred to and from a space as a result of a temperature gradient between a surface e.g. a window and air in the space. There are three main ways of transferring thermal heat:

1. Conduction
2. Convection
3. Solar radiation

A highly glazed building envelope is more sensitive to convective losses to the outdoor environment than corresponding opaque facades (Poirazis, 2008). Despite advancement of high performance glazing technologies, glass remains a thermal deficient component of a building envelope. Hereby, glazing generates a more volatile and seasonally fluctuating indoor climate, often leading to increased cooling and heating loads respectively. In winter, a window's effect on thermal discomfort depends mainly on insulative performance which refers to the heat transfer by conduction. The summer effect, however, depends on insulative performance as well as transmission of solar radiation. (Poirazis, 2008)

2.1.1.1 Solar radiation

There are three ways in which solar radiation through glazing impacts thermal comfort (Huizenga, et al., 2006), namely:

1. short-wave radiation
2. long-wave radiation
3. induced air motion (convective drafts)

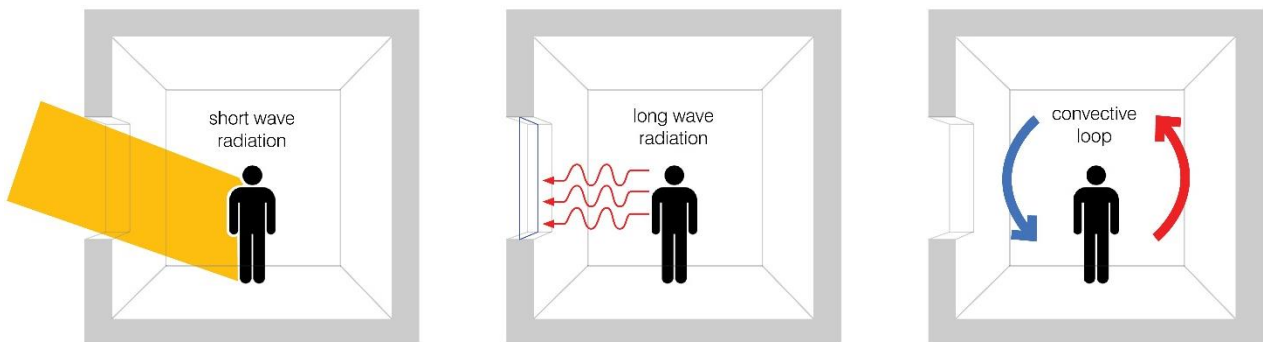


Figure 2: Window effect on thermal comfort

Short-wave radiation

Short-wave radiation is the radiation from the sun consisting of two components: direct and diffuse radiation (Huizenga, et al., 2006).

The direct component is the radiation from the direct solar beam. Direct radiation transmitted through glazing and falling on occupants, has the most significant impact on experienced thermal comfort (CIBSE, 2006), affecting the occupants in two ways; (1) directly when absorbed by the body and (2) indirectly by increasing the air and surface temperatures in a space (Huizenga, et al., 2006).

The diffuse component is the radiation which reaches the window after being scattered/reflected by clouds or air particles outside. The amount of sky covered in clouds is depicted as a fraction of total sky cover on a scale from 0 to 10, where 0 is clear skies and 10 is total cloud coverage. Amount of sky dome in tenths covered by clouds or obscuring phenomena. (Roudsari, 2015)

Long-wave radiation

Long-wave radiation refers to radiant heat transfer between objects. Long-wave radiation from warm or cold windows affects an occupant's comfort in two ways; (1) It affects the body's comfort perception by influencing the overall radiative heat exchange between the body and the surrounding surfaces and (2) as the glazing becomes warmer than other indoor surfaces it creates radiant asymmetry. In that case, the window acts as a radiator emitting additional heat to the room, which might become a source of discomfort (Huizenga, et al., 2006)

Apart from direct short-wave radiation falling on an occupant, long-wave radiation between the window and the rest of the room is the most significant factor influencing thermal comfort. (Lyons, et al., 1999)

Convective drafts

Convective drafts are air motions induced by a difference between the glass surface temperature and the adjacent air temperature. Convective draft occurs when indoor air hits the cooler surface of glass and sinks towards the floor, creating a circular air movement. In winter, drafts often cause a local cooling of a body. In summer, however, the air motion is desirable to stimulate natural ventilation in buildings (Huizenga, et al., 2006).

As the thermal comfort analysis in the thesis are restricted to temperature parameters, the effect of convective drafts has been ignored.

2.1.1.2 Optical properties of glazing

Solar heat gain through windows is dependent on two main components: transmitted and absorbed radiation. The transmitted radiation corresponds to how much short wave radiation reaches the occupant, while the absorbed radiation corresponds to how much the window temperature increases. (Huizenga, et al., 2006) Additionally, a certain fraction of solar radiation is being reflected from the glazed surface to the outside.

In *Figure 3*, relations between radiation absorbed, reflected and transmitted are being shown:

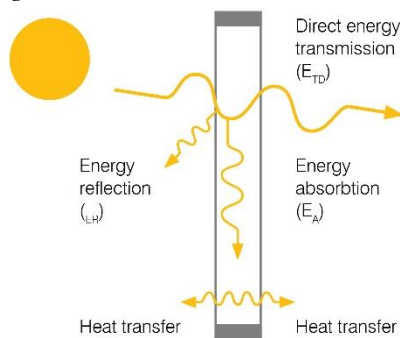


Figure 3: Solar heat energy transferred through a glazing.

Where,

$$E_R + E_{DT} + E_A = 1$$

Equation 1

E_R – Solar heat energy reflected to the outside

E_{DT} – Direct solar heat energy transmitted to the inside

E_A – Solar heat energy absorbed by the glazing

2.1.1.2.1 Simple window indices

The following three simple window indices are utilized for thermal calculations performed in this study (Arasteh, et al., 2009):

1. *U*-value

The rate of heat transfer through a window measured in $W/(m^2 \cdot K)$.

2. *g*-value

g-value (or Solar heat gain coefficient, SHGC) is a commonly used shading coefficient, representing the fraction of incident solar radiation transmitted by a window, where 1 represents maximum possible solar heat transmission, and 0 represents none. It is expressed as the sum of direct solar energy transmitted and the secondary internal heat transfer of energy absorbed in the glazing (Rosenfeld, 1996).

$$g\text{-value} = E_{DT} + E_{AT}$$

Equation 2

Where,

E_{DT} – direct energy transmitted to the inside (solar transmittance)

E_{AT} – fraction of energy absorbed by the glazing and transferred to the inside

It is important to understand, that when *g*-value alone is used to describe the solar radiation transmitted in building simulation, the results are approximate. Standardized *g*-values (EN 410) are determined for normal incidence, whilst the angular properties of different types of glazing vary with number of layers and coatings (Standards, 2011). Consequently, two windows of the same *g*-value might have different ratios of transmitted and absorbed solar radiations (Arasteh, et al., 2009).

3. Visible transmittance

The visual transmittance (*VT*) of a glazing is the amount of visible light which can pass through the glass. *VT* is influenced by glazing type, number of panes and any coatings.

2.1.1.3 Solar control of glazing

A common way of lowering *g*-value and thereby reducing the solar transmittance of a glazing, is to apply reflective coatings, which increases the glasses reflectivity. High performance tinted glass and low-e coatings are able to provide *g*-value for a double glazed window between *g*-value of 0.2 and 0.7 and a light transmittance between 0.3 and 0.8 W/m^2K (Poirazis, 2008). However, when very low *g*-value glass is applied uniformly across a façade, the light transmittance is likely to be insufficient and views to the outside might be disturbed with coating's coloring.

2.1.1.3.1 Fritted glass

An alternative solar control is frit glass. Frit is the name of a static shading material, added to a surface of a glazing system often in a specified pattern, as shown in *Figure 4*. Applied pattern of ceramic frit can be either opaque or translucent. The solar-control effect depends on the ratio of clear glass to fritted area. (Schittich, et al., 2007).

A number of different ceramic fritted glazing are available:

- Single pane with ceramic frit on interior side
- Double pane with ceramic frit placed on interior side of outer pane
- Triple pane with ceramic frit on exterior side of middle pane

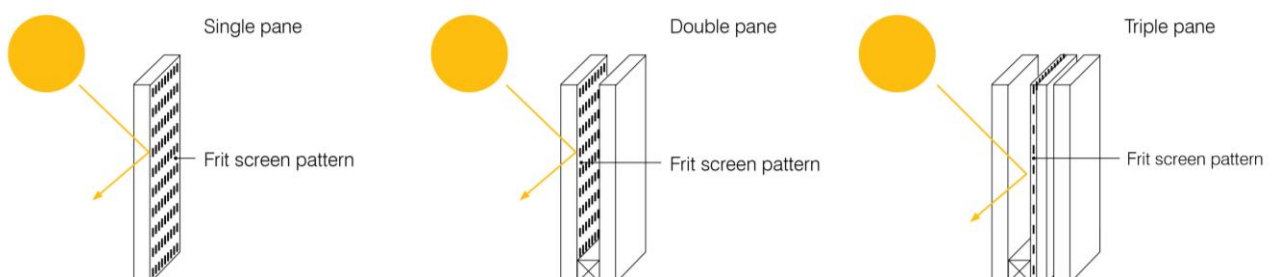


Figure 4: Frit glass assembly.

Fritted glass is available in various ranges of pattern as shown in *Figure 5*, with frit coverage up to 60%.

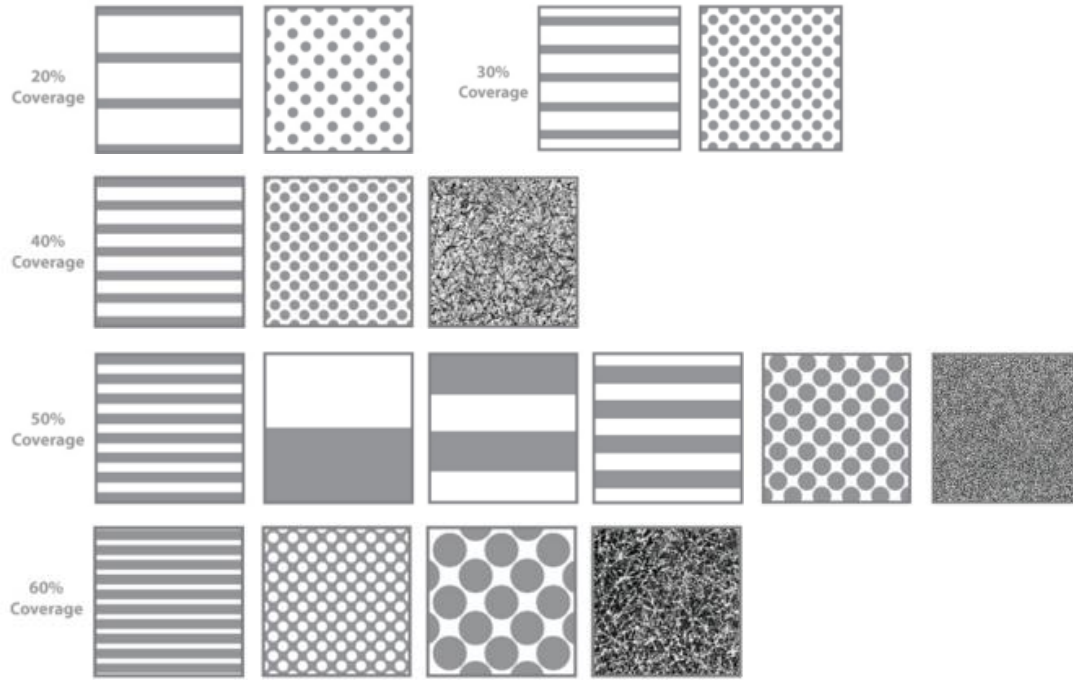


Figure 5: Silk-screen patterns. Examples by Viraspan TM Design ([www. viracon.com](http://www.viracon.com))

2.1.1.3.2 Shading coefficient of fritted glass

Glazing unit is a commonly used term to describe an independent part of a window usually separated with a frame. Glazing unit consists of specific types of glass and filling gases, for which every glazing unit may have its own specific characteristics such as g-value, U-value and visual transmittance.

For single pane glazing units with frit, the total average g-value could be defined as area-weighted sums of the individual area's g-values. (McCluney, 2002)

$$g_{av} = \frac{(g_1 * A_1) + (g_2 * A_2) + (g_3 * A_3) + (g_4 * A_4)}{A_1 + A_2 + A_3 + A_4}$$

Equation 3

Where,

A_1, A_2, A_3, A_4 – areas of individual glazing units

g_{av} - average g-value of a glazing

g_1, g_2, g_3, g_4 – g-values of individual glazing units

For specific types of multi-layered glazing units with frit, g-value is commonly defined by producers or can be calculated in more complex ways, which include angle-dependent g-values or three-dimensional heat transfer calculations (Karlsson, 1999). For these calculations many specific optical properties of the glazing, often difficult to obtain, are required. Hereby, for the purpose increasing the functionality of the method, the simplified calculation in *Equation 3* is utilized throughout the project.

2.1.1.4 Glazing to floor ratio

Glazing to floor ratio (*GFR*) indicates how much a space is glazed with regards to its floor area. A minimum sufficient level of GFR for a low-energy office buildings in cold climate is considered to be 12%. (Persson, 2006)

2.1.2 Comfort temperature parameters

According to CIBSE (2006), temperature is usually the most important environmental parameter affecting thermal comfort in spaces. Comfort temperature parameters of air temperature, mean radiant temperature and operative temperature are described below.

2.1.2.1 Air temperature (T_{air})

Air temperature is the physical temperature of the air. It is measured in spots exposed to the air but shielded from radiation and moisture.

2.1.2.2 Mean radiant temperature (MRT)

Mean radiant temperature represents an impact of long wave radiation (radiant heat) from the surrounding surfaces.

2.1.2.3 Operative temperature (T_{op})

Operative temperature is the average of air temperature and radiant temperature experienced by an occupant and can be calculated as follows:

$$T_o = \frac{T_{air} + MRT}{2} \quad \text{Equation 4}$$

Where,

T_o – operative temperature (°C)

T_{air} – air temperature (°C)

MRT – mean radiant temperature (°C)

Equation 3 is a simplified method of calculating T_o and is only relevant for occupants who are not exposed to direct sunlight or to air velocities greater than 0.20 m/s. (ANSI/ASHRAE Standard 55, 2010)

2.1.2.4 Adjusted mean radiant temperature (MRT_{Adj})

The solar component constitutes a significant part of what this thesis is analyzing, for which solar adjusted MRT is chosen as a determining factor for thermal comfort. MRT_{Adj} , as shown in Figure 6, represents an existing mean radiant temperature adjusted for shortwave solar radiation on a human body:

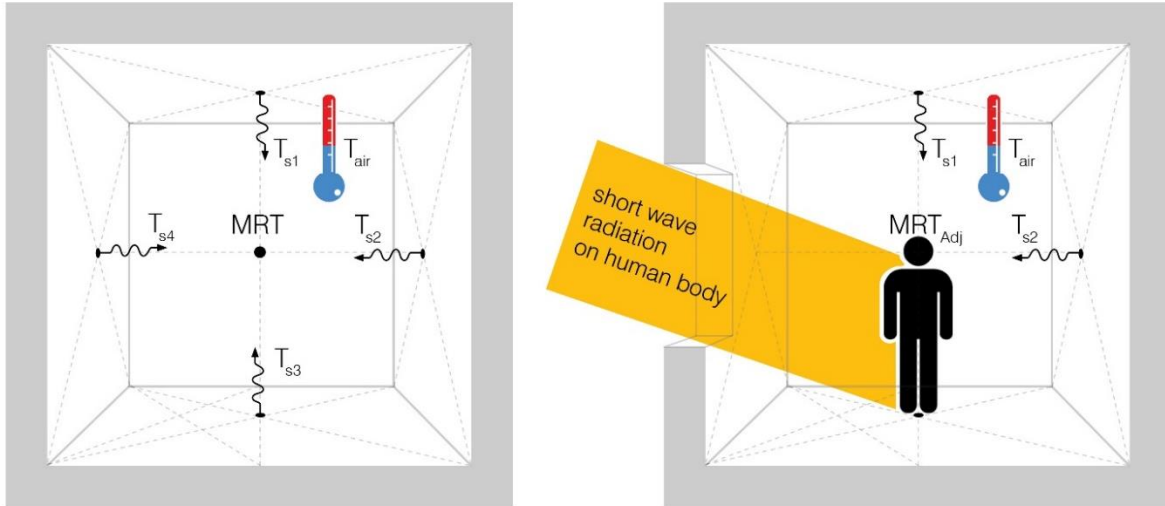


Figure 6: Temperature parameters of thermal comfort in a room without a window and a room with a window, where T_s - surface temperature, MRT - mean radiant temperature, MRT_{Adj} - solar adjusted MRT, T_{air} – air temperature.

The short wave radiation falling on an occupant is translated into an effective radiant field and solar adjusted mean radiant temperature according to SolarCal method. (Arens, et al., 2015)

SolarCal method

Arens (2015) presented a method for quantifying the solar radiation on the occupant. The SolarCal model is based on the effective radiant field (ERF). ERF is a measure of additional radiant heat flux to or from the human body and it can be calculated for an occupant exposed to both long-wave exchange with surfaces and short-wave radiation.

The surrounding surface temperatures are represented as mean radiant temperature (MRT) which can be related to ERF (from long-wave exchange with surfaces) by:

$$ERF = f_{eff} * h_r * (MRT - T_{air}) \quad \text{Equation 5}$$

Where,

f_{eff} - fraction of the body surface exposed to radiation from the environment (0.696 for a seated person)

h_r - radiation heat transfer coefficient ($W/m^2 K$)

T_{air} - air temperature ($^{\circ}C$)

When short-wave radiation absorbed on the body's surface is considered, the additional solar radiation flux (ERF_{solar}) can be calculated by:

$$ERF_{solar} = (0.5 * f_{eff} * f_{svv} * (I_{diff} + I_{TH} * R_{floor}) + (A_p * f_{bes} * I_{dir}/A_D) * T_{sol} (\alpha_{SW}/\alpha_{LW}) \quad \text{Equation 6}$$

Where,

f_{svv} - fraction of sky vault in occupant's view

I_{diff} - diffuse sky irradiance received on an upward-facing horizontal surface (W/m^2)

I_{TH} - total outdoor solar radiation on the horizontal plane (W/m^2)

R_{floor} - reflectance of the floor

A_p - projected area of the body

f_{bes} - fraction of body exposed to sun

I_{dir} - direct beam (normal) solar radiation (W/m^2)

A_D - the DuBois surface area of the assumed person (ca. 1.8 m^2)

T_{sol} - total solar transmittance of a window system

α_{SW} - short-wave absorptivity (0.67 for white skin and average clothing)

α_{LW} - long-wave emissivity/absorptivity, typically equal to 0.95

When ERF_{solar} is added to the longwave ERF , a new solar-adjusted mean radiant temperature (MRT_{Adj}) can be calculated with the Equation 4.

2.1.2.5 Adjusted operative temperature ($T_{op, Adj}$)

Solar adjusted operative temperature $T_{op, Adj}$, is obtained using the same relations as in Equation 3.

$$T_{op, Adj} = \frac{T_{air} + MRT_{Adj}}{2} \quad \text{Equation 7}$$

Where,

$T_{op, Adj}$ - solar adjusted operative temperature ($^{\circ}C$)

T_{air} - air temperature ($^{\circ}C$)

MRT_{Adj} - solar adjusted mean radiant temperature ($^{\circ}C$)

2.1.3 Comfort models

Currently, two models aiming to quantify perceived thermal comfort coexist. One model, Predicted Mean Vote (PMV) is based on the static heat balance of the body and the second model, adaptive model, considers the human thermoregulatory system's ability to adapt to its surroundings. (Brager & de Dear, 2001)

2.1.3.1 Adaptive comfort

"The adaptive model, which states that factors beyond fundamental physics and physiology play an important role in impacting people's expectations and thermal preferences" (Brager & de Dear, 2001).

The adaptive model is based on research done on field studies. The model refers to the human mechanisms of acclimatization being paramount to the way in which comfort is individually perceived. (Brager & de Dear, 2001).

2.1.3.2 Swedish recommendations

The Swedish department of health recommends operative temperature not to exceed $26^{\circ}C$ for an extended period of time. (Folkhälsomyndigheten, 2014)

2.2 Ray tracing

Ray tracing is a method for tracking light rays coming into a space and is as a result a method of rendering three-dimensional graphics with very complex light interactions. There are various types of ray tracing including backward, forward and hybrid ray tracing. For the purposes of this thesis, backward ray tracing is used, which implies that eyes are the light source and hereby source of the rays. The rays are further called solar vectors. The main principle of backward ray tracing and solar vectors bouncing off surfaces is shown in *Figure 7*. (Radiance, 2015).

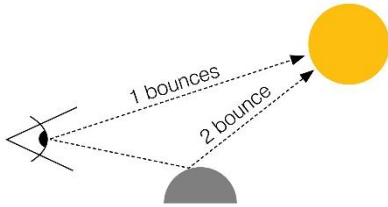


Figure 7: Backward ray tracing with 1 and 2 bounces.

2.3 View factor

View factor is a geometric quantity between 0 and 1 and describes the exchange of energy between two surfaces. Radiation heat exchange between surfaces depends on the orientation of the surfaces relative to each other. This dependence on orientation is accounted for by the view factor. (Cengel Y. A., 2011). As seen in *Figure 8*, the orientation of a surface highly impacts the radiative heat exchange to which the point is exposed.

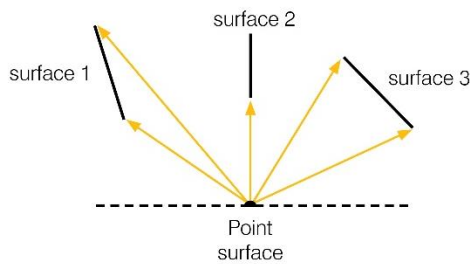


Figure 8: View factor concept.

3 Method

3.1 Overview / Project structure

The structure of the project comprises four steps, illustrated in *Figure 9*. The initial step, Step 0 is where the building geometry is modelled in Rhino. The following three steps constitute the core of the shade tracing method/tool developed in this thesis.

Step 1 is the thermal module, which analyses how thermal comfort is affected by solar gains in the existing geometry. Step 2 comprises the data module, handling and processing thermal results in Excel and Step 3, is the ray tracing module, which interprets shading need based on comfort results and redistributes g -value accordingly.

For iterative purposes, Step 4 was introduced. Step 4 follows the same methodology as Step 1, analyzing the effect of redistributed g -value on thermal comfort, enabling validation of the tool.

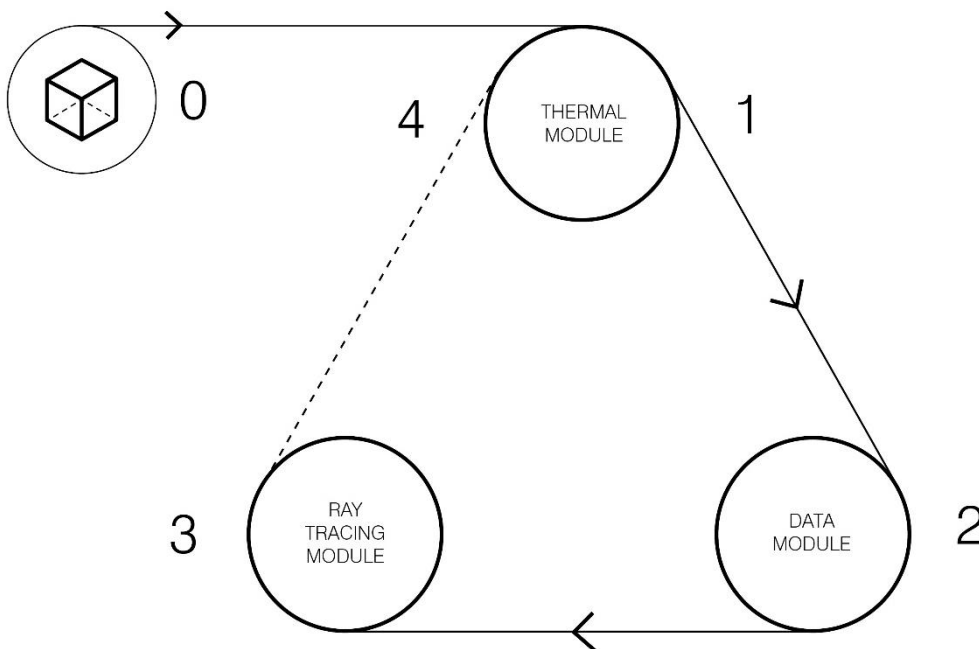


Figure 9: Project structure.

Step 1-3, has a defined input/output flow of information. Input to one step can be either output from the previous step or input of external data. All information outputted by one module and continuing to the next module, indicated by the arrows in *Figure 9*, is considered to be intermediate output, essential for the functionality of the tool but not extracted as results. Details of the input/output and intermediate output are explained further in the Method Section.

3.2 Software

The software tools utilized in the scripting of the tool were chosen due to their interoperability, alleviating the flow from tedious importing and exporting format collisions.

Each step explained in *Figure 9* has corresponding tools, depicted in *Figure 10*. It should be noted that, the operability of the used scripting tool Grasshopper, and consequently the environmental plugins Ladybug and Honeybee, rely on the geometry being modelled in the modelling tool Rhinoceros, for which Rhino was integrated in all the steps of the tool, but for illustrative reasons, is only included once in *Figure 10*.

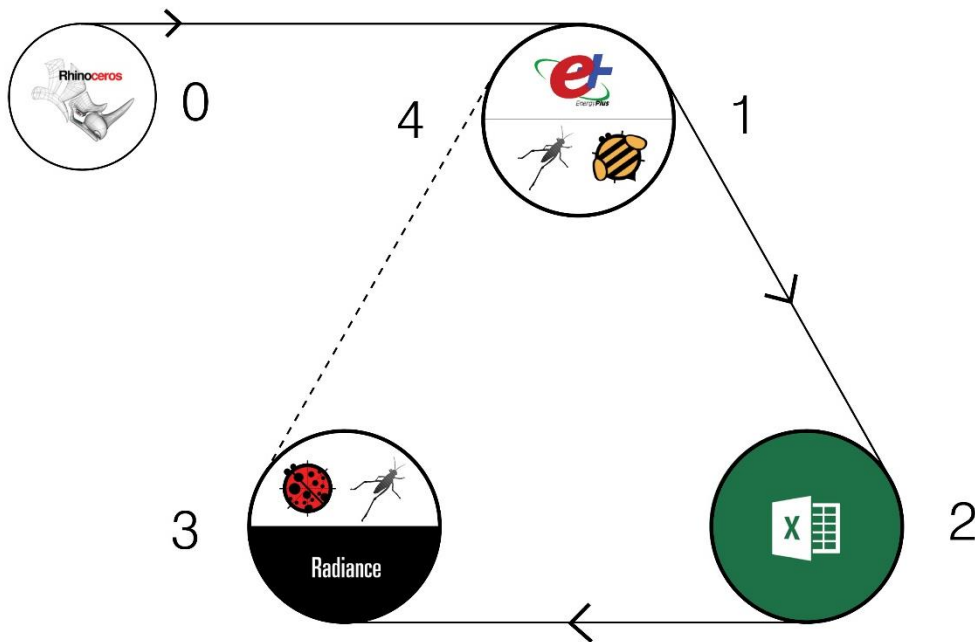


Figure 10: Software used in each step of the method.

3.2.1 STEP 0

Rhinoceros

Rhinoceros (*Rhino*) is a commercial 3D computer-aided design software, based on NURBS mathematical model, which is used for modelling a wide variety of products, including architecture modelling (McNeel, 2015). Rhino uses Boundary Representation (Brep) to compose 3D objects and be able to perform geometry manipulations (McNeel, 2015).

3.2.2 STEP 1/ STEP 4

Energy Plus

EnergyPlus (*E+*) is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting, and plug and process loads—and water use in buildings. (EnergyPlus, 2015)

Grasshopper

The Grasshopper (*GH*) plug-in is a graphical algorithm editor integrated within Rhino 3D CAD environment. The program allows a dynamic interaction with 3D geometry within Rhino, where all geometric changes are virtual, using the Rhino viewport to display the results of the GH definition. (grasshopper3d, 2015).

Terminology used in the report to describe work done in grasshopper:

- Component – a building-block that performs a specific action
- Definition – a network of grasshopper components - your Grasshopper 'model'
- Parameter – a special component that contains data (values) instead of performing an action

Honeybee

Honeybee (*HB*) is an open source environmental plugin for Grasshopper, enabling interaction with simulation engines of E+, Radiance, Daysim and OpenStudio for building energy and daylighting simulations (grasshopper3d, 2015).

3.2.3 STEP 2

Excel

Excel is a computer program which name stands for Electronic Spreadsheet Program. Storing, organizing and manipulating data are the main functions of Excel.

3.2.4 STEP 3

Radiance

Radiance is a lighting simulation tool making use of ray tracing methods i.a. backward ray tracing. (Radiance, 2015). Radiance is the base upon which Ladybug and Honeybee perform ray tracing analysis (for solar gains and daylight).

Ladybug

Ladybug is an open source environmental plugin for Grasshopper. With the aim to help architects and engineers create an environmentally-conscious building design, Ladybug imports standard EnergyPlus Weather files (.EPW) into Grasshopper (grasshopper3d, 2015).

3.3 Shade-tracing tool

3.3.1 STEP 0: Building geometry



A freestanding “shoebox” building with one thermal zone was modelled in Rhino, see *Figure 11*. No furniture or interior details were considered. This building geometry was used throughout the method.

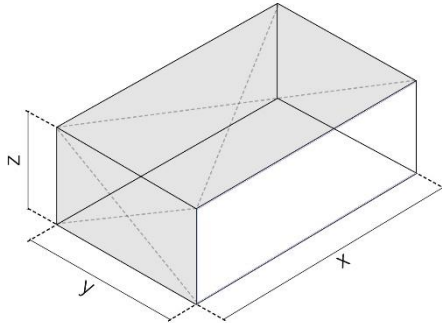
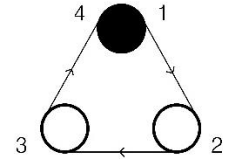


Figure 11: Geometry model.

3.3.2 STEP 1: Thermal module



The geometry introduced in Step 0 was thermally modelled in Honeybee (*HB*) and simulated with EnergyPlus (*E+*) engine in *HB*. The climate file, necessary model inputs and analysis period(s) and point(s) were defined and the intermediate thermal output attained was hereafter exported to Excel. All stages of the modelling were established as definitions in Grasshopper (*GH*).

Climate file

A valid .epw file and .stat file were inputted.

Geometric model input

The following model input, specific for the analyzed building case, were defined:

- Construction
 - Construction type for each surface i.e. façade, roof, floor and internal walls.
 - Thermal properties for each construction type including *U*-value.
 - If context or shading geometry were present in the model, the construction was considered to be opaque. No other material properties for context were considered.
- Glazing
 - Material properties of glazed surface
 - *g*-value
 - *U*-value and
 - Visible transmittance (VT)

Envelope surfaces encompass the thermal zone in which all simulations were carried out. The zone loads and schedules were assigned as follows:

- Loads and schedules
 - Zone loads and schedules for including equipment, lighting, infiltration, occupancy, ventilation per area and per person.

Analysis period

The period for which the thermal simulation was run was defined as an annual per default. All hours which were not occupied during the analysis period were removed from the output, in order to only account for overheating hours which were occupied.

Analysis point(s)

In order to simplify output and shorten output, thermal comfort parameters were analyzed for one point only. The point coordinate (*x*; *y*; *z*) were selected by dividing the floor surface into a desired grid and selecting a grid center-point.

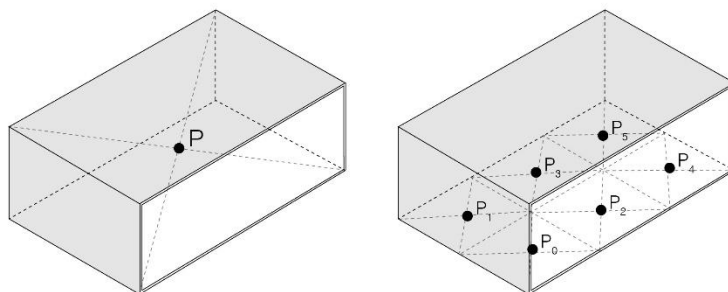


Figure 12: Location of calculation points in *E+* thermal simulations Point *P* and Honeybee_Microclimate Map Analysis mapping of thermal results in Point *P* to Point 0, 1, 2, 3, 4, 5

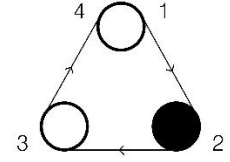
Simulation results

The thermal results from the *E+* engine consisted of temperature parameters for the analyzed zone during the analysis period. These results were post-processed in order to achieve results for a chosen analysis point and further adjusted to include the influence of direct solar radiation.

The post processing was performed utilizing an existing *HB* component based on the SolarCal method, described in *Section 2.1.3.5 Adjusted MRT*. The component, Microclimate map (Mackey, 2015), enables mapping of initial *E+* comfort results according to a chosen comfort model and requires input about an analysis point's view factor and four thermal outputs from *E+* simulation results, namely, average air temperature, air heat gain (for air stratification calculation), incoming airflow (also for air stratification) and indoor surface temperatures.

Moreover, the microclimate map component incorporates the effect of direct solar radiation to the comfort analysis, enabling results of adjusted thermal parameters of $T_{op,Adj}$, MRT_{Adj} and T_{air} for the chosen analysis period and point(s) to be retrieved and exported to excel in Step 2 for further handling. Hereby the comfort temperature parameters are considered to be an intermediate output, as explained in *Section 3.1 Overview*.

3.3.3 STEP 2: Data module



In the Data module, the procedure followed to handle and interpret intermediate thermal modelling output from Step 1 in Excel is presented below. The external input required in Step 2 was the adjusted operative temperature threshold above which point(s) experiencing overheating were further analyzed in Step 3. The intermediate output of Step 2, used as input for Step 3, is the solar overheating factor, explained further below. The result of Step 2 is graphical interpretations including duration diagrams and time distribution of overheating data.

$T_{op,Ajd}$ threshold input

A single operative temperature threshold was required, in order to remove hourly data which was not considered uncomfortable and limit the raw data handling in excel e.g. 26°C.

Local shading need evaluation

To evaluate shading need for point(s) exposed to direct solar radiation, a relation between thermal discomfort and shading need needed to be determined.

Since air temperature is independent of solar radiation, the solar influence on operative temperature was derived from the difference between MRT and operative temperature. This, based on the simplified temperature relationship specified in *Equation 7*.

$$\Delta T = MRT_{Adj} - T_{op,Ajd}$$

Equation 8

Where,

ΔT – derived impact of solar radiation on solar adjusted operative temperature

MRT_{Adj} – solar-adjusted mean radiant temperature (°C)

$T_{op,Ajd}$ – solar-adjusted operative temperature (°C)

Hereby, a larger ΔT implies a larger impact of solar radiation on adjusted operative temperatures at a certain point, and a greater shading need can thus fore be expected. A negative ΔT implies that a point experiences no solar contribution, and these hours were therefore ignored in further calculation.

Solar overheating factor, ΔT factor

To implement the influence of ΔT on shading need, a solar overheating factor, ΔT factor, was introduced. The factor is between 0 and 1, where a factor of 1 is allocated to points which have the largest contribution of solar gains on thermal discomfort, ΔT_{max} during the analysis period.

Remaining ΔT values are linearly scaled according to ΔT_{max} . When $MRT_{Adj} = T_{op,Ajd}$, there is no relative solar contribution to the discomfort for which a factor of 0 is allocated. See *Figure 13*.

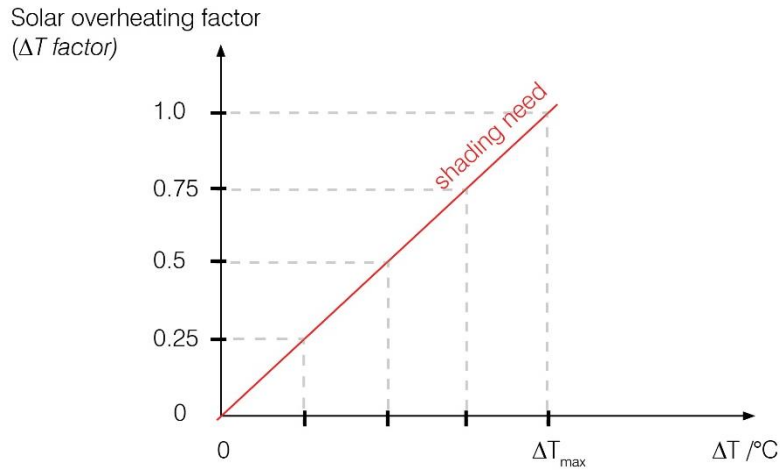


Figure 13: Shading need of an intersection point as a linear relation between ΔT and solar overheating factor.

As output, an excel spreadsheet with calculated ΔT factors for every hour of analyzed period and coordinates of the points of interest, is generated.

	A	EPH	EPI	EPJ	EPK	EPL	EPM	EPN	EPO	EPP
1	Hour of the year	3802	3803	3804	3805	3806	3807	3808	3809	3810
2	X_0, Y_0, Z_0	0.00	0.32	0.31	0.41	0.26	0.23	0.20	0.00	0.00
3	X_1, Y_1, Z_1	0.00	0.23	0.23	0.24	0.21	0.19	0.17	0.00	0.00
4	X_2, Y_2, Z_2	0.00	0.37	0.56	0.51	0.49	0.29	0.25	0.00	0.00
5	X_3, Y_3, Z_3	0.00	0.23	0.23	0.24	0.21	0.19	0.17	0.00	0.00
6	X_4, Y_4, Z_4	0.00	0.59	0.59	0.53	0.52	0.30	0.26	0.00	0.00
7	X_5, Y_5, Z_5	0.00	0.25	0.25	0.26	0.23	0.20	0.18	0.00	0.00

Figure 14: Example of excel spreadsheet with ΔT factors for analysis points (column A) and hours of analyzed period. (row 1), where x,y,z represents coordinates of each point.

3.3.3.1 Thermal data output

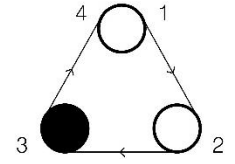
Duration diagrams

Graphs showing the duration for which $T_{op,Adj}$ exceeds assigned threshold temp for the analysis point during the analysis period.

Time distribution

Hourly and weekly time distribution was analyzed to show which hours of the day the analysis points were receiving the highest temperatures. This was done with Grasshopper native components. The time distribution was further combined with cloud cover from the weather data file to give a better understanding of the output.

3.3.4 STEP 3: Ray tracing module



The ray tracing module included four stages of processing data: ray tracing intersections points, calculating shading area, re-distributing g -values and arranging frit pattern on the façade. All four stages of the processing were established as definitions in Grasshopper (*GH*).

3.3.4.1 Ray tracing

Ray tracing definition was created for locating and visualizing intersection points on the façade. The definition was based on backward ray tracing method, utilizing the Ladybug component “Bounce_From_Surface” in *GH*. The component generates the solar vectors directed from the points which are defined by the user to the sun. When the number of bounces is set to 1 as input to the Bounce_From_Surface component, see Section 3.2.4 Radiance, the direct solar vectors are traced.

Solar vectors were traced for hours when solar radiation contribute positively to discomfort (ΔT factors > 0), for which the intersection points between the vectors and the glazing were established and recorded in *GH*.

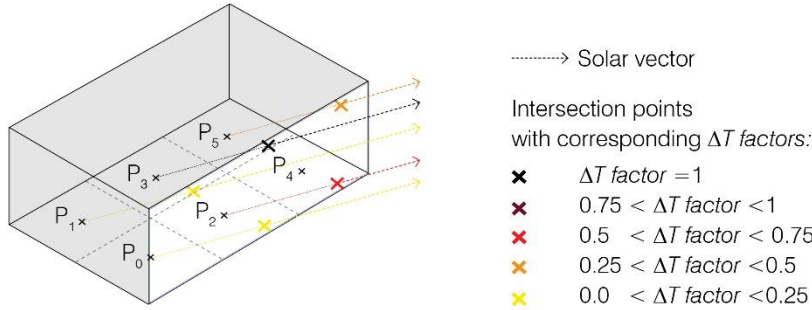


Figure 15: Solar vectors, generated with backward ray tracing, intersect with a glazed façade.

3.3.4.1.1 Ray tracing output

The ray tracing definition outputs the pattern of intersections on the façade. The pattern represents the position and ΔT factors of intersection points, as shown graphically in Figure 16. The colors in represents a threshold of ΔT factor, illustrating the relative impact of overheating from each intersection. ΔT factor is described in Section 3.3.3 STEP 2: Data Module. Numerically, the output was further handled for calculating areas of shading frit and g -values of glazing units as described in Section 3.3.4.2 Shading area and Section 3.3.4.3 Redistributed g -value, accordingly.



Figure 16: Position of the intersection points with equivalent thresholds of ΔT factors

3.3.4.2 Shading area

A shading area definition was created to determine the shading frit size, according to its position on the façade. By adopting Equation 3, frit was applied to the facade to reduce the average g -value.

The calculation of requires input of average g -value of a glazed façade (g_{av}), non-shaded glass g -value and frit transparency (TR_{sh}). Moreover, the following two conditions must be met:

1. Non-shaded glass g -value need to be higher than desired average g -value
2. Frit transparency need to be lower than the desired average g -value

The total area of shading frit needed is calculated as follows:

$$A_{sh} = \frac{g_{ave} - g_{non-shaded}}{TR_{sh} - g_{non-shaded}} \times A_{facade} \quad \text{Equation 9}$$

Where,

g_{ave} – average g -value of the facade
 A_{sh} – Total shading frit area need, m²
 A_{facade} – Total façade area, m²
 TR_{sh} – Shading frit transparency
 $g_{non-shaded}$ – Non-shaded glass g -value

Main principle of the calculation is illustrated in Figure 17.



Figure 17: Facade g -value calculation principle.

The single frit area corresponding to the shading need (ΔT factor) at each intersection point on the façade, is calculated as follows:

$$A_{\Delta T factor} = \frac{\sum \Delta T factor}{A_{sh}} \quad \text{Equation 10}$$

Where,

$A_{\Delta T factor}$ – Single frit area relative to ΔT factor, m²
 $\sum \Delta T factor$ – Sum of all ΔT factors at intersections points on the facade
 A_{sh} - Total shading frit area need, m²

Main principle of a single frit relative area calculation is illustrated in Figure 18.

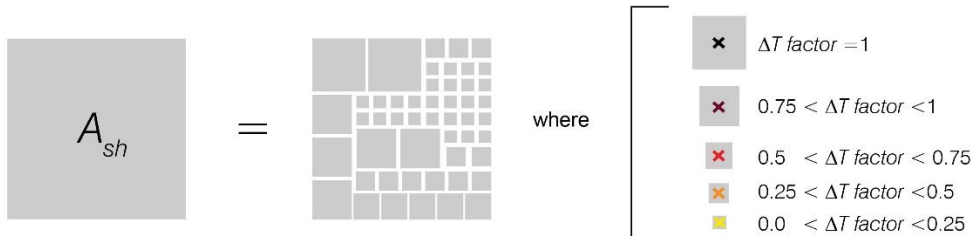


Figure 18: Single frit relative area calculated according to corresponding ΔT factor.

3.3.4.2.1 Shading area output

The shading area definition outputs a non-uniformly distributed frit pattern, as shown in Figure 19. Each geometry of frit was assigned to location of the corresponding intersection points (see Chapter 3.3.4.1 Ray tracing).

As illustrated in Figure 19, resulted frit surfaces are likely to overlap, which reduces the absolute area of the shading. In order to obtain the frit pattern, which meets the need of the total shading frit area, each frit was scaled.

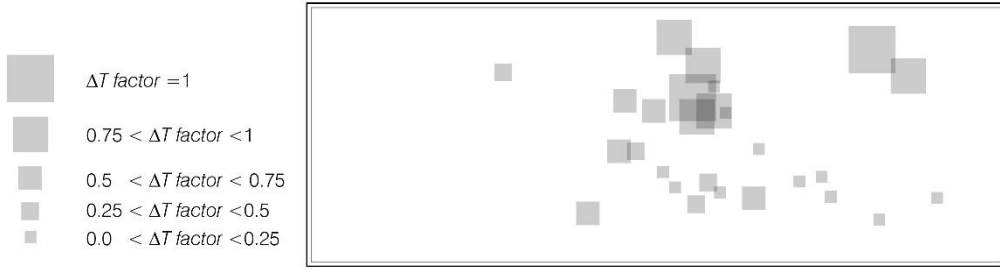


Figure 19: Resulted non-uniformly distributed frit pattern.

3.3.4.3 Redistributed g-value

Large glazed areas, such as glazed facades, are commonly divided into grids of smaller glazing units, see Figure 20. As described in Section 2.1.1.3.1 Shading Coefficient of fritted glass, each glazing unit may have its own specific g-value.

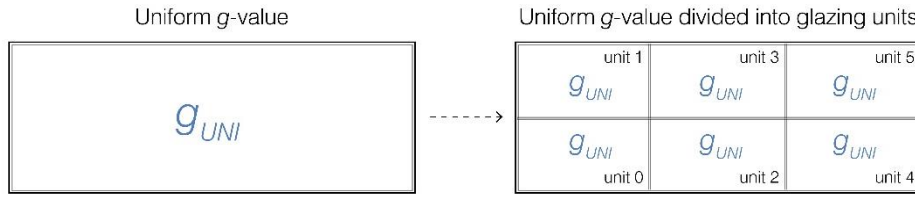


Figure 20: Facade with uniform g-value of glazing before and after being divided into a grid of six glazing units.

Re-distributed g-value definition was created in order to distribute g-values on the glazing units of the façade corresponding to the need for shading indoors, determined according to method described in Chapter 3.3.4.1 Raytracing. The shading area needed was determined according to method described in Chapter 3.3.4.2 Shading area.

A shading area needed was calculated for every glazing unit according to Equation 11. The higher the sum of ΔT factors within a glazing unit, the higher the shading area needed for that glazing unit.

$$A_{sh,unit} = \sum \Delta T_{factor,unit} \times A_{\Delta T factor} \quad \text{Equation 11}$$

Where,

$A_{sh,unit}$ – Shading area needed for a glazing unit, m²

$A_{\Delta T factor}$ – Single frit area relative to ΔT factor, m²

$\sum \Delta T_{factor,unit}$ - Sum of ΔT factors within a glazing unit

After the shading area needed for each glazing unit was defined, the g-values for the glazing units (g_{unit}) could be calculated according to Equation 12. The assumption that average g-value of a glazing unit is equal to area weighted sum of shading frit g-value and non-shaded glass g-value, described in Section 2.1.1.3.1 Shading Coefficient of fritted glass was made. Hereby, a resulted glazing unit g-value is highly dependent on previously calculated shading frit area needed, transparency of shading frit and non-shaded glass g-value.

$$g_{unit} = \frac{(A_{sh} * TR_{sh}) + ((A_{unit} - A_{sh}) * g_{non-shaded})}{A_{unit}} \quad \text{Equation 12}$$

Where,

A_{unit} – Area of a glazed unit, m²

A_{sh} – Total shading area need, m²

TR_{sh} – Frit transparency

$g_{non-shaded}$ – Non-shaded glass g-value

3.3.4.3.1 Redistributed g-value output

The redistributed g-value output included a list of g-values between 0 and 1. The number of g-values corresponds to the number of glazing units which the façade was divided into.

unit 1 g_1	unit 3 g_3	unit 5 g_5
g_0 unit 0	g_2 unit 2	g_4 unit 4

Figure 21: Glazed facade divided into 6 glazing units, with corresponding g-values assigned to each unit

Resulting g-values below zero suggest that the shading need was greater than what is achievable by reducing the g-value. Hereby, if resulted g-value were negative, the non-fritted glass g-value needed to be lowered to compensate for the higher shading need.

3.3.4.4 Uniformly distributed frit pattern

Alternatively to the redistributed g-value, a geometry of uniformly distributed frit pattern could be generated. The calculation was performed based on a single frit area (A_{frit}). The number of single frits (F) per glazing unit was individually calculated according to Equation 15:

$$F = \frac{A_{frit,unit}}{A_{frit}} \quad \text{Equation 13}$$

Where,

F - Number of frits per glazing unit

A_{frit} - Area of a single frit, m²

$A_{frit,unit}$ - Total frit area needed for a glazing unit, m²

The resulted number of frits were evenly distributed on a grid on the glazing unit.

3.3.4.4.1 Uniformly distributed frit pattern output

The redistributed g-value definition outputs either the values of calculated g-values or the uniformly distributed frit pattern by displaying them on the 3D model, as shown in Figure 20.

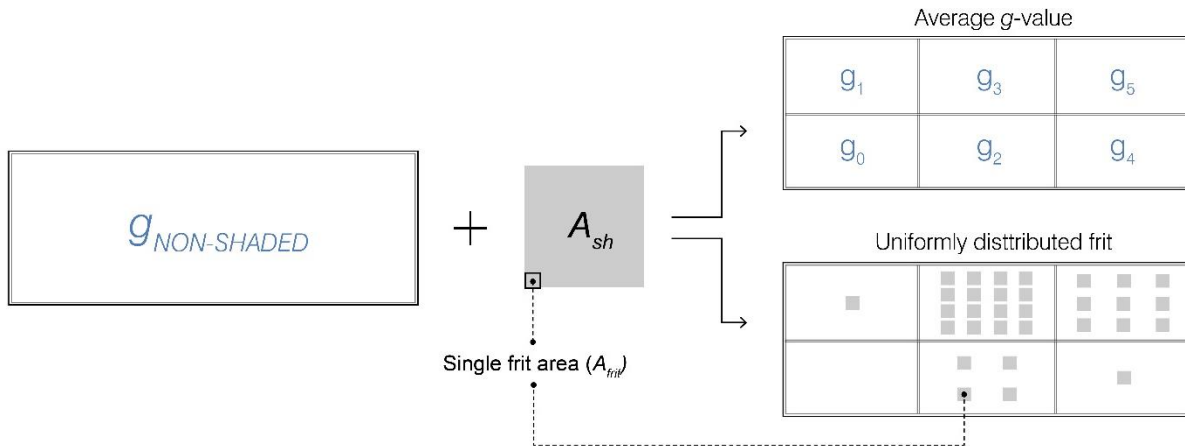
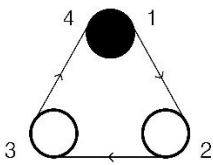


Figure 22: Glazed facade before and after distribution of g-values, Non-uniformly and uniformly distributed frit patterns.

3.3.5 STEP 4: Thermal iteration



Step 4 represents an iterative step in the method, following the same procedure as in Step 1, aiming to test the solution provided in the ray tracing module in Step 3. Step 4 aimed to confirm the functionality of Step 0-3 of the tool.

In Step 4, there is one exception to the methodology explained in Step 1 and that how the glazed façade(s) is modelled in Honeybee. The glazed surface(s) were divided into units, or sub-surfaces, representing size of glazing used in the Step 3, see figure 22. The resulting redistributed g -values, referred to as average g -values from Step 3 were assigned and the $E+$ simulation was rerun.

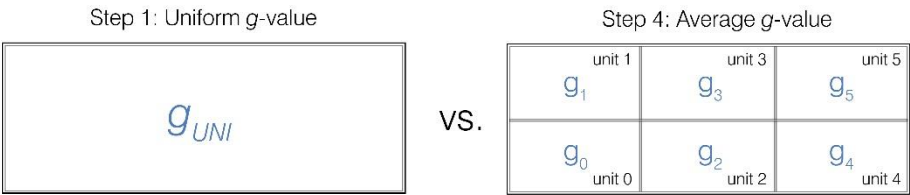


Figure 23: Glazed facade with corresponding g -values in Step 1 and Step 4, accordingly.

The results were exported and compared to the results from Step 2, results displayed in *Section 5 Results*.

3.4 Validation

3.4.1 Reference Case

The developed method and shade-tracing tool were tested on a Reference Case building. The settings used for the Reference Case, following the order of the overview in *Section 3.1*, are presented in *Figure 21*.

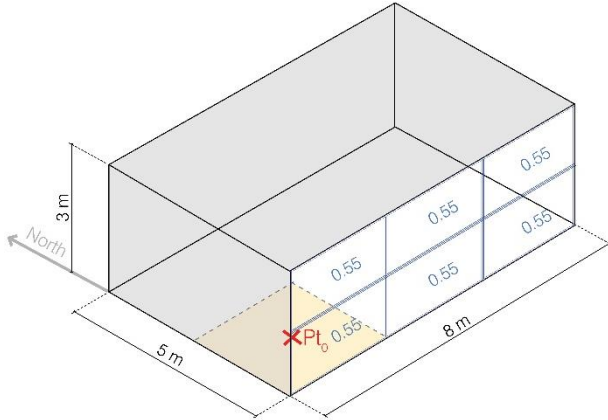


Figure 24: Reference Case geometry.

STEP 0: Geometry

A simple “shoe box” geometry with of dimension 8 m·5 m·3 m was modelled in Rhino.

STEP 1: Thermal module

The floor of the geometry was divided into a grid of 3·2 divisions, with a one floor grid corresponding to an area of 2.7 m·2.5 m. One test point in, Point 0, was chosen to be analyzed in terms of thermal discomfort and shading need. The weather data used for the reference was Copenhagen climate file. The zone was set to be an office occupied on weekdays between 8 and 18, with a lunchbreak between 12 and 13. The density of people was 0.05 people/m².

Annual thermal simulations were made, measuring the impact on adjusted operative temperature before and after applying the method/tool.

Glazing type and grid

The southern façade was fully glazed, resulting in a glazing to floor ratio (*GFR*) of 60%. In EnergyPlus (*E+*). All glazing, was modelled with Simple window indices explained in *Section 2.1.1.2*. The following double glass window type was used for all glazing units throughout the study.

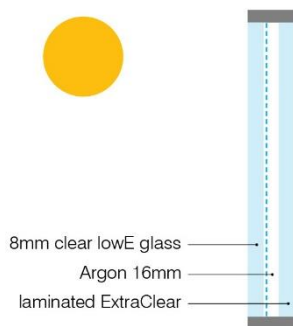


Figure 25: Reference glazing unit.

Table 1: Reference glazing unit physical properties.

Glazing	<i>LT</i> / %	<i>g</i> -value	<i>U</i> -value / W/(m ² ·K)
Double glazing unit (<i>DGU</i>)			
Outer pane:			
1. 8 mm clear Low-E glass			
Cavity:			
2. 16 mm argon			
Inner pane:			
3. 44.2 mm laminated float glass			
	78	0.55	1.1 (vertical) 1.7 (inclined)

Construction

Materials from the *E+* material library were assumed, with *U*-values as close to recommended values by Blomsterberg (2013). It is possible to personalize the constructions but for the purpose of simplifying the method, available constructions were utilized.

Table 2 Construction details for Reference Case

Construction element	U -value /W/(m ² ·K)
Ground floor	0.56
Roof	0.16
Wall	0.22

Construction airtightness of 1.8 l/(s·m²) at 50 Pa was chosen according to Swedish airtightness requirements for office buildings. (Blomsterberg, 2007)

Ventilation

The ventilation system employed to the Reference Case is an ideal load system with the following set points and set-backs:

Table 3 Heating and cooling set point temperatures for Reference Case

Cooling set point	24 °C
Cooling set back	26.7 °C
Heating set point	21 °C
Heating set back	15.6 °C

Heat gains

Heat gains of 7.6 W/m² and 9.0 W/m² were set for the Reference Case model, according to common heat gains in a modern office building in Sweden. (Blomsterberg (2007))

Comfort model

The adaptive comfort model was assumed for the Reference Case and throughout the sensitivity study, since it was considered to provide most realistic interpretation of thermal comfort considering the presence of solar adjusted comfort parameters.

STEP 2: Data module

According to national recommendations for indoor operative temperature, (Folkhälsomyndigheten, 2014), a thermal comfort threshold of 26°C was chosen for adjusted operative temperature.

STEP 3: Ray tracing module

The optical properties of glazing are input to the shade-tracing tool, as follows:

Non-shaded glass g -value: 0.7

Average glass g -value 0.55

Shading frit transparency: 0.0

STEP 4: Thermal iteration

The fully glazed southern façade was divided into 6 modules with dimensions of 2.7 m·1.5 m, and the g -value was distributed according to solutions attained in Step 3.

3.4.2 Sensitivity study

The sensitivity of the tool with respect to changing parameters was evaluated by performing sensitivity studies on various parameters. Results were compared with regards to time distribution of temperatures above a set comfort threshold before and after distributing the g -value according to the method presented in *Section 3*.

The parameters analyzed in the sensitivity study are described below:

3.4.2.1 Frit geometry

Instead of merely altering the g -value of the glazing unit, it was of interest to test the tools applicability to change the g -value of glazing by applying physical shading on the exterior of the glass. This was done by introducing frit shading to the simulations.

The following types of frit were tested:

- Uniformly distributed frit
- Non-uniformly distributed frit

The non-uniform frit pattern was scaled to compensate for area of overlapping frits.

3.4.2.2 Climate file

Two additional climates were chosen to analyze the relation between environmental conditions and the functionality of the tool. 1. Madrid, Spain and 2. Abu Dhabi, United Arab Emirates. Madrid's temperate climate has hot summers and cool winters, ranking as one of Europe highest receivers of sunshine hours. Abu Dhabi has a hot desert climate, with extremely hot summers and warm winters. The outcome of the tool for these climates were compared to the Reference Case simulations, performed with a Copenhagen climate file.

3.4.2.3 One point on the floor

In order to identify how the tool function for different locations in a space, comfort results for Point 1, Point 2, Point 3, Point 4 and Point 5 were analyzed and compared to the Reference Case results performed on Point 0.

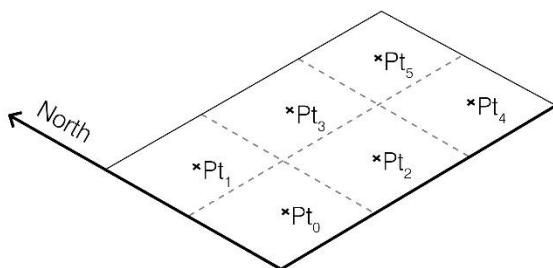


Figure 26: Location of points of interest on the floor.

3.4.2.4 Several points on the floor

To evaluate the effect of the size of the analyzed area and the effectiveness of the method, three combinations of points were tested and compared to the Reference Case results performed on Point 0:

- Points 0 and 2
- Points 0, 1, 2, 3
- All points

3.4.2.5 Cooling set point temperature

Excess heat not blocked by shading devices or due to internal gains can distort the actual effect of the tool, since temperatures already amply exceeding comfortable levels cannot be removed by merely altering the g -value retrospectively. Hereby, the ventilation set points may impact the outcome of the tool significantly, for which it was of interest to test the tool on different cooling set points. The following set point temperatures were analyzed and compared to the Reference Case set point of 24 °C:

- No conditioning
- 28°C

- 26°C
- 22°C

3.4.2.6 Glazed facade grid

By minimizing the façade grid size, the problematic regions of the facade may become more defined, for which the outcome of varying the façade grid size is of interest.

The following divisions of the façade grid were tested and compared to the Reference Case division of 2·3:

- 2·2 (1.5 · 4.0 m)
- 3·4 (1.0 · 2.0 m)
- 5·6 (0.6 · 1.7 m)

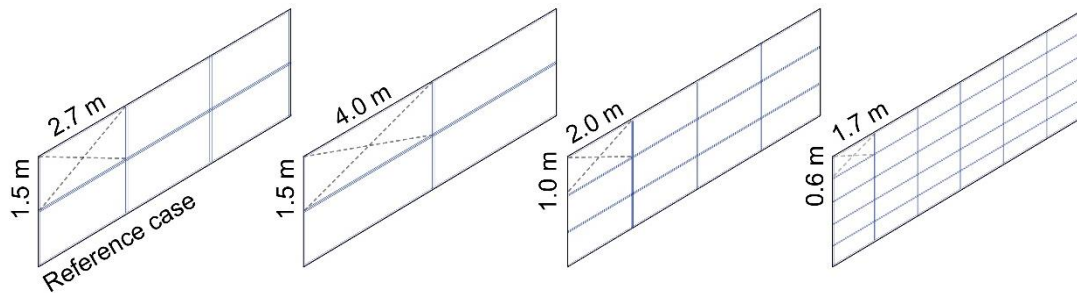


Figure 27: Divisions of the facade grid tested and compared to the Reference Case (1.5x2.7 grid dimensions).

3.4.2.7 Factoring method

The factoring method, described in Section 3.3.3 Data module, considers the effect of the direct solar component on thermal comfort and applies a ΔT factor between 0-1 accordingly. The ΔT factor used does not differentiate between the intervals within the ΔT factor, for which the influence of smaller intervals was of interest to analyze.

First, two cases: Reference Case with ΔT factors between 0-1 and case with all ΔT factors set to 1, were compared. The solar overheating factors for point 0 were summed within every month and compared to the absolute sum of the solar overheating factors.

Next, the method was tested on annual basis using six different intervals of ΔT factors, as described in table 7.

Table 4: Cases with different factoring methods tested in parametric study.

Case name:	Description:
1. Reference Case	Case for which all positive ΔT factors were chosen
2. Factors 0.2-1	Case for which only ΔT factors with values higher than 0.2 were chosen
3. Factors 0.4-1	Case for which only ΔT factors with values higher than 0.4 were chosen
4. Factors 0.6-1	Case for which only ΔT factors with values higher than 0.6 were chosen
5. Factors 0.8-1	Case for which only ΔT factors with values higher than 0.8 were chosen
6. Factors 1	Case for which all positive ΔT factors are replaced by values of 1 and as such used for g-value calculations

3.4.2.8 Geometry scale

The scale of the analyzed geometry was scaled up in order to see the impact of the method on larger scales. The following scaled geometries were analyzed and compared to the Reference Case scale of 1:1.

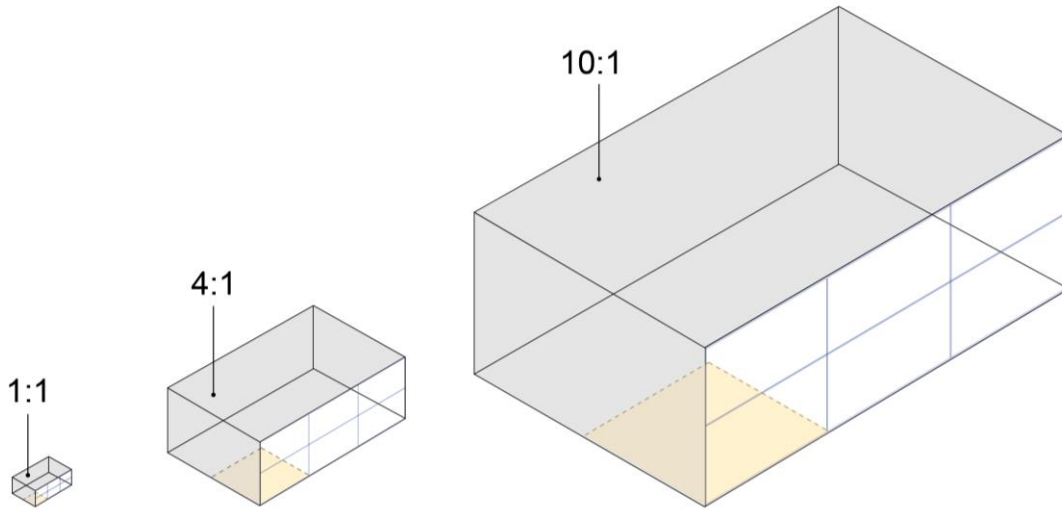


Figure 28: Tested scales of the geometry in comparison with the Reference Case (1:1).

Important to note, since internal gains and ideal loads for ventilation were assigned $/m^2$, their impact on the zone were scaled correspondingly with the geometry. The floor grid and the location of Point 0 were scaled as well.

3.4.2.9 Orientation

The orientation of the glazed surface(s) play an important role as to when the space experiences solar gains. The influence of the building orientation on the performance of the method was tested by rotating the building in an easterly and westerly cardinal direction and comparing the results to the Reference Case with a Southerly orientation. Location of the analyzed Point 0 was rotated as well.

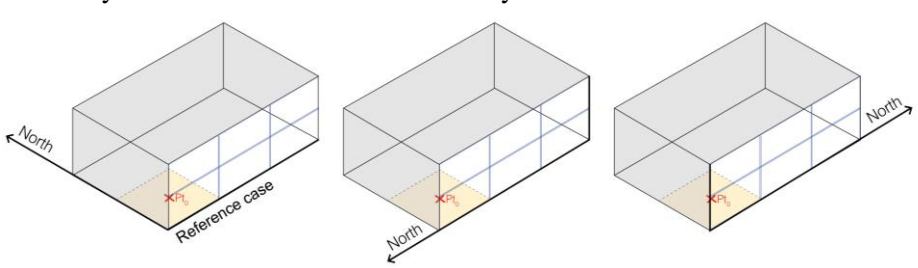


Figure 29: East and west-oriented facade tested.

3.4.2.10 Glazing ratio

The glazing ratio plays a significant role for the amount of direct solar heat gains entering a space. Similarly to the cooling set point temperature, the effectiveness of the tool maybe be limited to the ratio of glazing. It is hereby of interest to analyze the method's functionality for spaces with varying glazing ratios.

The following glazing ratios were tested and compared to the Reference Case ratio of 60%:

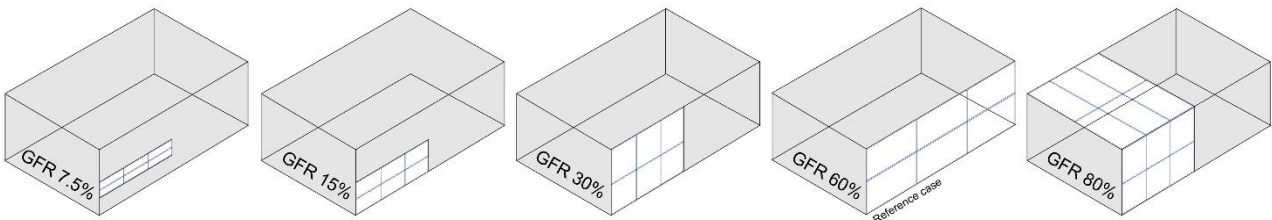


Figure 30: Four types of tested geometries with glazing to floor ratios of 7.5%, 15%, 30% and 80% in comparison to the Reference Case with GWR of 60%.

For GFR 80%, the U -value of the horizontal glazing (roof) was increased to $1.7 \text{ W}/m^2K$ to account for angular dependency of glazing U -value, see Table 1.

3.4.2.11 Average g -value of glass

By altering the average g -value of the facade, the thermal exchange upon which the method is based, is changed. Unexpected trends of altering this parameter could potentially limit the usability of the tool for cases with other thermal requirements of the envelope.

The distribution of the following initial g -value cases have been re-calculated and compared to the Reference Case average g -value of 0.55:

- 0.35
- 0.45
- 0.65

3.4.2.12 Analysis period

The period of time for which the tool is run can influence how the output correlates to and affects the overheating problem. The analysis period was shortened and analyzed for:

- one season (summer),
- one month (August),
- one week (in August) and
- one day (2nd August)

The effect of the tool for different analysis periods was compared to the Reference Case (based on annual analysis period).

3.4.2.13 Saving potential

Saving potential refers to the savings which could potentially be made by applying the tool. For example, economic savings on glazing costs, if the use of solar controlled glass could be limited to a certain areas of the facade. Additionally, energy (and economic) savings on reduced cooling loads. Thirdly, improvements in wellbeing for occupants by increasing daylight availability and clear views, if certain glass in a space could be clearer. The potential to save was done by altering the average g -value of the façade until the temperature threshold of the analyzed point surpasses a given limit.

4 Shade tracing tool

4.1 Data flow

The resulted outline of relations between input and output of the three main of the tool is shown in *Figure 28*. In the first stage, with the model geometry created, following data for thermal modeling need to be input:

- grid size /density of the glazed façade
- g -value for initial uniform distribution of glazing
- buildings thermal input such as U -values of construction elements, heat gains and comfort model
- points of interest on the floor for which thermal comfort was calculated
- occupancy schedule

Next, the input data is processed in Honeybee and output to Excel as annual temperature data. In the second stage of the method, an input value of comfort threshold need to be defined. It is used to analyze the temperature results from thermal modelling. Two types of output are generated in Excel:

- time distribution of overheated hours during a year
- solar overheating factors (ΔT factors) for every point of interest and every hour of analyzed period

In the third stage, the tool is supplied with: ΔT factors, the set points for shading transparency and non-shaded glass g -value. As a final result, following output can be achieved:

- intersection points on the façade with corresponding ΔT factors
- new distribution of glazing with a range of g -values based on the calculated shading need
- frit pattern geometry

In the fourth, additional, step the effect of redistributed g -value on thermal comfort can be validated.

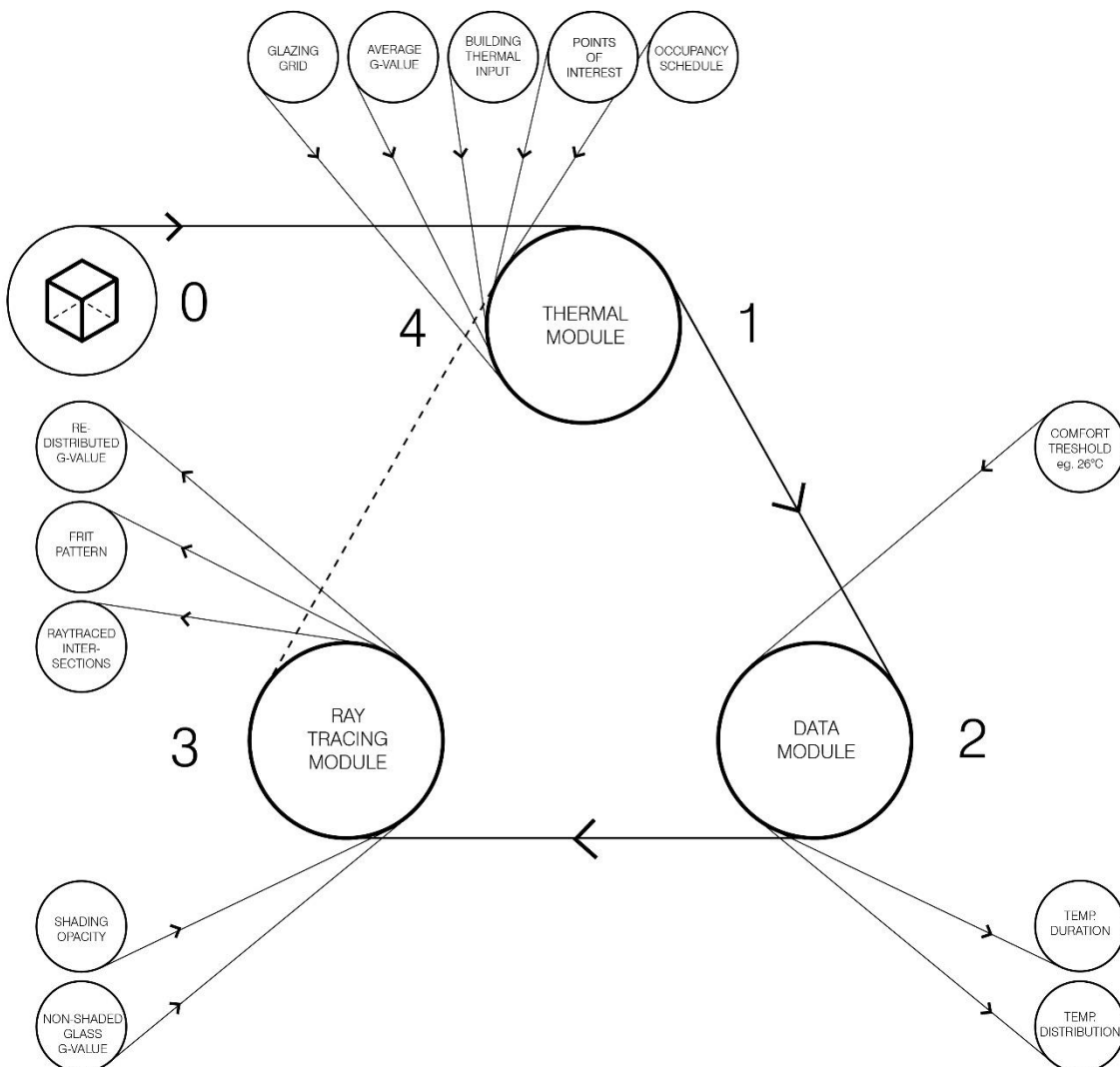


Figure 31: Resulted flow of input/output data through the tool.

5 Results

In this chapter, results are shown according to the principle shown in figure 32. The uniform g -value represents a case before the application of the method, while the average g -value stands for a corresponding case after application of the method.



Figure 32: Glazed facade with uniform g -value and average g -value, for which results were obtained and are presented in the section 5: Results.

5.1 Reference Case

Following the steps presented in the *Section 3.4.1 Reference Case*, results attained from the thermal module and ray tracing module were combined and compared to evaluate the functionality of the tool.

5.1.1 Ray tracing module output

Ray-traced intersections

The tool display the distribution of intersections points on the façade with the corresponding values of solar overheating factors. The factors are categorized into five thresholds and colored-coded, see Figure 29.

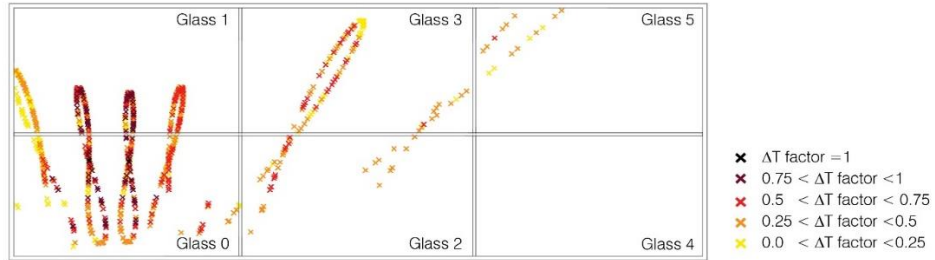


Figure 33: Distribution of intersections points with corresponding solar overheating factors in thresholds.

Re-distributed g -value

The tool redistributes g -value from a uniform distribution of 0.55 to an average distribution of 0.55 subsequently referred to as uni-g 0.55 and ave-g 0.55 respectively. This redistribution is displayed on the analyzed glazing as can be seen in Figure 30.

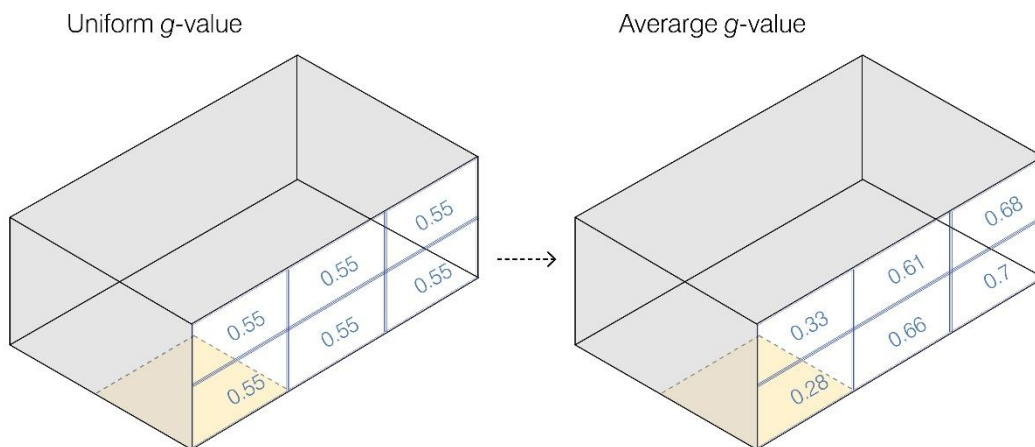


Figure 34: Distribution of g -values before and after applying the method.

Frit pattern

Following the problematic intersection points displayed in Figure 29, the tool presents two frit patterns, non-uniformly distributed frit (left), and translates this into uniformly distributed frit (right), see Figure 31.

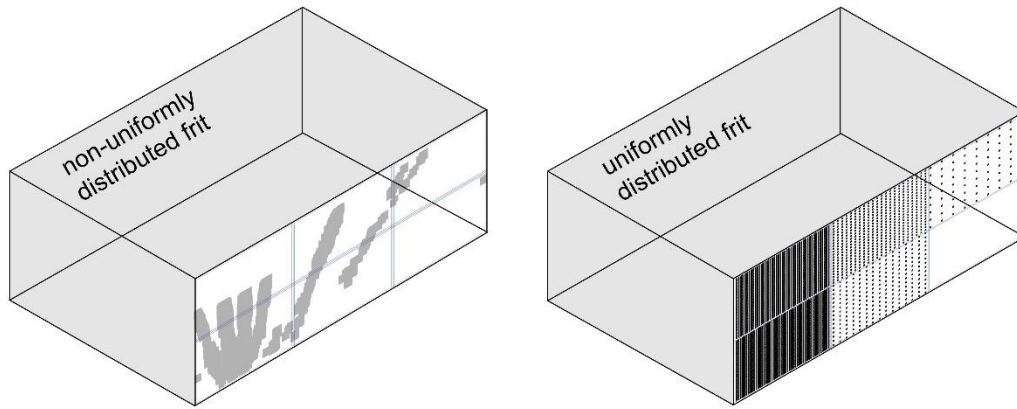


Figure 35: Graphic output of non-uniformly distributed frit and uniformly distributed frit patterns, respectively.

5.1.2 Validation output

Duration diagram - Adjusted operative temperature ($T_{o,Adj}$)

The distribution diagram was made on an annual basis for the Reference Case, for which the number of hours above a solar adjusted operative temperature ($T_{o,Adj}$) of 26°C decrease after applying the tool, showing a greater relative decrease with increased temperatures. Figure 32 shows a clear reduction in overheating at higher temperatures. Uni-g 0.55 represents the initial duration diagram with a single g-value of the entire façade of the Reference Case equal to 0.55 and Ave-g 0.55 represents the duration diagram for the same façade, with distributed g-value for the façade according to the method.

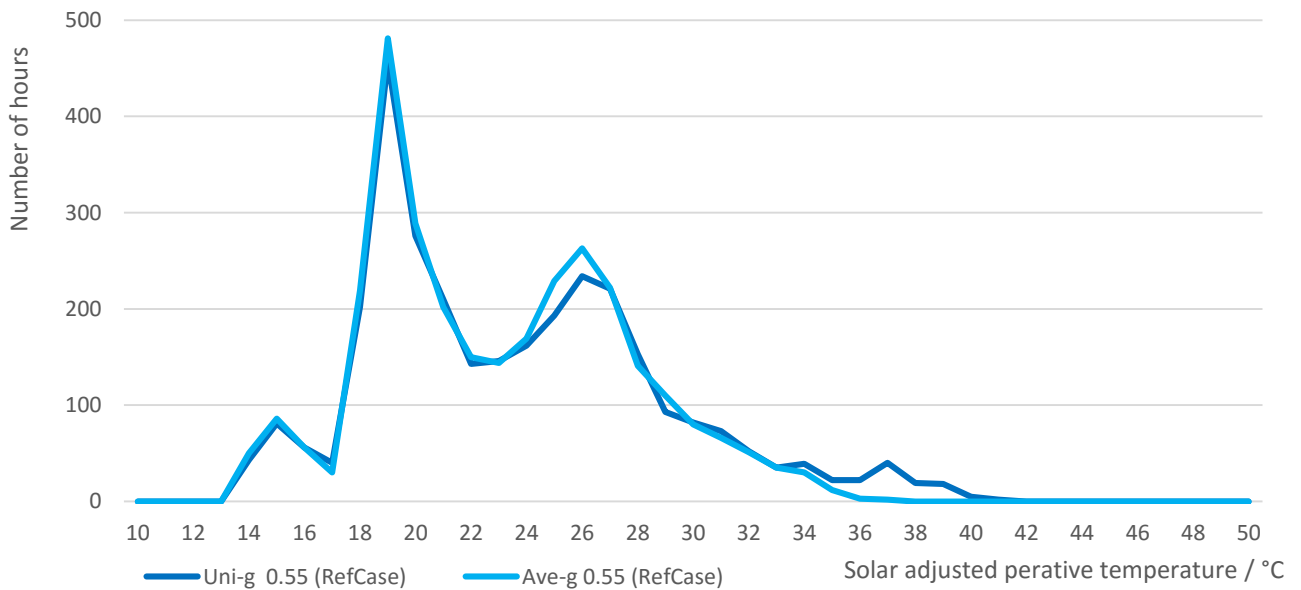


Figure 36: Annual $T_{o,Adj}$ duration diagram

All hours above the thresholds analyzed show improvements after applying the tool. The most significant advantage of the tool is apparent for overheating hours $>35^{\circ}\text{C}$, showing an annual reduction of hours by 87%. Percentage improvement of hours with $T_{o,Adj} > 26^{\circ}\text{C}$, 28°C , 30°C are 9%, 19% and 32%, respectively, shown in Figure 33.

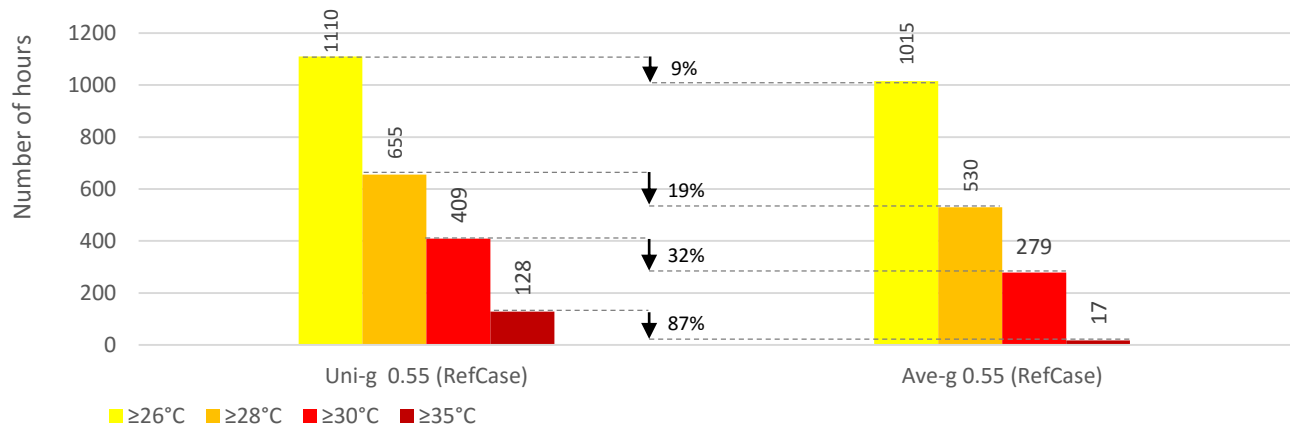


Figure 37: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the initial uniform glass g-value and redistributed g-values with average g-value of 0.55 for both cases.

Time distribution

The functionality of the tool was observed on a weekly basis during three weeks of the year, namely an extremely hot, a typical and an extremely cold week relative Copenhagen climates conditions. The weather data from these weeks are taken from the .epw files. The cloud cover during the same periods is also analyzed to observe their effect on the tool. Cloud coverage is measured on a scale from 0-10, when zero indicated no clouds and ten is full coverage.

The extremely hot week in August, shown in Figure 34, is clear during most days, during which the temperature profiles before and after applying the method, look similar. However towards the end of the week, when the cloud cover increases, the peak temperatures decrease, and so does the efficiency of the tool. This correlation indicates the tools preferable functionality for periods with high solar irradiance.

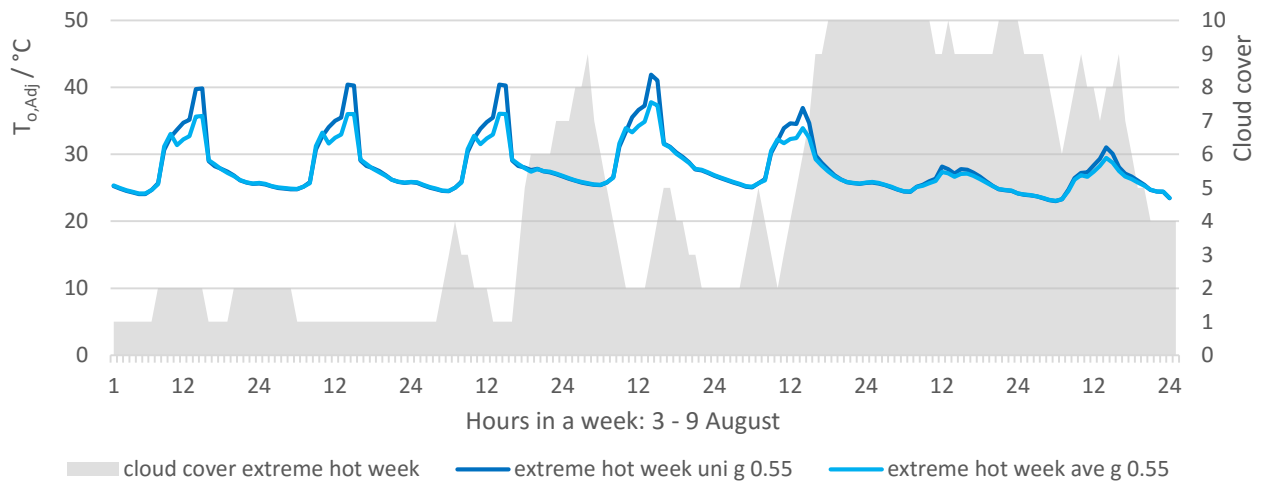


Figure 38: Extreme hot week 3-9/8

A typical week in September, shows more encompassing cloud coverage throughout most of the week, allowing for marginal efficiency of the tool.

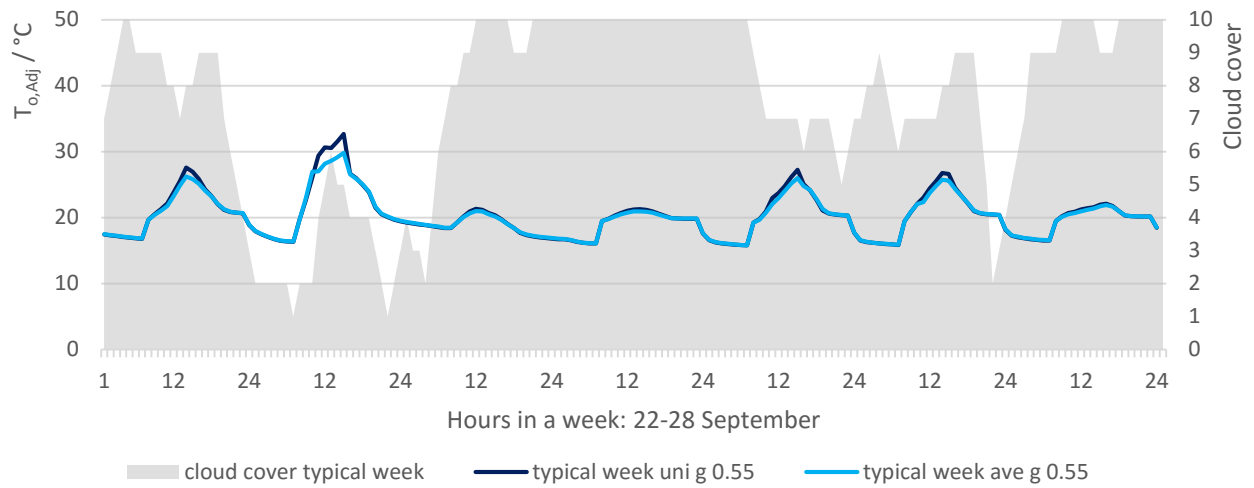


Figure 39: Typical week 22-28/9

The extremely cold week, in February, displays clear conditions during the day for the first half of the week, with corresponding performance of the tool.

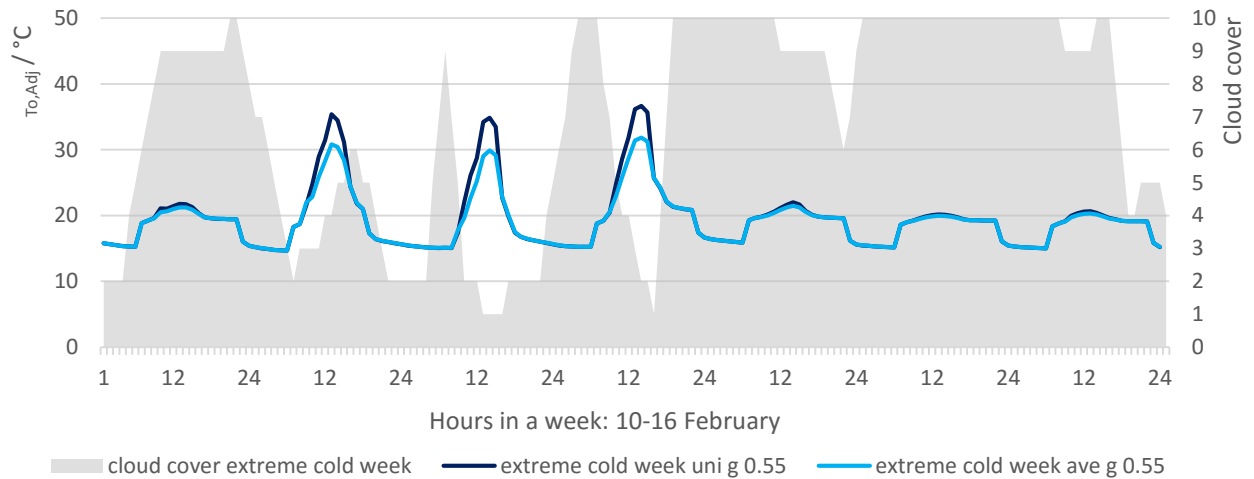


Figure 40: Extreme cold week 10-16/2

Moreover, an hourly distribution of an annual simulation shows the reduction in overheating hours occur predominantly in the morning and early afternoon, shown by the light blue bars in Figure 37. This trend reflects the southerly orientation of the façade and the location of the analysis point, since it is mostly exposed to direct sun during the morning and early afternoon.

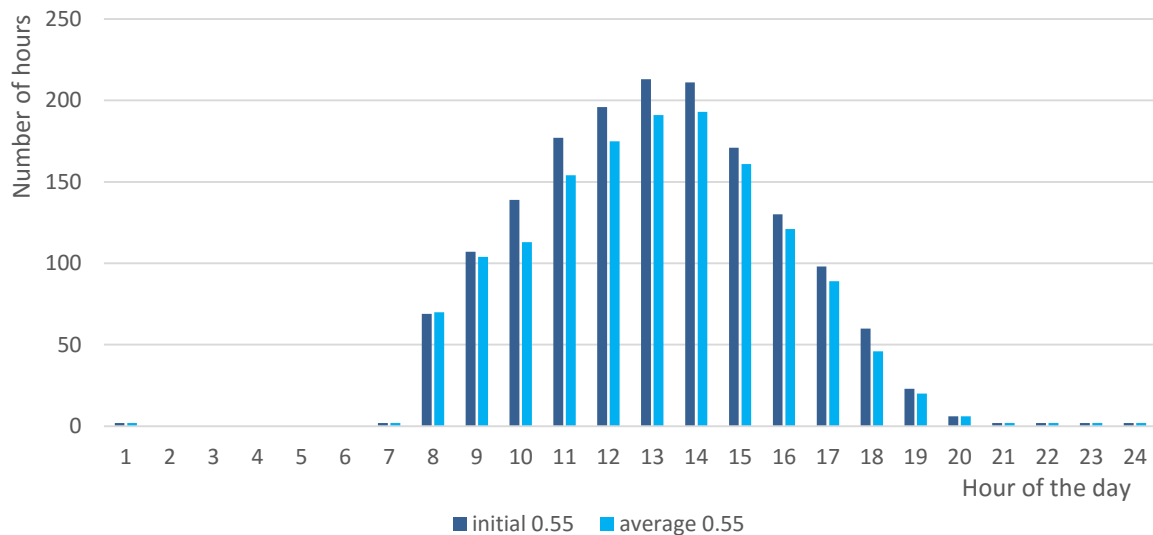


Figure 41: Hourly distribution of $T_{o,Adj} > 26^{\circ}\text{C}$ on annual basis.

5.2 Sensitivity study

5.2.1 Frit geometry

The Reference Case geometry and input settings were tested with the addition of physical frit to the exterior of the glazing. Two types of frit patterns were tested; a uniform and non-uniform pattern. The frit was assumed to be opaque with an area corresponding to shading need of the glazing with a g -value of 0.7. The effectiveness of the method at improving thermal comfort in Point 0 was analyzed with the frit patterns and compared to the output for the Reference Case.

The tool output for the analyzed weather files is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.1.1 Ray tracing module output

As can be seen in Figure 42, the uniform and non-uniform frit patterns correspond to the re-distributed average g -value of the Reference Case.

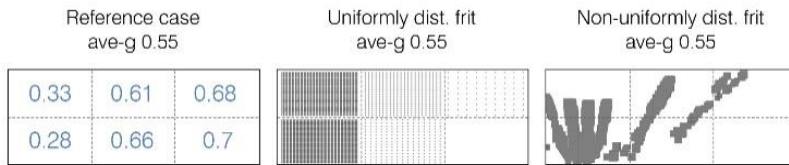


Figure 42: Ray tracing module output of re-distributed g -value, uniform frit pattern and non-uniformly distributed frit based on positions of intersections.

5.2.1.2 Thermal data output

Table 5 shows the number of hours (annually) above each threshold before (uni-g 0.55) and after (ave-g 0.55) applying the method to the comfort analysis of Point 0 for each frit pattern. The number of hours above all threshold show similar trends for both patterns, indicating a good translation of g -value to frit area.

Table 5: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the Reference Case with re-distributed g -values and two cases with physical geometry of frit in form of uniformly distributed frit and non-uniformly distributed frit.

	Ref case uni g 0.55 /h	Ref case ave g 0.55 /h	Uniformly dist frit ave g 0.55 /h	Non-uniformly dist frit ave g 0.55 /h
$\geq 26^\circ\text{C}$	1110	1015	985	915
$\geq 28^\circ\text{C}$	655	530	516	451
$\geq 30^\circ\text{C}$	409	279	204	166
$\geq 35^\circ\text{C}$	128	17	52	48

The percentage differences between uni-g 0.55 and ave-g 0.55 for the Reference Case and both frit patterns are shown in Figure 43. The tool shows comparable potential for all methods of attaining the desired average g -value of 0.55. However, the case with re-distributed g -values performs best for high temperature threshold of 35°C , while both frit patterns are more effective for reducing temperatures of lower thresholds such as 26°C and 28°C . What is more, the non-uniformly distributed frit reduces the number of hours above all threshold slightly more than the uniform frit pattern.

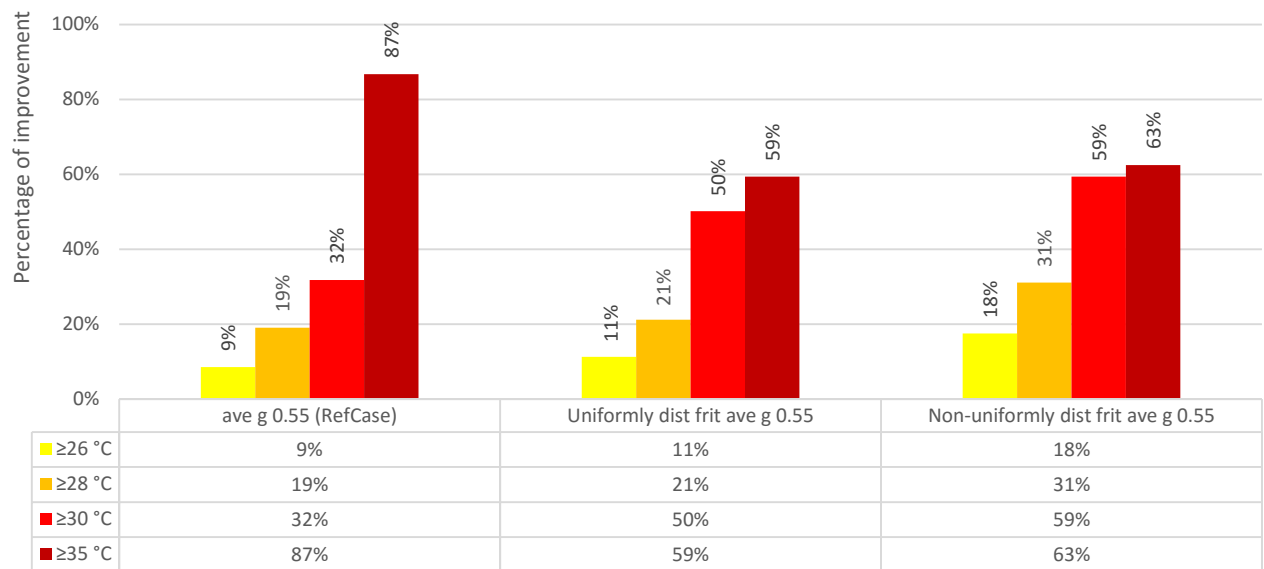


Figure 43: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the Reference Case with re-distributed g-values and two cases with physical geometry of frit in form of uniformly distributed frit and non-uniformly distributed frit.

5.2.2 Climate file

The Reference Case geometry and input settings were tested for two additional climates; Madrid and Abu Dhabi. The effectiveness of the method at improving thermal comfort in Point 0 was analyzed in the additional climates and compared to the output for the Reference Case climate of Copenhagen.

The tool output for the analyzed weather files is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.2.1 Ray tracing module output

As can be seen in Figure 44, for the Madrid climate, the g -value is re-distributed to the bottom left corner of the façade, indicating a stronger need for shading there. In Abu Dhabi, the re-distribution of g -value on the façade is similar to Copenhagen.



Figure 44: Ray tracing module output of re-distributed g -value and uniform frit pattern for Copenhagen (Reference Case), Madrid and Abu Dhabi.

5.2.2.2 Thermal data output

Table 6 shows the number of hours (annually) above each threshold before (uni-g 0.55) and after (ave-g 0.55) applying the method to the comfort analysis for each climate. The number of hours above all thresholds are considerably higher in Abu Dhabi, indicating an acute overheating problem at Point 0 in this climate.

Table 6: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with weather data for Copenhagen (Reference Case), Madrid and Abu Dhabi.

	Copenhagen uni-g 0.55 (RefCase) /h	Copenhagen ave-g 0.55 (RefCase) /h	Madrid uni-g 0.55 /h	Madrid ave-g 0.55 /h	Abu Dhabi uni-g 0.55 /h	Abu Dhabi ave-g 0.55 /h
$\geq 26^{\circ}\text{C}$	1110	1015	1766	1554	2974	2923
$\geq 28^{\circ}\text{C}$	655	530	1075	761	1542	1447
$\geq 30^{\circ}\text{C}$	409	279	706	391	867	804
$\geq 35^{\circ}\text{C}$	128	17	327	64	550	313

The percentage differences between uni-g 0.55 and ave-g 0.55 for each climate file are shown in Figure 45. The tool shows promising potential for all thresholds in Madrid and less probably prospective for Abu Dhabi.

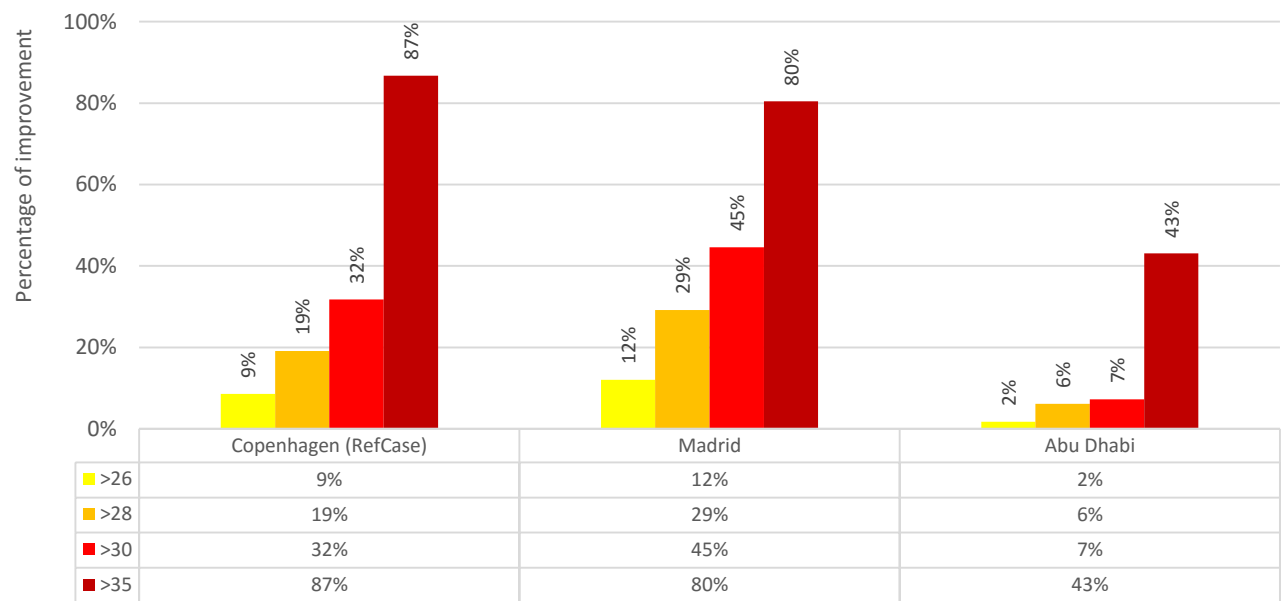


Figure 45: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with weather data for Copenhagen (Reference Case), Madrid and Abu Dhabi.

5.2.3 One point on the floor

Thus far, only Point 0 has been subject to thermal analysis in the analyzed zone. Hereby, the effectiveness of the method at improving thermal comfort in Point 1, 2, 3, 4 and Point 5 was tested and compared to the output for the Reference Case analysis of Point 0.

The tool output for the analyzed points is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.3.1 Ray tracing module output

As can be seen in Figure 46, the g -value distribution varies significantly depending on which point is chosen as analysis point.

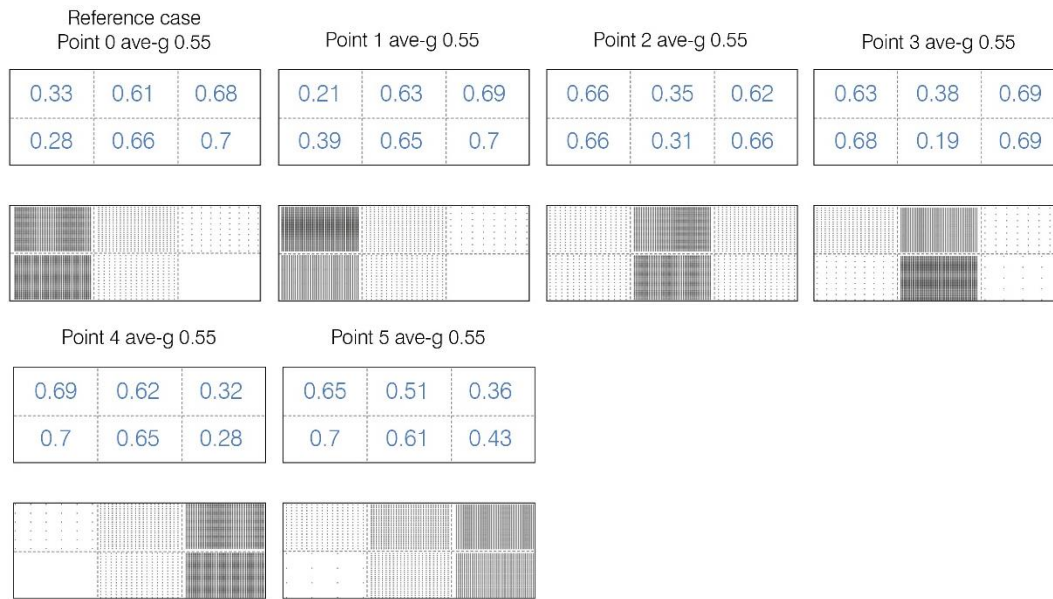


Figure 46: Ray tracing module output of re-distributed g -value and uniform frit pattern for cases with six various locations of an analyzed point.

5.2.3.2 Thermal data output

Table 7 shows the number of hours (annually) above each threshold before (uni-g 0.55) and after (ave-g 0.55) applying the method to the comfort analysis for each point on the floor. The number of hours above all thresholds are considerably higher for Point 0, 2 and 4 which were located next to the glazed facade, indicating a greater overheating problem due to direct solar radiation.

Table 7: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with six various locations of an analyzed point.

	Point0 uni-g 0.55 /h	Point0 ave-g 0.55 /h	Point1 uni-g 0.55 /h	Point1 ave-g 0.55 /h	Point2 uni-g 0.55 /h	Point2 ave-g 0.55 /h	Point3 uni-g 0.55 /h	Point3 ave-g 0.55 /h	Point4 uni-g 0.55 /h	Point4 ave-g 0.55 /h	Point5 uni-g 0.55 /h	Point5 ave-g 0.55 /h
$\geq 26^\circ\text{C}$	1110	1015	604	621	1154	1103	644	644	1045	946	671	678
$\geq 28^\circ\text{C}$	655	530	107	99	770	685	142	136	704	572	168	166
$\geq 30^\circ\text{C}$	409	279	33	19	524	440	54	43	496	361	72	67
$\geq 35^\circ\text{C}$	128	17	7	0	191	110	18	15	182	87	21	17

The percentage differences between uni-g 0.55 and ave-g 0.55 for all thresholds and for each point are shown in Figure 47. The tool shows more potential for improving comfort in spaces exposed to more direct sunlight.

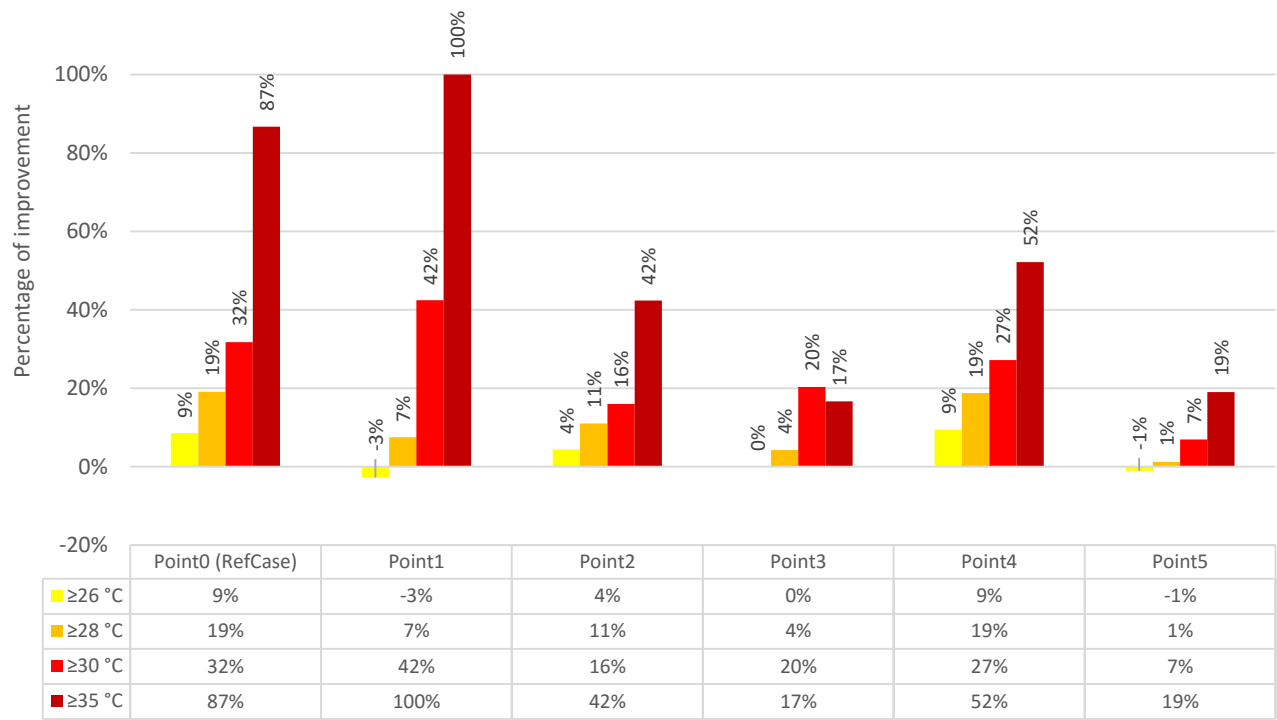


Figure 47: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with six various locations of an analyzed point.

5.2.4 Several points on the floor

Thus far, only Point 0 has been subject to thermal analysis in the analyzed zone. Hereby, the effectiveness of the method at improving thermal comfort in more than one point at a time, encompassing a larger analysis area, was tested and the resulting comfort for Point 0 was compared to the output for the Reference Case.

The tool output for the analyzed points is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.4.1 Ray tracing module output

Figure 48 shows how the average g -value distribution varies depending on how many points are simultaneously chosen as analysis points. It can clearly be seen that the larger the analyzed floor area, more wide spread the distribution becomes.

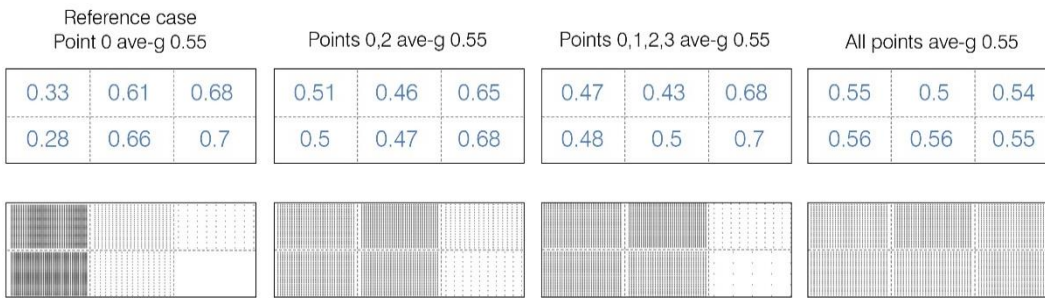


Figure 48: Ray tracing module output of re-distributed g -value and uniform frit pattern for cases with point 0, points 0 and 2, points 0, 1, 2 and 3, and all points analyzed.

5.2.4.2 Thermal data output

Table 8 shows the number of hours (annually) above each threshold after (ave-g 0.55) applying the method to the analysis for each combination of points on the floor. The results are compared to the Reference Case (uni-g 0.55).

Table 8: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with point 0, points 0 and 2, points 0, 1, 2 and 3, and all points analyzed.

	Point 0 uni-g 0.55 (RefCase) /h	Point 0 ave-g 0.55 (RefCase) /h	Points 0+2 ave-g 0.55 /h	Points 0+1+2+3 ave-g 0.55 /h	All Points ave-g 0.55 /h
$\geq 26^{\circ}\text{C}$	1110	1015	1063	1053	1106
$\geq 28^{\circ}\text{C}$	655	530	609	588	650
$\geq 30^{\circ}\text{C}$	409	279	372	356	399
$\geq 35^{\circ}\text{C}$	128	17	107	95	131

The percentage differences between uni-g 0.55 and ave-g 0.55 for all thresholds and for each combination of points are shown in Figure 49. Increasing the spread of analysis points (i.e. increasing the analyzed floor area) shows a clear tendency of reducing the effectiveness of the tool. The results show that the case with only one analysis point, Point 0, experiences the highest thermal improvement with distributed g -value. The worst effect on thermal comfort in Point 0 occurs when all points are considered for the analysis, which even shows a degradation of comfort $\geq 35^{\circ}\text{C}$ compared to the Reference Case.

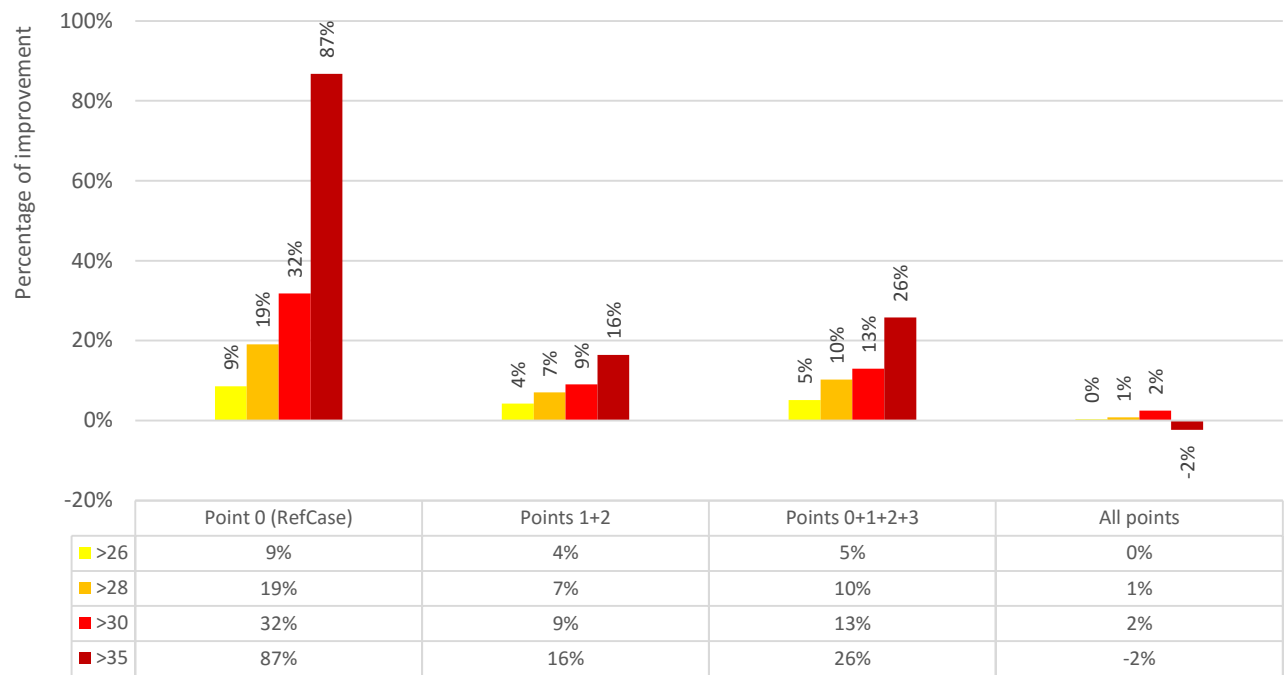


Figure 49: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with point 0, points 0 and 2, points 0, 1, 2 and 3, and all points analyzed.

5.2.5 Cooling threshold

The Reference Case geometry and input settings were tested for various cooling set point temperatures of the ventilation system. The effectiveness of the method at improving thermal comfort in Point 0 was analyzed at the cooling set points and compared to the output for the Reference Case set point temperature of 24°C.

The tool output for the analyzed set point temperatures is comprised of 1. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.5.1 Thermal data output

Table 9 shows the number of hours (annually) above each threshold before (uni-g 0.55) and after (ave-g 0.55) applying the method to the comfort analysis for each set point temperature.

Table 9: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with cooling set points of 28°C , 26°C , 24°C (Reference Case), 22°C , 21°C and the case with no cooling applied.

	no condition ing uni-g 0.55 /h	no condition ing ave-g 0.56 /h	set pt 28 uni-g 0.55 /h	set pt 28 ave-g 0.55 /h	set pt 26 uni-g 0.55 /h	set pt 26 ave-g 0.55 /h	set pt 24 uni-g 0.55 (Ref case) /h	set pt 24 ave-g 0.55 (Ref case) /h	set pt 22 uni-g 0.55 /h	set pt 22 ave-g 0.55 /h
$\geq 26^{\circ}\text{C}$	1441	1436	1276	1236	1238	1189	1110	1015	769	632
$\geq 28^{\circ}\text{C}$	1361	1344	1030	980	911	822	655	530	479	341
$\geq 30^{\circ}\text{C}$	1245	1245	710	629	500	397	409	279	290	150
$\geq 35^{\circ}\text{C}$	1163	1151	215	115	172	53	128	17	85	0

The percentage differences between uni-g 0.55 and ave-g 0.55 for all thresholds and for each set point are shown in Figure 50. The tool shows almost no effect without conditioning of the space. Lowering the cooling set point temperature shows a clear tendency of increasing the effectiveness of the tool.

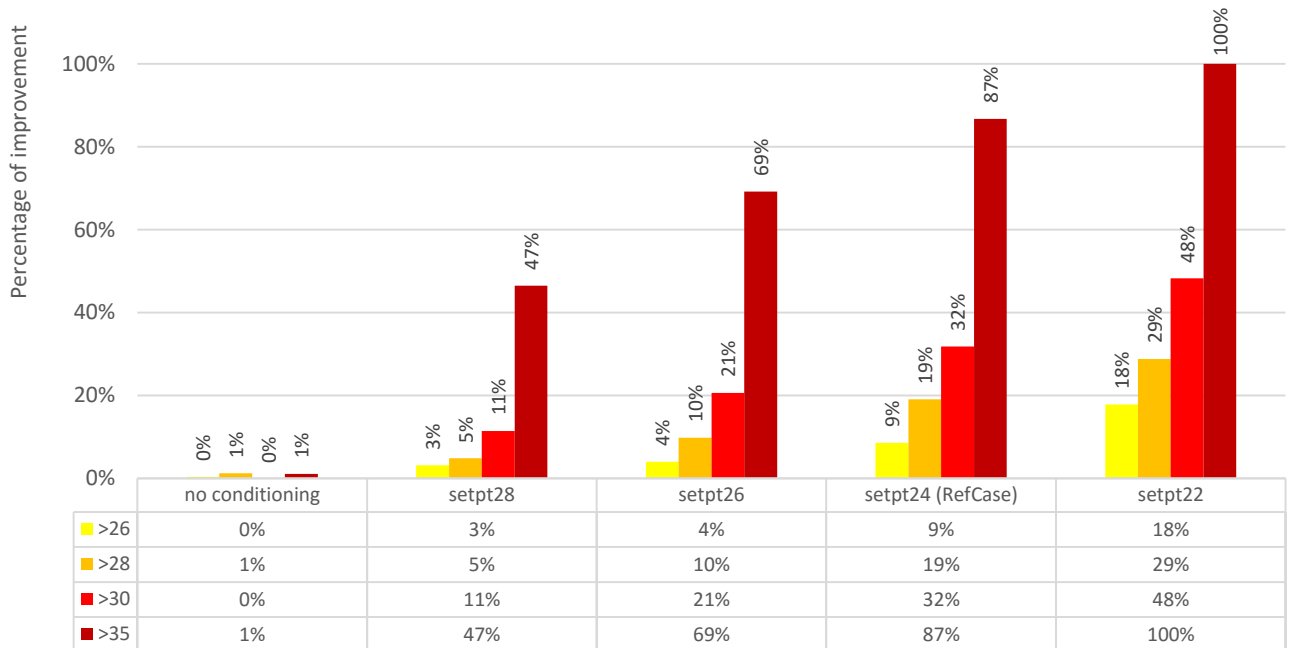


Figure 50: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with cooling set points of 28°C , 26°C , 24°C (Reference Case), 22°C , 21°C and the case with no cooling applied.

5.2.6 Glazed façade grid

Thus far, the method has been tested only for glazed façade divided into the grid of 2·3 with glazing unit dimensions of 1.5 · 2.7 m. Hereby, the effectiveness of the method at improving thermal comfort for cases with façade grid of 2·2, 3·4 and 5·6 was tested. The dimensions of glazing units for the cases are 1.5 m · 4.0 m, 1.0 m · 2.0 m and 0.6 m · 1.7 m accordingly.

The tool output for the analyzed glazed façade grid is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.6.1 Ray tracing module output

Figure 51 shows how the average g -value distribution varies depending on how dense is the glazed façade grid. It can clearly be seen that the denser the grid, more wide spread the distribution becomes. It can also be noticed, that the g -value is re-distributed to the middle left side of the façade, indicating a stronger need for shading there. Consequently, for the case with 3·4 grid, a shading need of the middle left grid exceeded the available area of the unit. Hereby, as described in section 3.3.4.3 Redistributed g -value, the non-shaded glass g -value was lowered to 0.65 in order to compensate.

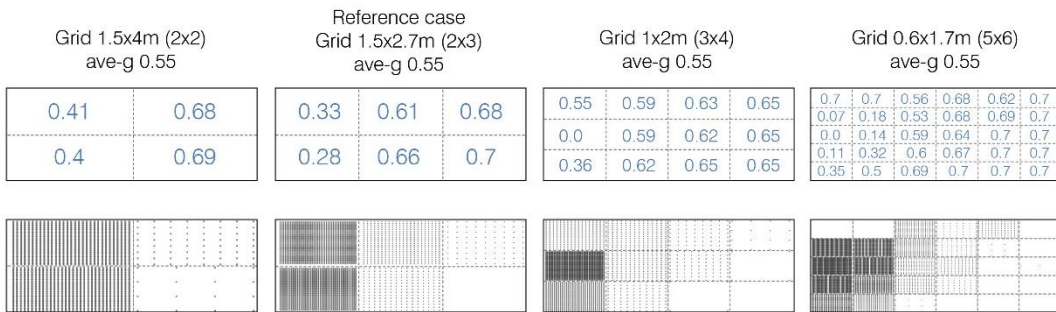


Figure 51: Ray tracing module output of re-distributed g -value and uniform frit pattern for cases with grid dimensions of: 1.5 x 4.0 m (2x2), 1.0 x 2.0 m (3x4), 0.6 x 1.7 m (5x6) and 1.5mx2.7m (3x2) as the Reference Case.

5.2.6.2 Thermal data output

Table 10 displays the relative impact of the façade grid size on the number of hours above each threshold.

Table 10: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with grid dimensions of: 1.5 x 4.0 m (2x2), 1.0 x 2.0 m (3x4), 0.6 x 1.7 m (5x6) and 1.5mx2.7m (3x2) as the Reference Case.

	1.5x2.7 (3x2) uni-g 0.55 (RefCase) /h	1.5x4.0 (2x2) ave-g 0.55 /h	1.5x2.7 (2x3) ave-g 0.55 (RefCase) /h	1.0x2.0 (3x4) ave-g 0.55 /h	0.6x1.7 (5x6) ave-g 0.55 /h
$\geq 26^\circ\text{C}$	1110	1030	1015	947	908
$\geq 28^\circ\text{C}$	655	545	530	419	318
$\geq 30^\circ\text{C}$	409	311	279	166	85
$\geq 35^\circ\text{C}$	128	54	17	24	0

The percentage differences between uni-g 0.55 and ave-g 0.55 for all thresholds and for each of façade grid size are shown in Figure 52Figure 50Figure 49. A clear trend of reducing the number of hours above all thresholds by increasing the density of the grid can be observed.

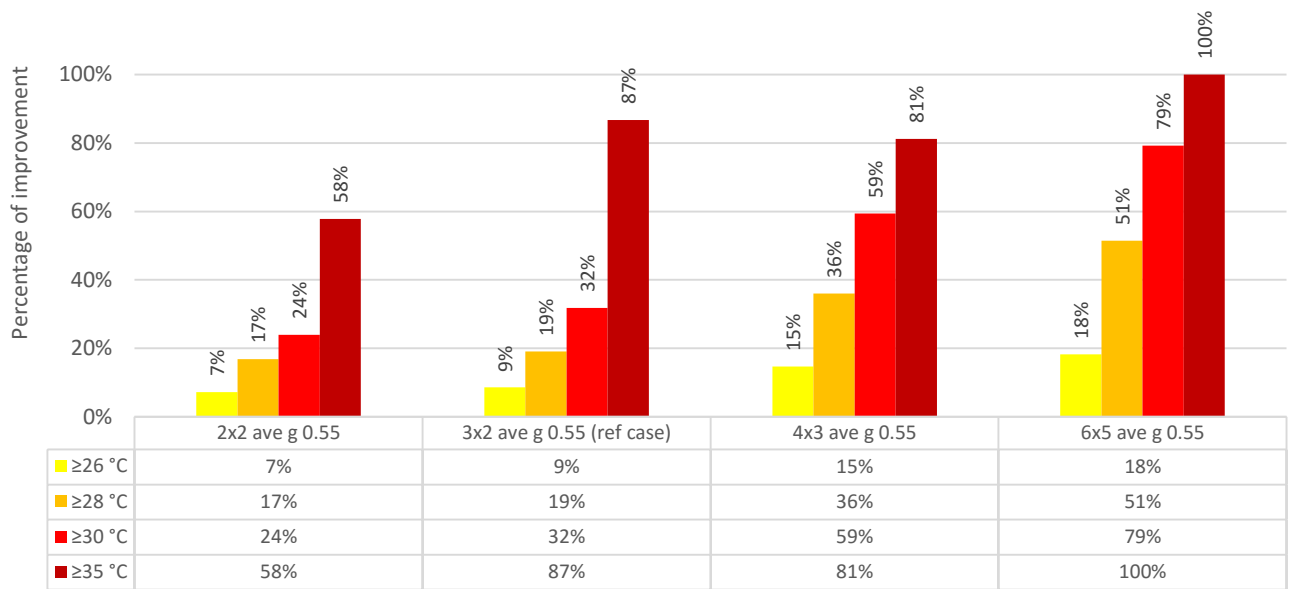


Figure 52: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with grid dimensions of: $1.5 \times 4.0 \text{ m}$ (2x2), $1.0 \times 2.0 \text{ m}$ (3x4), $0.6 \times 1.7 \text{ m}$ (5x6) and $1.5\text{m} \times 2.7\text{m}$ (3x2) as the Reference Case.

5.2.7 Factoring methods

The tool was tested for five additional factoring methods, described in section 3.4.2.7 Factoring methods:

- Factors 1
- Factors 0.2-1
- Factors 0.4-1
- Factors 0.6-1
- Factors 0.8-1

The effectiveness of the method at improving thermal comfort in Point 0 was analyzed for each of the factoring method and compared to the output for the Reference Case for which all factors between 0-1 were used.

The tool output for the analyzed factoring methods is comprised of 1. Ray tracing module output, including re-distributed average g -values, uniform frit pattern and ray-traced intersections, and 2. Thermal data output, including the numbers of hours above analyzed thresholds for the Reference case and five additional factoring methods.

5.2.7.1 Ray tracing module output

Figure 53 shows how the average g -value distribution varies depending on what type of factoring intervals are applied. The largest differentiation of g -values were achieved with the factoring methods of 0.6-1 and 0.8-1, while case with all factor set to 1 resulted with the least diverse g -values on the façade.

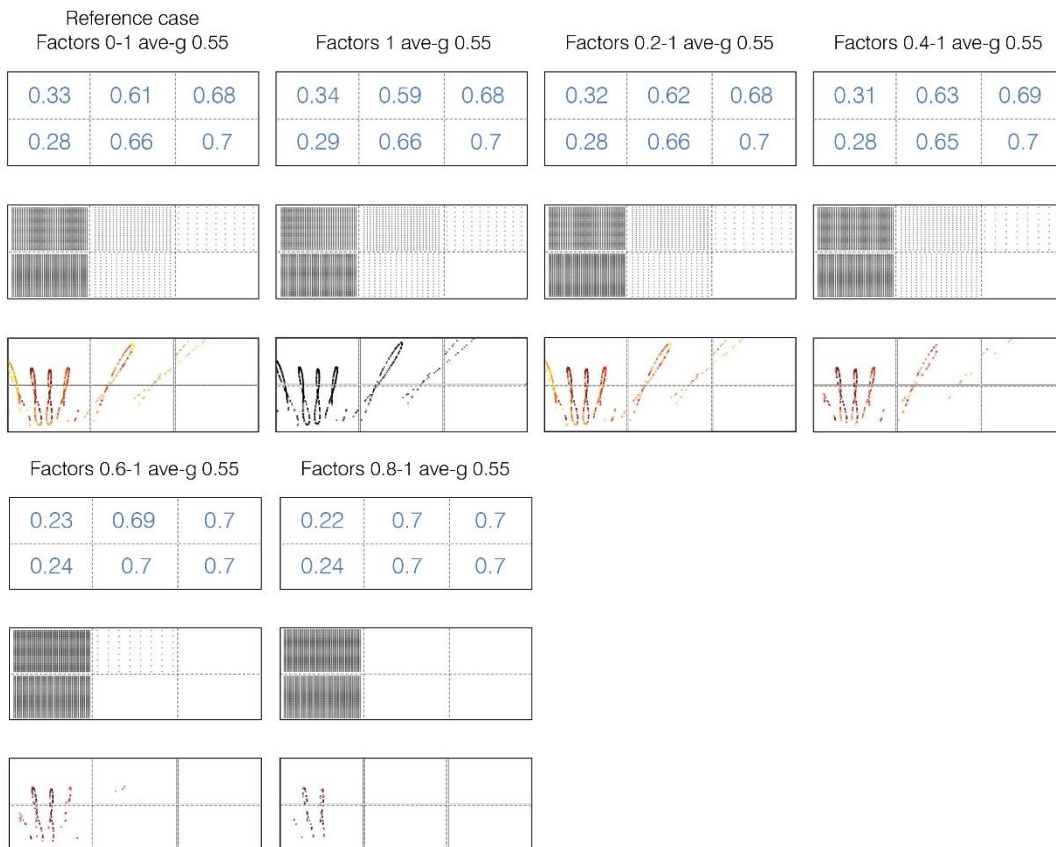


Figure 53: Ray tracing module output of re-distributed g -value, uniform frit pattern and ray-traced intersections for six types of factoring methods.

5.2.7.2 Thermal data output

The two graphs in Figure 51 portray how the monthly distribution of solar overheating factors is effected by the choice of factoring method. Two factoring methods were tested: Factors 0-1 (Reference case) and Factors 1. The right pie chart represents the Reference Case with factors between 0-1 and shows slightly higher relative importance of each solar overheating factor from July to August than the case with all factors of 1, represented by the left pie chart. Consequently, the case with all factors set to 1 reveals slightly higher relative importance of solar overheating factors from February to May.

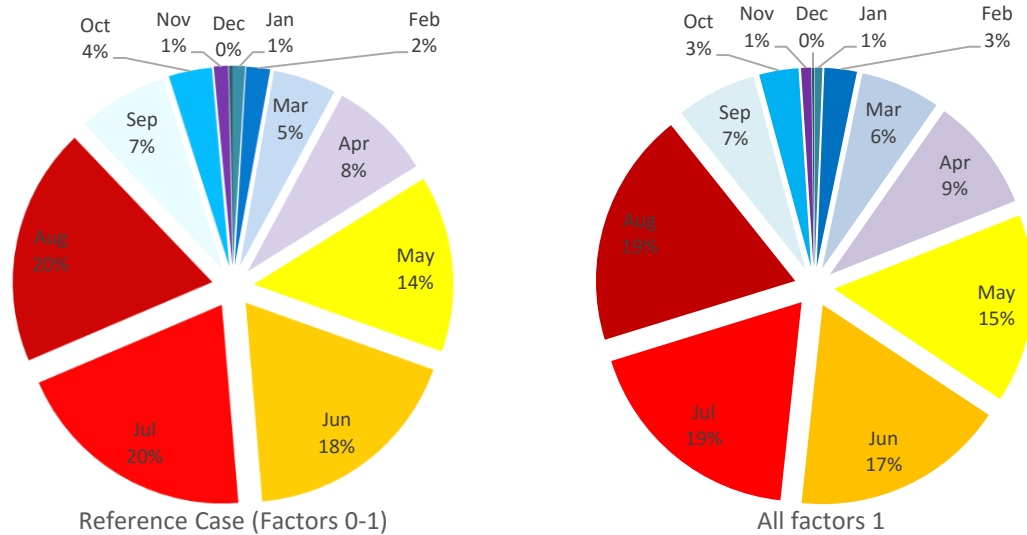


Figure 54: Monthly distribution of solar overheating factors for case with applied factors between 0-1 (Reference Case) and case with all applied factors equal to 1.

Table 9 shows the number of hours (annually) above each threshold for cases after (ave-g 0.55) applying the method with each of the tested factors intervals. The results are compare with the results for the Reference case before (uni-g 0.55) the application of the method.

Table 11: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with factors of 1, factors 0.2-1, factors 0.4-, factors 0.6-1, factors 0.8-1 and factors between 0-1 (Reference Case).

	Uni-g 0.55 (RefCase) /h	Factors 0-1 Ave-g 0.55 (RefCase) /h	Factors 1 Ave-g 0.55 /h	Factors 0.2-1 Ave-g 0.55 /h	Factors 0.4-1 Ave-g 0.55 /h	Factors 0.6-1 Ave-g 0.55 /h	Factors 0.8-1 Ave-g 0.55 /h
$\geq 26^\circ\text{C}$	1110	1015	1023	1013	1012	988	988
$\geq 28^\circ\text{C}$	655	530	539	529	527	488	488
$\geq 30^\circ\text{C}$	409	279	288	277	275	246	244
$\geq 35^\circ\text{C}$	128	17	22	11	11	2	2

Figure 55 shows the effect of the tested factoring methods on number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C . In general, the choice of the principle how the intersections points are factored, shows a limited impact on the effectiveness of the tool. However, the lowest advantage of the tool can be noticed when all factors are set to 1, and as such no factoring method is applied.

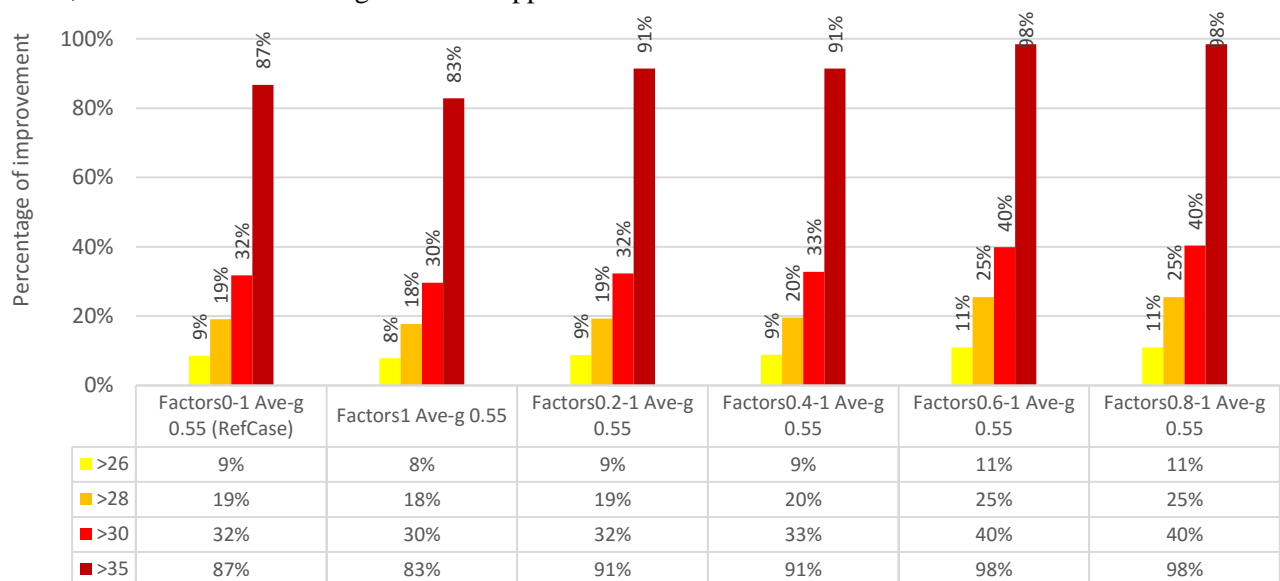


Figure 55: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with factors of 1, factors 0.2-1, factors 0.4-, factors 0.6-1, factors 0.8-1 and factors between 0-1 (Reference Case).

5.2.8 Geometry scale

Thus far, the geometry with floor dimensions of 5m by 8m and height of 3m has been subject to thermal analysis. Hereby, the effectiveness of the method at improving thermal comfort in spaces enlarged by four and ten was tested.

The tool output for the analyzed geometry scales is comprised of 1. Ray tracing module output, including re-distributed average g -values and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.8.1 Ray tracing module output

Figure 56 shows how the scale of geometry influence the average g -value distribution. No significant changes in the g -value distribution can be noticed for cases enlarged with the scale factor of two and ten, in comparison to the results for the Reference Case (scale 1:1).

Reference case Scale 1:1 ave-g 0.55			Scale 4:1 ave-g 0.55			Scale 10:1 ave-g 0.55		
0.33	0.61	0.68	0.33	0.61	0.69	0.34	0.61	0.69
0.28	0.66	0.7	0.28	0.66	0.7	0.28	0.65	0.7

Figure 56: Ray tracing module output of re-distributed g -value for the enlarged geometries and the Reference Case.

5.2.8.2 Thermal data output

Table 12 displays the number of hours (annually) above each threshold after (ave-g 0.55) applying the method to the analysis for each scaled geometry. The results are compared to the Reference Case (uni-g 0.55).

Table 12: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the enlarged geometries and the Reference Case.

	Scale 1:1 Uni-g 0.55 (RefCase) /h	Scale 1:1 Ave-g 0.55 (RefCase) /h	Scale 4:1 Uni-g 0.55 /h	Scale 4:1 Ave-g 0.55 /h	Scale 10:1 Uni-g 0.55 /h	Scale 10:1 Ave-g 0.55 /h
$\geq 26^\circ\text{C}$	1110	1015	1132	1046	1140	1051
$\geq 28^\circ\text{C}$	655	530	661	547	669	542
$\geq 30^\circ\text{C}$	409	279	409	287	402	283
$\geq 35^\circ\text{C}$	128	17	131	18	130	20

The percentage differences between uni-g 0.55 and ave-g 0.55 for all thresholds and for the scaled geometries are shown in Figure 57. Increasing the scale of the geometry does not change noticeably the effectiveness of the method.

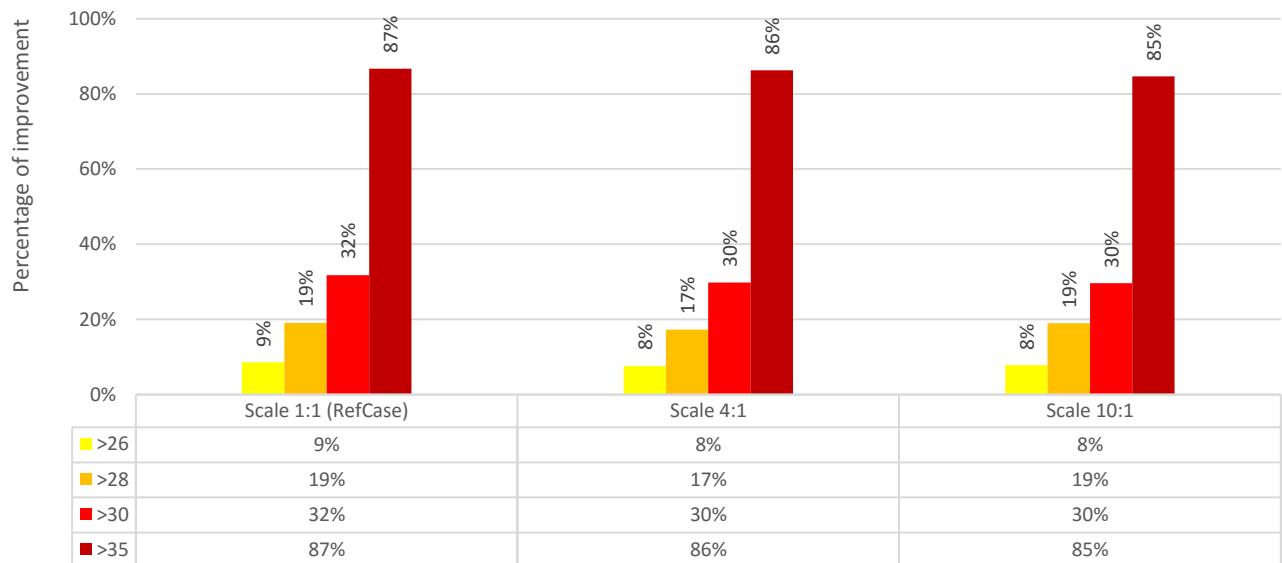


Figure 57: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the geometries enlarged with scale of two and ten, and the Reference Case.

5.2.9 Orientation

Thus far, the geometry with glazed façade oriented to the South has been subject to thermal analysis. Hereby, the effectiveness of the method at improving thermal comfort in spaces with glazed façade oriented to the East and to the West was tested.

The tool output for the analyzed glazed façade orientation is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.9.1 Ray tracing module output

As can be seen in Figure 58, for the eastern orientation, the g -value is re-distributed to the bottom left corner of the façade, indicating stronger need for shading there. For the western orientation, the lower g -values are also re-distributed to the bottom left corner, however the shading need applies to larger number of the glazing units.



Figure 58: Ray tracing module output of re-distributed g -value and uniform frit pattern for south- (Reference Case), east- and west-oriented cases.

5.2.9.2 Thermal data output

Table 13 shows the number of hours (annually) above each threshold before (uni-g 0.55) and after (ave-g 0.55) applying the method to the comfort analysis for each orientation case. The number of hours above all thresholds are considerably higher for the space with southerly oriented glazed façade than for spaces with easterly or westerly oriented glazed facades.

Table 13: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for south (Reference Case), east and west oriented cases.

	South Uni-g 0.55 (RefCase) /h	South Ave-g 0.55 (RefCase) /h	East Uni-g 0.55 /h	East Ave-g 0.55 /h	West Uni-g 0.55 /h	West Ave-g 0.55 /h
$\geq 26^\circ\text{C}$	1110	1015	866	525	746	561
$\geq 28^\circ\text{C}$	655	530	351	97	417	290
$\geq 30^\circ\text{C}$	409	279	170	47	291	140
$\geq 35^\circ\text{C}$	128	17	21	7	93	18

Figure 59 displays the relative impact of the façade orientation on the number of hours above each threshold. Clearly, the southern and western orientations show biggest advantage of the method for high $T_{o,Adj}$ threshold of 35°C , while eastern orientation performs best for threshold of 28°C .

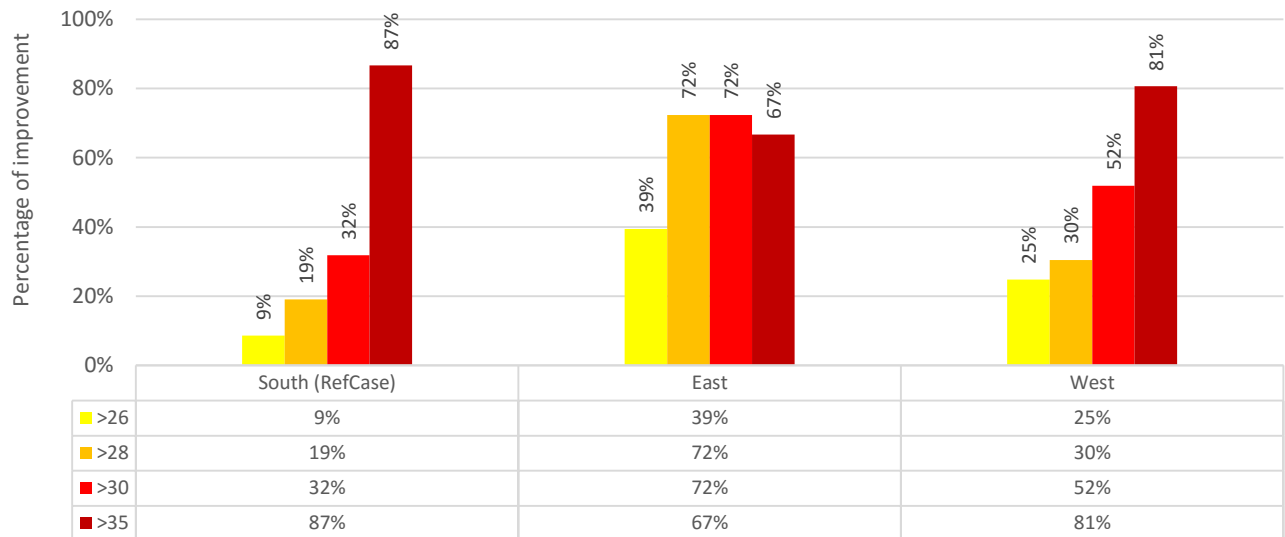


Figure 59: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for south (Reference Case), east and west oriented cases.

As shown on a weekly time distribution graph in Figure 60, a clear reduction of peak operative temperatures on a sunny and moderately cloudy afternoon is noticeable for west orientation. As expected and shown in Figure 61, the east-oriented case displays a potential of reducing peak operative temperatures on sunny days before noon. Moreover, the results shows a significant reduction of overheating hours on cloudy days for east-oriented case, most likely due to high impact of diffuse radiation on perceived operative temperatures.

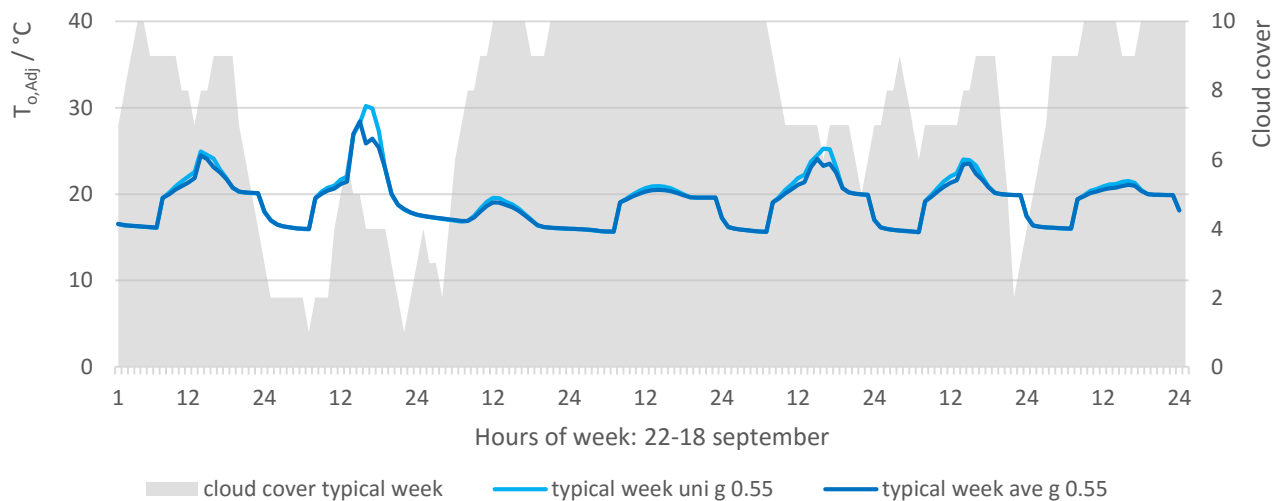


Figure 60: $T_{o,Adj}$ distribution in typical week for west orientation

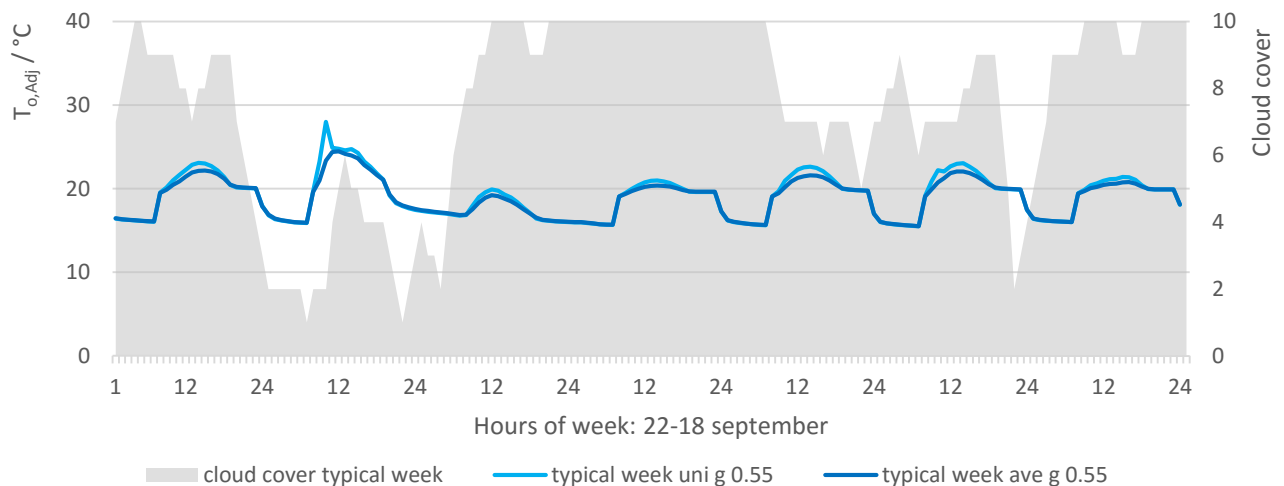


Figure 61: $T_{o,Adj}$ distribution in typical week for east orientation.

5.2.10 Glazing ratio

The Reference Case geometry and input settings were tested for four additional glazing to floor ratios:

- GFR 7.5 %
- GFR 15 %
- GFR 30 %
- GFR 80 %

The effectiveness of the method at improving thermal comfort in Point 0 was analyzed for the additional glazing cases and compared to the output for the Reference Case with the GWR of 60 %.

The tool output for the analyzed glazing ratios is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.10.1 Ray tracing module output

As can be seen in Figure 62, the g -value distribution varies significantly depending on which glazing ratio is tested. It can also be noticed, that for the case with GWR of 80% and glazing on the façade and the roof simultaneously, the g -values are lowered only on the façade, indicating that no shading is needed on the roof.

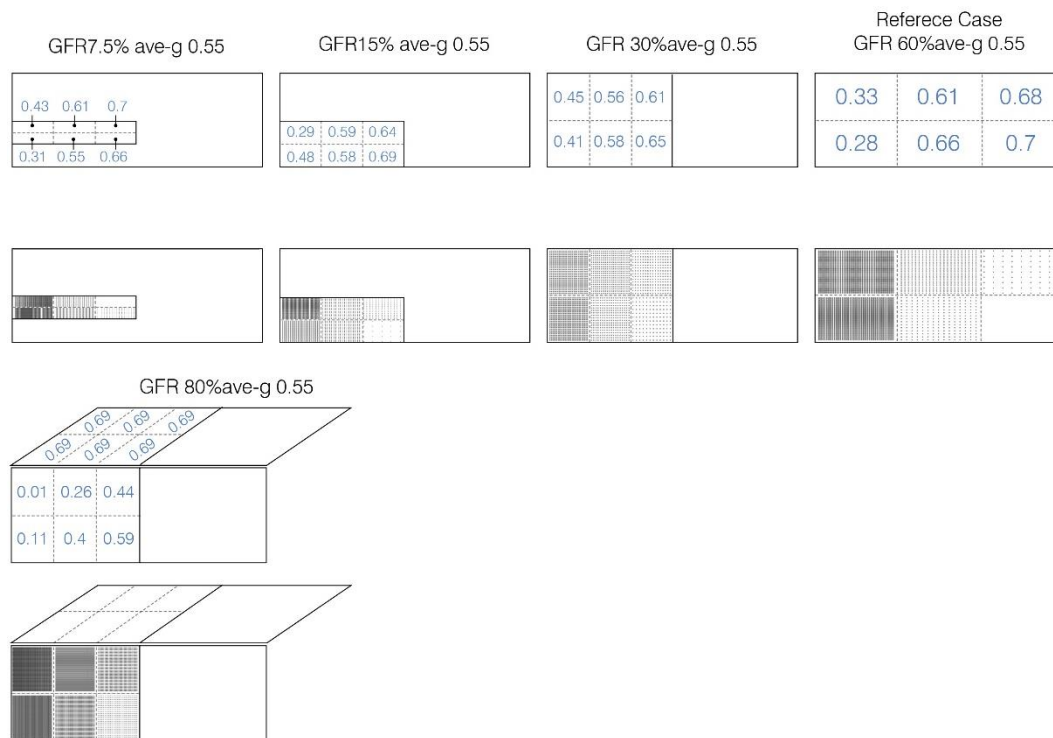


Figure 62: Output of re-distributed g -value and uniform frit pattern for the cases with GWR 7.5%, GWR 15%, GWR 30%, GWR 80% and GWR 60% (Reference Case).

5.2.10.2 Thermal data output

Testing different glazing to floor ratios indicates that the method performs better for cases with lower percentage of fenestration. However, it is important to note that location of a window on a façade might have a high impact on the result and thus each case should be treated individually.

Table 14 shows the number of hours (annually) above each threshold before (uni-g 0.55) and after (ave-g 0.55) applying the method to the comfort analysis for each glazing ratio. The number of hours above all thresholds are considerably higher for cases with higher ratios of glazing.

Table 14: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the cases with GWR 7.5%, GWR 15%, GWR 30%, GWR 80% and GWR 60% (Reference Case).

	GFR7.5% Uni-g 0.55 /h	GFR7.5% Ave-g 0.55 /h	GFR15% Uni-g 0.55 /h	GFR15% Ave-g 0.55 /h	GFR30% Uni-g 0.55 /h	GFR30% Ave-g 0.55 /h	GFR60% Uni-g 0.55 (RefCase) /h	GFR60% Ave-g 0.55 (RefCase) /h	GFR80% Uni-g 0.55 /h	GFR80% Ave-g 0.55 /h
≥ 26	64	54	122	104	560	527	1110	1015	1210	1167
≥ 28	42	16	58	32	289	279	655	530	892	833
≥ 30	26	4	40	2	190	166	409	279	561	489
≥ 35	0	0	2	0	55	10	128	17	174	15

The results in Figure 63 show that the best performance of the method was achieved for glazing ratio of 15%. What is more, for cases with lower glazing ratios, the method was also preferred for lower thresholds of operative temperatures such as 26°C and 28°C .

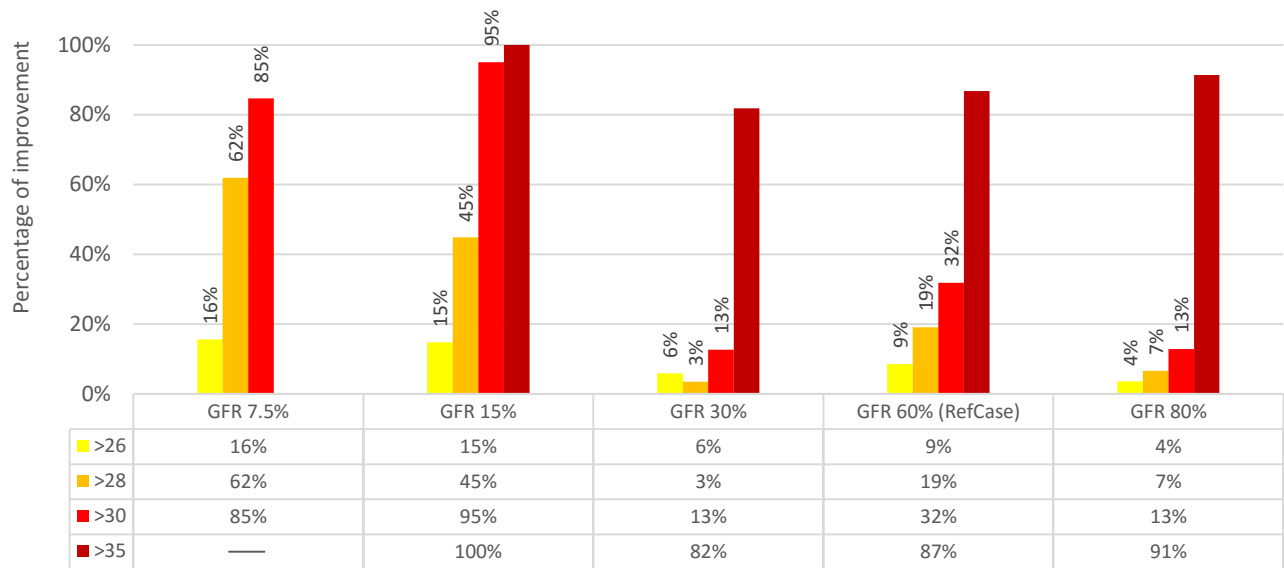


Figure 63: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the cases with GWR 7.5%, GWR 15%, GWR 30%, GWR 80% and GWR 60% (Reference Case).

5.2.11 Average g -value of glass

The method was tested for three additional cases with different average g -values of glass:

- average g -value of 0.65 (ave- g 0.65)
- average g -value of 0.45 (ave- g 0.45)
- average g -value of 0.35 (ave- g 0.35)

The effectiveness of the method at improving thermal comfort in Point 0 was analyzed for the additional cases and compared to the output for the Reference Case with average glass g -value of 0.55.

The tool output for the analyzed cases of average glass g -value is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.11.1 Ray tracing module output

As can be seen in Figure 64, the lower the average glass g -value, the wider spread the distribution becomes.

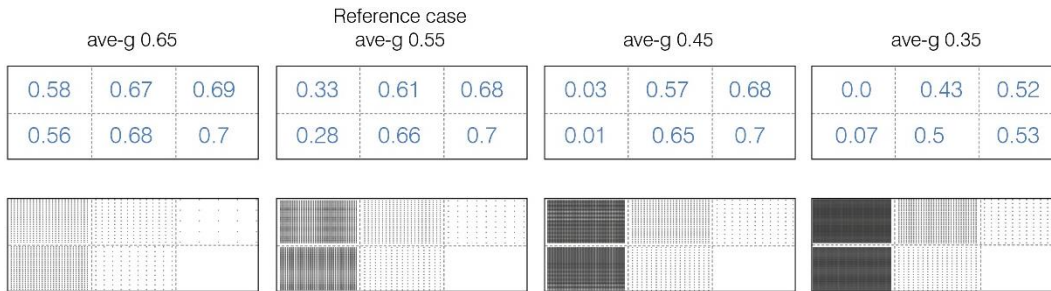


Figure 64: Output of re-distributed g -value and uniform frit pattern for the cases with average g -value of 0.65, 0.55 (Reference Case), 0.45 and 0.35.

5.2.11.2 Thermal data output

By changing the average g -value of glazed façade a clear trend of higher advantage of the method for cases with lower average g -value can be noticed. In other words, cases with less extensive overheating problems are more likely to benefit from the method.

Table 15 shows the number of hours (annually) above each threshold before (uni- g) and after (ave- g) applying the method to the comfort analysis for each average glass g -value case. The number of hours above all thresholds are considerably higher for a case with highest average glass g -value of 0.65.

Table 15: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the cases with average g -value of 0.65, 0.55 (Reference Case), 0.45 and 0.35.

	Uni-g 0.55 (RefCase) /h	Ave-g 0.55 (RefCase) /h	Uni-g 0.65 /h	Ave-g 0.65 /h	Uni-g 0.45 /h	Ave-g 0.45 /h	Uni-g 0.35 /h	Ave-g 0.35 /h
$\geq 26^\circ\text{C}$	1110	1015	1317	1280	835	620	651	145
$\geq 28^\circ\text{C}$	655	530	929	857	423	175	318	25
$\geq 30^\circ\text{C}$	409	279	574	523	252	36	165	0
$\geq 35^\circ\text{C}$	128	17	216	178	43	0	2	0

As displayed in Figure 65, the case with average g -value of 0.35 displays a potential of reducing the overheating risk of 651 hours with $T_{o,Adj}$ over 26°C by 78%. Moreover, the results clearly show that the method is more favorable to eliminate high ranges of $T_{o,Adj}$, such as 35°C .

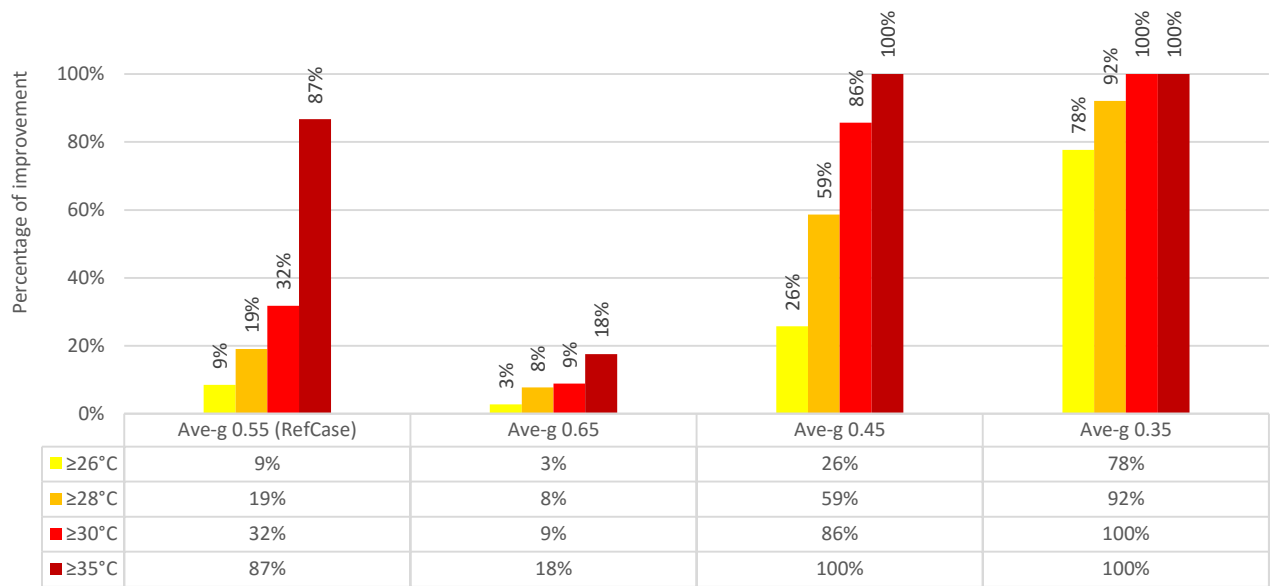


Figure 65: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the cases with average g -value of 0.65, 0.55 (Reference Case), 0.45 and 0.35.

5.2.12 Analysis period

Thus far, only the annual basis has been subject to thermal analysis of the Reference case. Hereby, the effectiveness of the method at improving thermal comfort was tested for four more periods:

- one season (summer),
- one month (August),
- one week (in August) and
- one day (2nd August)

The effectiveness of the method at improving thermal comfort in Point 0 was analyzed for the additional periods and compared to the output for the Reference Case with annual analysis period.

The tool output for the analyzed periods is comprised of 1. Ray tracing module output, including re-distributed average g -values and uniform frit pattern, and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.12.1 Ray tracing module output

Figure 66 shows how the average g -value distribution varies depending on the chosen analysis period. It can clearly be seen that the shorter analysis period is, the wider spread of g -value distribution becomes.

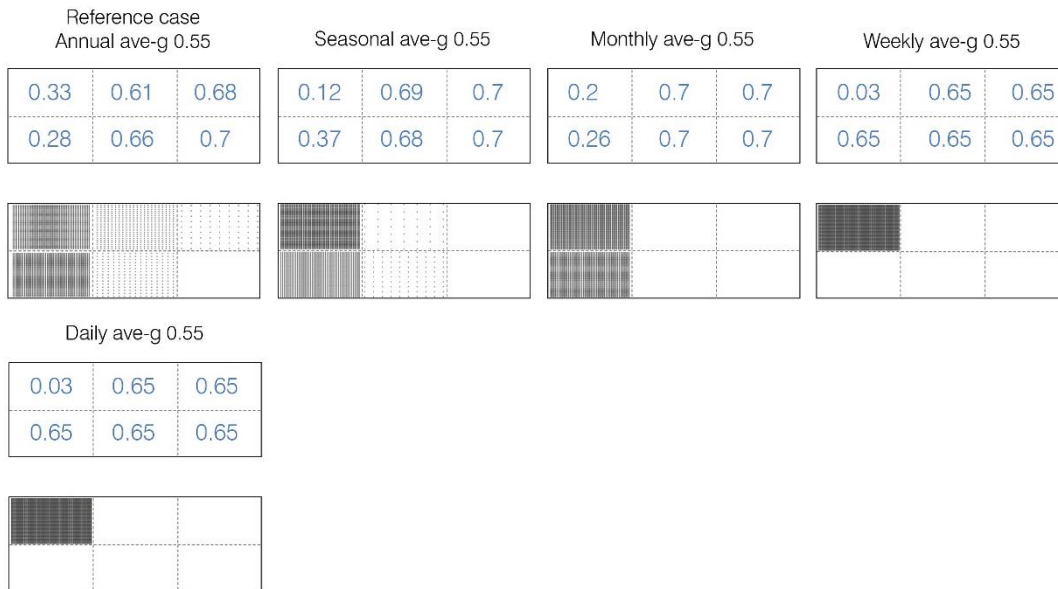


Figure 66: Ray tracing module output of re-distributed g -value and uniform frit pattern for the cases with annual (Reference Case), seasonal (summer), monthly (August), weekly (3.-9. August) and daily (2.August) analysis period.

5.2.12.2 Thermal data output

Table 16 shows the number of hours (annually) above each threshold before (uni-g 0.55) and after (ave-g 0.55) applying the method to the comfort analysis for each analysis period.

Table 16: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the cases with annual (Reference Case), seasonal (summer), monthly (August), weekly (3.-9. August) and daily (2.August) analysis period.

	Annual uni-g 0.55 (RefCase) /h	Annual ave-g 0.55 (RefCase) /h	Season uni-g 0.55 /h	Season ave-g 0.55 /h	Month uni-g 0.55 /h	Month ave-g 0.55 /h	Week uni- g 0.55 /h	Week ave- g 0.55 /h	Daily uni-g 0.55 /h	Daily ave-g 0.55 /h
$\geq 26^{\circ}\text{C}$	1110	1015	629	592	213	194	58	58	10	10
$\geq 28^{\circ}\text{C}$	655	530	339	261	128	109	46	46	9	9
$\geq 30^{\circ}\text{C}$	409	279	184	96	78	51	33	25	6	4
$\geq 35^{\circ}\text{C}$	128	17	52	1	23	2	10	0	2	0

As displayed in Figure 67, changing the period for which the simulation is run, shows a tendency to eliminate higher temperatures more effectively with shorter analysis periods. The effect of the method becomes clearer.

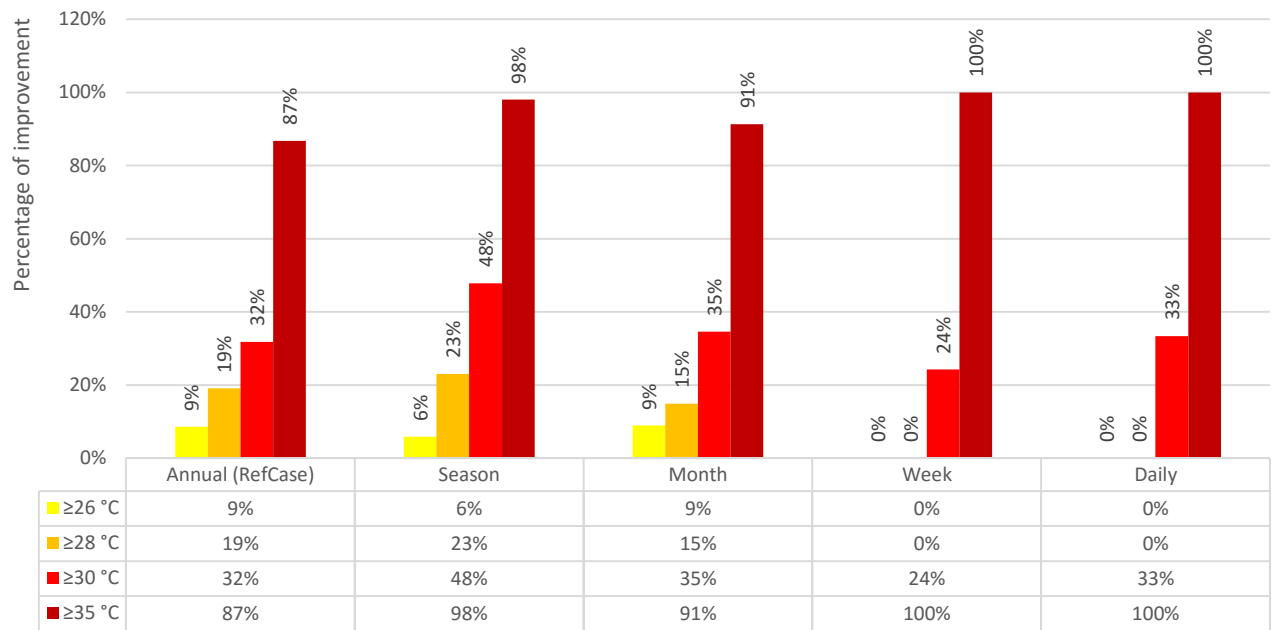


Figure 67: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for the cases with annual (Reference Case), seasonal (summer), monthly (August), weekly (3.-9. August) and daily (2.August) analyzis period.

5.2.13 Saving potential

The thermal requirement of the case was assumed adjusted to a fixed uniform glass g -value, in this case 0.55. Hereby, the thermal performance difference between the uniform and the average glass g -value distribution can be “compensated” by increasing the average g -value while maintaining thermal performance in the range of uniform glass g -value of 0.55 scenario. Savings can be reflected in the form of higher light levels or lower glazing costs (assuming that glazing with higher g -value is less expensive).

The method was tested for four additional cases with slightly higher average g -values than the Reference case:

- average g -value of 0.56 (ave- g 0.56)
- average g -value of 0.58 (ave- g 0.58)
- average g -value of 0.60 (ave- g 0.60)
- average g -value of 0.62 (ave- g 0.62)

The effectiveness of the method at improving thermal comfort in Point 0 was analyzed for the additional cases and compared to the output for the Reference Case with average glass g -value of 0.55.

The tool output for the analyzed saving potential is comprised of 1. Ray tracing module output, including re-distributed average g -values and 2. Thermal data output, including the numbers of hours above analyzed thresholds before and after applying the method.

5.2.13.1 Ray tracing module output

Figure 68 shows how the average g -value distribution varies depending on the desired average glass g -value.

Reference case ave- g 0.55	ave- g 0.56	ave- g 0.58	ave- g 0.60
0.33 0.61 0.68	0.35 0.62 0.69	0.4 0.63 0.69	0.45 0.64 0.69
0.28 0.66 0.7	0.31 0.66 0.7	0.37 0.67 0.7	0.42 0.67 0.7
ave- g 0.62			
0.5 0.65 0.69			
0.48 0.68 0.7			

Figure 68: Ray tracing module output of re-distributed g -value for cases with average g -value of: 0.55 (Reference Case), 0.56, 0.58, 0.60, and 0.62.

5.2.13.2 Data output

Table 17 shows the number of hours (annually) above each threshold before (uni- g) and after (ave- g) applying the method to the comfort analysis for the analyzed average glass g -values.

Table 17: Number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with average g -value of: 0.55 (Reference Case), 0.56, 0.57, 0.58, 0.59, 0.60, 0.61, 0.62, 0.63.

	uni- g 0.55 (RefCase) /h	ave- g 0.55 (RefCase) /h	ave- g 0.56 /h	ave- g 0.57 /h	ave- g 0.58 /h	ave- g 0.59 /h	ave- g 0.60 /h	ave- g 0.61 /h	ave- g 0.62 /h	ave- g 0.63 /h
$\geq 26^\circ\text{C}$	1110	1015	1061	1086	1113	1119	1144	1175	1204	1226
$\geq 28^\circ\text{C}$	655	530	583	614	632	646	671	709	754	791
$\geq 30^\circ\text{C}$	409	279	329	347	370	388	400	423	448	474
$\geq 35^\circ\text{C}$	128	17	36	53	64	81	96	111	123	140

The results in Figure 69 show that, depending on which threshold temperature the client asks for, the average g -value can be increased according to the method. For example, for the Reference Case, the average g -value can be increased from 0.55 to 0.59 (distributed g -value) and still maintain the performance of the uniform g -value 0.55 scenario.

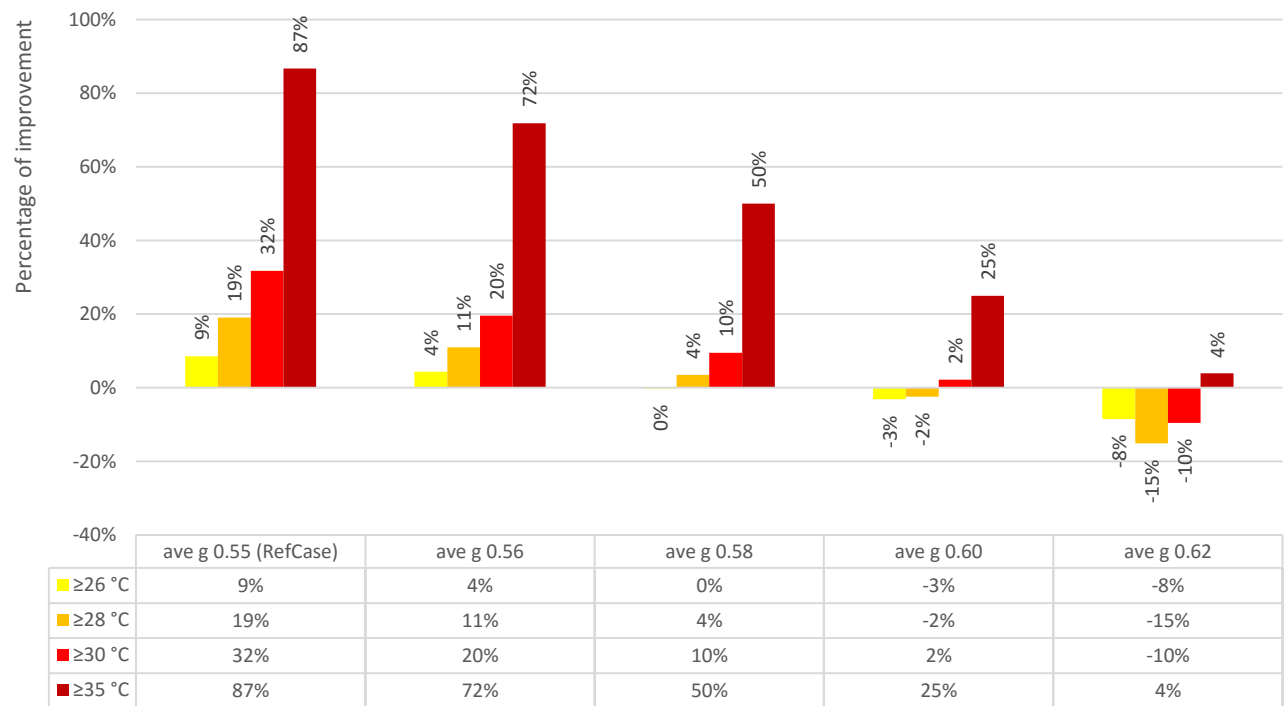


Figure 69: Difference in number of hours with $T_{o,Adj} > 26, 28, 30$ and 35°C for cases with average g -value of: 0.55 (Reference Case), 0.56, 0.58, 0.60, 0.62.

6 Analysis/Discussion

The relation between thermal comfort and average g -value is the basis upon which this thesis has evolved. The complexity of this relationship has revealed itself through several pursuits of trial and error, gradually shaping an understanding of the impacts of the proposed shade tracing tool's limitations and potential to influence design.

A limitation of applying only simple window indices to thermal exchange calculations is that the g -value assigned to the glass represents the shading coefficient at normal incidence. Normal incidence however, is a rare occurrence in building simulations since the majority of incoming rays have a high angle of incidence. The absolute consequence of this simplification on the results of this study is unknown. However, one could presume that heat gains through glass with non-angular g -values, as assumed to be the case in this study, may, at times of high solar incidence angles, be misestimated.

A fundamental assumption of this study is that the average g -value of a glazing unit is equivalent to an equally sized glazing unit with a higher g -value, combined with an area of opaque frit corresponding to the difference in g -value. This assumption accounts for thermal effects of adding frit to the exterior of a single pane window and does not consider physical complexities of more advanced glazing systems. Hereby, a potential source of error is introduced when applying the shade-tracing methodology to more advanced glazing systems.

Another central assumption of the methodology, is how the method values the direct solar component's influence on thermal discomfort. For example, does the shading need for a point change, relative the magnitude of the direct solar component and if so, how? Since the physical relation of these parameters were not known, a simplification was made, assuming a linear correlation.

A linear weighing factor between 0 and 1 was assigned to all "problematic intersection" on the façade with a high relative solar component, in order to declare the relative comfort deterioration of each intersection. The factor is derived from the difference between measured mean radiant (MRT) and adjusted operative temperature ($T_{op,Adj}$), delta T, in a point at a certain hour, where the maximum delta T for the analysis period is assigned a factor 1. Since delta T is an absolute value, the weighing factor does not differentiate between if delta T is for example the difference between 26°C and 36°C or the difference between 36°C and 46 °C. Hereby, the factor does not include the real thermal influence of delta T, creating an unknown source of error. One could expect, that the relative impact of the factor should increase as the influence of MRT increases. Additionally, the factor does not consider the influence of duration of overheating, for which there is no understanding of whether four hours of 30°C is better or worse than three hours of 40°C, a correlation which requires in depth understanding of human discomfort and tolerance. Theory connecting comfort to for example productivity could be incorporated into the method, to expand the influence of time on discomfort further in the method. Nevertheless, the linear weighing factor seems to correspond to the trends of significant overheating in this project, which suggests that the relation may be an adequate simplification.

To validate the functionality of the simulation tool, a comprehensive Reference Case was essential. The input settings, in particular with regards to parameters enhancing initial overheating problems, prove to be of outmost importance to the favorability of the tool. Such parameters include; thermal transmittance of the envelope (both g -value and U -value), glazing to floor ratio, ventilation set point temperatures and climate conditions.

Another clear result is how the efficiency of the tool decreases with increased analysis area. As expected, by increasing the analyzed area (number of analysis points), the precision of the tool is diluted, since the redistributed g -value is spread over a larger area on the façade. Correspondingly, the tool shows greater efficiency with diminishing façade grid size, since the precision of the problematic region of the façade increase. Secondary effects of increasing the precision of analysis points and façade grid size, are the altered and potentially decreased comfort levels in other parts of the space. When the g -value is redistributed with preference to a defined/specific area, remaining areas in the space may be exposed to direct and indirect effects of increased solar loads including increased internal reflection and heat storage etc.

With regards to scaling geometry, the tool proves to have analogous efficiency with scales above and below the Reference Case scale. Nevertheless, there may be reason to believe that more complex geometries may have secondary and even tertiary implications on the tools functionality.

Time distribution results of changing the Reference Case orientation, indicate, as expected, that the tool reduces morning and afternoon peaks from and easterly and direction respectively. The magnitude of these time specific reductions correlate strongly to the cloud coverage at the time of comparison. However, rather unexpectedly, the tool proves to reduce peaks even with higher cloud coverage during the same period, providing reason to believe that there may be an influence of diffuse radiation.

Since annual results are not always of outmost relevance for shading need, the analysis period was shortened. Seasonal simulations, performed for the summer season, was the most beneficial for the indoor comfort. Generally, it can be observed that shorter analysis periods prove more efficient for the tool. In this case, the summer season proves most efficient since this period is most problematic for overheating in the analyzed zone.

If a designer has a requirement of maximum overheating hours above a certain threshold temperature, which is common comfort regulation in Sweden, the tool is able to inform if and how much an average distributed g -value can be increased in order not to override certain threshold temperatures. The tool is hereby able to indicate a saving potential to the user of the method. For the Reference Case in this study, the average g -value of the glazed façade could be increased from 0.55 to 0.62 without exceeding the initial hours above 35°C. The potential increase in average g -value could correspond to economic savings by being able to install cheaper glazing units (with less solar control), energy savings by reducing local peak temperatures, and increase the wellbeing of occupants by elevating daylight levels and clear views to the outside. Furthermore, variations in light and heat transmission through a façade may have positive impacts on occupants' and perhaps encourage physiological adaptation

Overall, the results from the sensitivity analyses are case specific, and can therefore not guarantee comparable outputs for other cases. However, the results from the sensitivity study coincide in three main conclusions for the tool; 1. The more defined the location of the overheating problem is, the greater the efficiency of the method, 2. The more excessive the initial overheating problem is, the lesser the value of the method and 3. The method successfully eliminates peak temperatures to a greater extent in all observed cases.

Without significant deviation, the correlation of results within these main conclusions give reasons to justify the reliability and purpose of the methodology developed, namely to inform designer of the potential to improve local thermal comfort with the shade-tracing tool.

7 Conclusion

A methodology has been developed to correlate overheating with shading need. The method gives numerous visual and numerical output, informing designers of how to distribute the g -value of glazed façades in order to mitigate local discomfort to the extent possible with static shading design. The methodology has been developed into a design tool, scripted in Rhino/Grasshopper, enabling parametric applicability. The general conclusions, drawn from the analysis of the results are stated below:

- Thermal discomfort due to solar gains in highly glazed spaces, can be improved by redistributing g -values of the glazing according to this method.
- Regions of a façade source to problematic solar gains, can be clearly defined both numerically and visually on a geometric model, for which accurate portrayal of local shading need is easily attainable.
- The usefulness of the method is dependent upon the extent of the initial overheating problem, showing greater effectiveness for lower glazing ratios, lower average g -values and cooling set points respectively.
- For all parameters, the method is more effective at reducing higher temperature peaks.
- The more defined the analysis area of floor and the grid on the façade, the higher the effectiveness of the method.
- The method shows considerable improvements for overheating in glazed spaces in moderate climates with high solar radiation. The method becomes less effective for glazed spaces in very hot climates.
- Cloud coverage impacts the effectiveness considerably.
- The method has the same effect on comfort in geometry irrespective of scale.

More specific conclusions regarding “shoe box” Reference Case located in Copenhagen are summarized below:

- The method works differently depending on orientation, showing considerable improvements for an East facing glazed façade.
- The method works most efficiently for a seasonal analysis period.

More specific conclusions regarding the tool are summarized below:

- Tool enables parametric design.
- No geometric limitations, cases with numerous glazing surfaces, analysis points and surrounding context can be evaluated with the tool.
- The method gives simple means of comparative analysis, useful for weighing alternatives against each other.

7.1 Future work

The following aspects are considered necessary for further development of the methodology of the shade tracing tool.

1. Evaluate the relation of advanced glazing types/systems and frit.
2. The actual impact of degree hours on shading need (g -value). i.e. explore the limitations of the linear factoring/weighting method developed in this thesis. Potentially correlate to economic factors such as productivity (loss) of occupants.
3. Evaluate the secondary effects of distributing g -value with regard to increasing discomfort in points/areas not analyzed by the tool.
4. Study the impact of angular g -value with detailed glazing definitions in E+
5. Although diffuse radiation is included in the weather files, the influence of diffuse solar component on comfort levels is not accounted for in this method. The influence of the diffuse component should be analyzed further.
6. Explore the tools functionality on complex cases for example to establish appropriate situations for the tool to be used successfully. i.e. climates, building types, occupancy, construction details, HVAC capacities, regulations etc.
7. Verify the tool with physical measurements
8. Consider the impact on visual comfort

9. Other shading types than frit, varying opacity and adaptability
10. Reverse the outcome of the tool, Glazing need = 1-shading need
11. Further develop the linear correlation between shading need and thermal discomfort due to direct solar component assumed in this project.

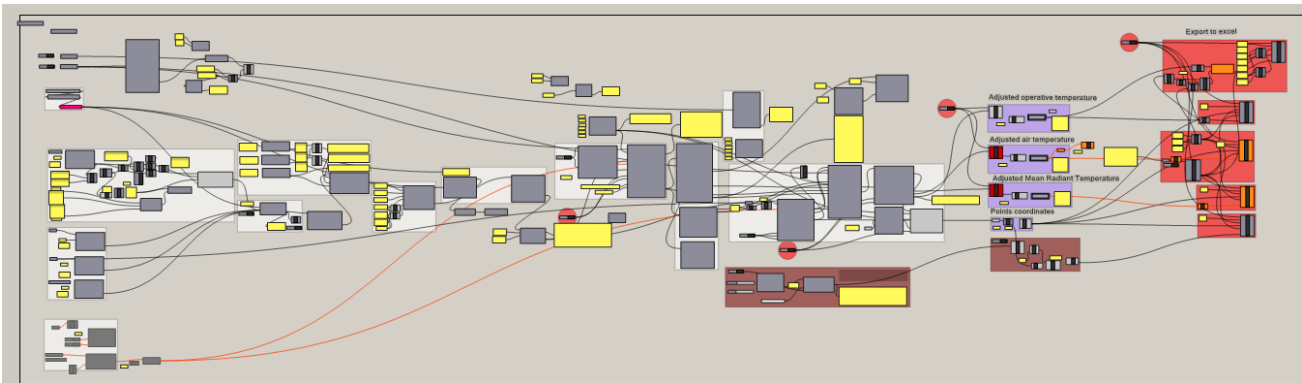
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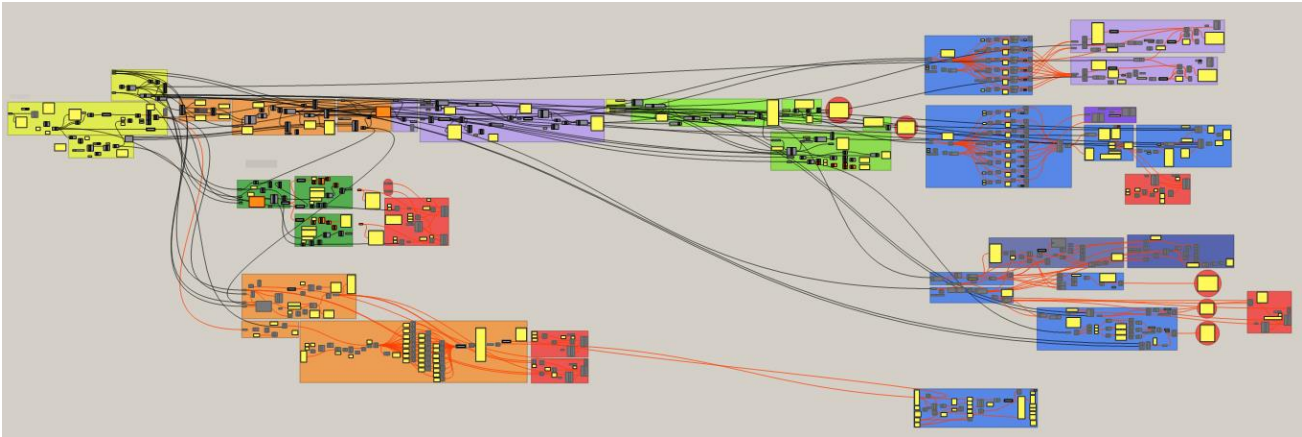
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8 Appendix

The thermal module was structured as follows.



The shade tracing tool was defined as follows





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Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services%