ADAPTIVE FACADE, THE ACTIVE CONNECTION BETWEEN INDOOR AND OUTDOOR

Visual and Thermal evaluation of an adaptive façade in the urban context of Copenhagen

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

Lund University

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

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

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Abstract

This study explores the connection between the indoor and outdoor environment and how through the use of shading devices they affect each other. The chosen location for the study is a well-known street in the urban context of Copenhagen. Through different façade and shading evaluations, this thesis aims to investigate the possibility of achieving desired visual and thermal comfort levels for the indoors, while the designer also actively influences those comfort metrics for the outdoors.

Parametric design strategies were used with the aid of the software Grasshopper for Rhino, and climate based dynamic simulations were carried out with Radiance and Energy Plus for daylight and thermal analysis respectively. According to indoor daylight levels and operative temperature the shading system was optimized through the use of an evolutionary solver.

Four different solutions were simulated and analysed. Firstly, by changing the façade's window to wall ratio (WWR), secondly by using a static venetian blind, thirdly by having the same venetian blind operable and finally by using a sun-tracking fenestration system. For both dynamic solutions the option of closing the shading outside of occupancy times was explored, to increase daylight on the street canyon.

The results show a clear relationship between the indoor and outdoor environment regarding thermal and visual comfort. The use of a dynamic façade system shows a possibility to actively influence both environments.

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Contributions

This master thesis was developed as a combined effort of the two authors Angel A. Perez Morata and Chenhong Wang. While the majority of the work was done together and through daily dialogue, a large part was developed and done separately.

The parts referring to geometry design, 3D modelling, advanced workflow planning and introduction and methodology writing were shared and reviewed unanimously. The parts referring to thermal comfort and thermal energy demand were researched, developed, simulated and analysed by Chenhong Wang. Daylight and electrical lighting potential savings were taken over in equal form by Angel A. Perez Morata. For the scripting and simulation, Chenhong deepened her knowledge and developed the shading optimisation workflows and the shading state schedule components. Angel developed the scripts for creating the movements of the shading systems and the integrated daylight and thermal simulation for the holistic proposal.

In terms of report writing, both took over the parts where each author had worked more for better explanation of each phase. Angel took over daylighting parts of introduction, methodology, results and discussion while Chenhong took the thermal and energy parts.

Contents

Nomenclature & Abbreviations

ALE	Annual Light Exposure
ASE	Annual Solar Exposure
ASHRAE	American Society of Heating, Refrigerating and A-C Engineers
BBR	Boverkets Byggregker
BR	BygningsReglementet
BREEAM	Building Research Establishment Environmental Assessment Method
HSE	Health and Safety Executive
IRCv	Vertical Internally Reflected Component
ISO	International Organization for Standardization
LEED	Leadership in Energy and Environmental Design
RGB	Red, Green, Blue
SHGC	Solar heat gain coefficient
Ta	Air temperature
UTCI	Universal thermal climate index
U-value	Overall heat transfer coefficient
UHI	Urban Heat Island
USGBC	United States Green Building Council
VT	Visible transmittance
WWR	Window to Wall Ratio

Definitions

Visual performance: defined as the parameter that references eye working speed and the needed accuracy for the performance of a work. (Csanyi, 2018)

Daylight Factor (DF): daylight measurement for overcast sky conditions that relates the illuminance of an indoor and outdoor point, simultaneously (IQ, 2018).

Illuminance (E): measurement that describes the quantity of light received over a given surface. Its base units are the lux (lx) (Zumtobel, 2018)

Luminance (L): Describe both the visual parameters of the light source (intensity) and the surface (reflection). Its unit is the candela per square meter (cd/m^2) (Zumtobel, 2018)

Daylight Autonomy (DA): the amount of time as a percentage when a point in a surface receives more than 300 lux throughout the year. (Reinhart, Mardaljevic, & Rogers, 2006)

Spatial Daylight Autonomy (sDA): Similar to DA sDA defines the percentage of a given area that receives more than a specified illuminance (usually 300 lux) for more than a certain percentage of an analysis period (usually 50% of the occupancy) (IES, 2013).

Useful Daylight Autonomy (UDI): Based on illuminance over a surface, it measures the percentage of time when the point receives light between 100 and 2000 lux. (Reinhart, Mardaljevic, & Rogers, 2006)

Thermal Comfort: defined as "the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE Standard 55, 2017).

Mean Radiant Temperature (MRT): defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform enclosure (Romana, Dell'Isola, Palella, Riccio, & Russi, 2013)

Operative Temperature (To): is defined as a uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. (Operative temperature, 2018).

The Predicted Mean Vote (PMV): predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. A mean vote is obtained for a given condition by finding the mean value of the feeling given by all subjects for that condition. (Djongyang, Tchinda, & Njomo, 2010, 14(9))

The Universal Thermal Climate Index (UTCI) is expressed as an equivalent ambient temperature of a reference environment providing the same physiological response of a reference person as the actual environment (Weihs P, 2011).

1 Introduction

1.1 Background

People in industrial countries spend between 80 % and 90% of their time indoors (Klepeis, et al., 2001). Therefore, architects and building engineers have been seeking ways to improve indoor thermal comfort (Forgiarini Ruppa, Giraldo, & Lambert, 2015). For many years, mechanical systems have been widely accepted for providing desired indoor temperature, but this may also lead to a high operational energy use. Around 30% of fossil fuels is used in building stocks (Taleghani, Tenpierik, Kurvers, & Dobbelsteen, 2013). To balance energy use and indoor thermal comfort, passive design strategies for buildings have regained more attention recently. There are many types of building standards, certification systems and building codes aiming at reducing energy use while achieving acceptable thermal conditions. Electrical lighting of buildings also has a big impact when aiming to reduce energy demand of buildings. For the case of office and commercial buildings, electrical lighting is accounted to represent between 20 and 60% of the energy demand. According to Moore (2000), maximizing the daylight exposure would reduce this demand and if optimized properly also the cooling demand as natural light heats less than artificial lighting per supplied lumen on a given surface.

Building and architectural research has mainly focused on the indoor environment in terms of daylight, even when assessing the urban morphology (Nasrollahi & Shokri, 2016) (Sokol & Martyniuk-Peczek, 2016). This makes sense, as mentioned before, humans spend the majority of their life inside build environments. But new lines of research are exploring the visual comfort and daylight related metrics also for the urban environment. In the case of urban thermal research, one of the biggest concerns relates to Urban Heat Island, which is highly influenced by the direct surfaces of build environment, such as façades (Kim, 1992). For this kind of research, advanced simulations tools are a necessity to understand the effects of highly dense urban areas on solar access and the visual perception of its inhabitants (Polo Lopez, Sala, Tagliabue, Frontini, & Bouziri, 2016).

It was concluded, that there is a necessity in the academic field for a research of the effects dynamic façades have and can produce over the direct urban context, without disregarding its prime functions towards the indoor environment.

1.2 Goals & Problem Motivation

After the literature study on adaptive façades for both the indoor and outdoor environment, one idea came to view. This idea was that although many have studied adaptive facades for the indoor environment there was no line of research that analysed the potentials of adding one more feature of study to the field, i.e. the possibility of affecting and manipulating the outdoor environment through the use of dynamic façade systems that could increase or decrease the illuminance and possible glare in terms of daylight but also increase or decrease the MRT and therefore the perceived comfort. All this would only be reasonable if also the indoor environment is considered, as the priority of a building component is the actual interior of building.

Research Questions

- Can daylight and thermal implications of a shading system be accounted for simultaneously and how?
- Can urban and building design be interlaced through the façade to achieve common human comfort goals?
- Can the outdoor environment be affected and/or manipulated by a dynamic/adaptive façade system?

Hypotheses

- The outdoor daylight evaluation will be mainly affected by the reflectivity and shading angle.
- The outdoor thermal comfort will be affected mainly by short and long wave radiation exposure from the building.
- Making the shading system adaptive will have an improvement on thermal and visual comfort compared with static solutions.

1.3 Limitations

The study and analysis presented in this thesis have a clear objective and workflow but had to be limited in multiple ways. The first and most frustrating, was limiting the colour study to only black OR white surfaces, and that only for the daylight evaluation the shading devices could have the colours.

Secondly, due to the impossibly met computational required power, the schedules of the dynamic and adaptive façade were not fully optimized as in previous steps of the design. Same thing happened with the morning and afternoon states of the adaptive façade.

Thirdly, in term of geometry, the complexity of the building details was disregarded and due to the lack of indoor plans, rooms were of theoretical size. If it would have been a real retrofitting study and not a research study, it would have been necessary to be faithful to the building’s geometry and dimensions, but it would only make the study less focused.

Fourthly, the climatic data used for the study was limited. As will be mentioned further, the weather file from the airport of Copenhagen was used, but for a detailed study of the urban heat island effect in Copenhagen, a new weather file that accounts for it should have been created. Given that all phases were studied with the same weather file, it was considered unnecessary to go that deep into climatic data and climate weather file modification.

Finally, there was a lack of real-world data. When proposing an idea, specially based on a design, it is desirable to build a mock-up model and test the values obtained from the same metrics used during the Point-In-Time simulations.

2 Theoretical Background

This chapter focused on the theoretical background study about the concept of visual and thermal comfort, including both indoor and outdoor comfort. It also introduced parametric design for shading systems and modern development of adaptive façade.

2.1 Literature Review

To be able to fully understand the state of the art of both daylight and thermal studies a literature review was conducted. Through the use of Lund University's academic paper search engine *LUBsearch* (Lund University, 2016) a series of articles were analysed. The aim of this pre-analysis was to determine what are the current metrics used in the field and the research topics to see a possible lack or trend of research in the academic field, see Table 1.

Table 1. Background related studies

Author / year	**Metric**	**Purpose of the paper**
J. Mardaljevic and A. Nabil (2006)	DF, DA, UDI	Assess UDI application for office buildings
J. Mardaljevic et al (2012)	Illu, UDI, DGP	Investigation UDI and DGP
A. Eltaweel and Y. SU (2017)	DA, Illu, DF	Literature review of parametric design
G. C. Jensen Skarning et al (2017)	Illu, DA	Effect of dynamic shading for energy and daylight fo Cph and Rome
(Du & Sharples, 2010)	DFv, IRCv	Impact of reflectance and geometries on daylight in atria
(Bellia, Marino, Minichiello, & Pedace, 2014)	DF, Illu, DA, UDI, Uni, DGI	Overview of shading system publications
(Dubois, 2001)	Illu, Lumin, DF, Uni	Comparison of Shading device on daylight metrics
(Cammarano, Pellegrino, Lo Verso, & Aghemo, 2015)	ALE, DA, DA_{max}, and UDI	Parametric analysis of indoor daylight through façade
(Krüger & Suga, 2009)	Illu	Parametric analysis of indoor thermal & daylight
(Tzempelikos, Bessoudo, Athienitis, & Zmeureanu, September 2007)	MRT, Operative temperature, Air temperature	The impact of shading on thermal comfort conditions in perimeter zones with glass facades
(Wilfried, Walikewitz, Jänicke, Langner, & Meier, 2015)	MRT, Operative temperature	The difference between the mean radiant temperature and the air temperature within indoor environments: A case study during summer conditions

(Alfano, Dell'Isola, Palella, Riccio, & Russi, 2013)	MRT	On the measurement of the mean radiant temperature and its influence on the indoor thermal environment assessment
(Hwang & Shu, 2011)	MRT, air temperature, Operative temperature, PMV	Building envelope regulations on thermal comfort in glass façade buildings on energy-saving potential for PMV-based comfort control
(Paolo, Fabrizio, & Filippi, 2008)	PMV, Operative temperature, MRT	The impact of indoor thermal conditions, system controls and building types on the building energy demand
(Park, Tuller, & Jo, 2014)	UTCI, outdoor thermal comfort	Application of Universal Thermal Climate Index (UTCI) for microclimate analysis in urban thermal environments
(Bröde, Krüger, & Fiala, 2012)	UTCI, outdoor thermal comfort	Predicting urban outdoor thermal comfort by the Universal Thermal Climate Index UTCI – a case study in Southern Brazil
(Allegrini, Dorer, & Carmeliet, 2012)	Heating, cooling	Influence of the urban microclimate in street canyons on the energy demand for space cooling and heating of buildings

From this short pre-study it became clear that daylight climate-based metrics like DA or UDI are becoming more and more significant, while MRT and UTCI are the most recent thermal metrics used when relating to thermal comfort.

In the daylight research field, it became clear that there is a lack of impact of building in the visual perception at the urban or simply outdoor scale. Thermal research already showed a clear interest in urban mitigation strategies and thermal impact of buildings on the urban scale.

2.2 Daylighting Metrics

“Light wielded in both a meaningful as well as a functional way is one of the hallmarks of a great building”

Marietta S. Millet
Professor of Architecture
University of Washington, Seattle

Daylight is a critical element for the everyday life of human beings, it sets the natural time for awakening and sleeping and is the basis for the visual performance of the activities done between. Both biological and psychological health are affected by the exposure to natural light, e.g. vision is the sense which inputs more information to brain. On the other side, the over exposure to direct sun rays can cause skin and eye damage beyond repair (Tregenza & Wilson, 2011). Another risk of visual discomfort is called visual noise. This consists of a large perceived contrast between the object or plane looked at and the rest of the surroundings (Egan & Olgyay, 2002). In other words, this perceived contrast or brightness is affected by the luminance of the background objects, but also it depends on the current illuminance of the room and of the previous stance (Egan & Olgyay, 2002).

Having the right quality and quantity of either natural or artificial light is fundamental and is dependent on the task. This is not only in terms of health but also in terms of productivity and efficiency (Egan & Olgyay, 2002). Therefore, the first step is to supply the right amount of natural light and then select the materials taking into consideration the colour and reflectance. Illuminance (E) is the measurement that will describe the supplied amount of light. Figure 1 shows expected illuminance values for daylight depending on sky conditions.

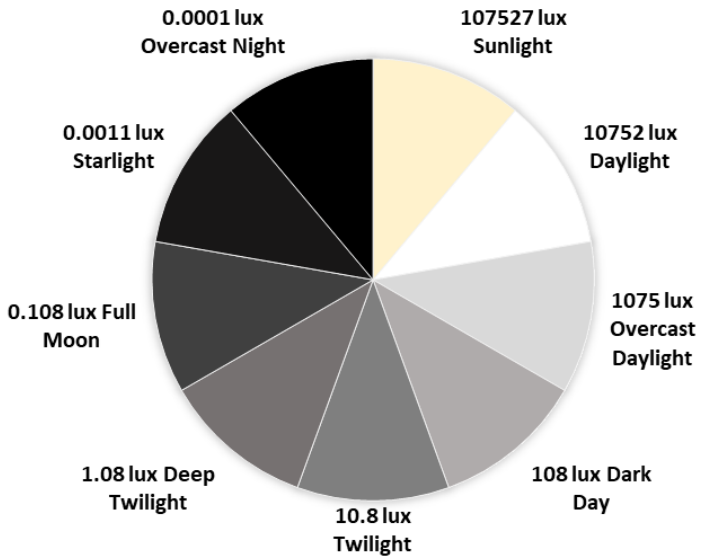


Figure 1. Common Outdoor Illuminance Readings (Toolbox, 2004)

These supplied levels of illuminance from daylight form the basis for defining the tasks for which the study or design is being done. An example of task related regulation is the British Health and Safety Executive (HSG) 38: Lighting at Work (HSE, 1997). It sets a certain guideline of minimum values that the employer must achieve, see Table 2.

Table 2. Lighting design parameters in HSG 38 (Ltd, 2016)

Safe Visual Environment	Lighting Health Requirements
Hazards should be noticeable	Correct illuminance for every task
Safe emergency light levels	Uniformity of illuminance levels should be considered for adjacent areas
Colours must be noticeable for safety reasons	No veiling reflections
Maintenance has to be taken into account	Light sources must never create risky environments
Needs of each employee should be met	No flickering, stroboscopic or glare effects should come from the lighting

Regarding specific illuminance values the UK certification standard BREEAM® (B.R.E., 2014) states the average and minimum daylight illuminance for a minimum of 80% of the area to comply for a series of area types. A simplification of this table of values is shown in Table 3. In the American certification system, LEED v4 (U.S. GBC, 2000), there are two options for daylight simulation assessment. One is to achieve illuminance levels between 300 and 3000 lux for more than 75% of the studied zone, the other is to have Spatial Daylight Autonomy (sDA) for at least 55% of the same studied zone (LLC, 2016).

Table 3. Space type and Illuminance requirements (BRE, 2018)

Area type	1 credit	2 credits	Av. Daylight Illuminance	Min. Daylight Illuminance
Educational spaces - occupied areas	60%	80%	>300 lux >2000 h/year	>90 lux > 2000 h/year
Residential living rooms, studies, dining rooms		100%	>100 lux >3450 h/year	>30 lux >3450 h/year
Residential communal occupied spaces	80%		>200 lux >2650 h/year	>60 lux >2650 h/year
Office: All occupied spaces	80%		>300 lux >2650 h/year	>300 lux >2650 h/year

Finally, directly from illuminance comes the metric Illuminance Uniformity (Uni), which separates the percentage of time there is insufficient, desirable and overwhelming illuminance levels throughout the year for task-related studies (Veitch & Newsham, 1998). Included in this metric there are three other variants; uniformity ratio, coefficient of variation (CV) and uniformity gradient (UG) (Ashdown, 2016).

$$Uniformity\ ratio = Eh_{min}/Eh_{max} \quad (1)$$

$$CV = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n}}}{\bar{x}} \quad (2)$$

$$UG = {}^{E_1}/_{E_2} \quad (3)$$

Where:
Eh_{min} = Lowest Illuminance (lux)
Eh_{max} = Highest Illuminance (lux)

X_i = *Horizontal illuminance at each point*
$\bar{x}$ = Mean illuminance of all points
n = number of points

In terms of uniformity ratio, studies have shown that values of uniformity ratios above 0.8 are desired when electrical lighting is used (Slater, Perry, & Carter , 1993) (Saunders, 1969). However, according to (Slater & Boyce, 1990), when natural light is introduced from side windows the user acceptance is increased, therefore there is no conclusive value for those cases.

Reflectance

Selecting materials and their colour carefully is, after direct daylight, the second major role in daylight analysis. This is due to that if the background of the working plane is surrounded by bright surfaces that reflect the direct daylight, they can turn into a bright glare source (Egan & Olgyay, 2002). To further understand the relation between materials and their reflectance see Table 4.

Table 4. Typical reflectance of finishing materials (Flynn & Mills, 1962)

Material	**Reflectance / %**	**Material**	**Reflectance / %**
Metals		Glass	
Aluminium brushed	55-58	Clear	5-10
Aluminium,	70-85	Reflective	20-30
Aluminium,	60-70	Ground cover	
Stainless steel	50-60	Asphalt	5-10
Tin	67-72	Concrete	40
Masonry		Grass or vegetation	5-30
Brick, dark buff	35-40	Snow	60-75
Brick, light buff	40-45	Paint (refer to manufacturer)	
Brick, red	10-20	White	70-90
Cement, grey	20-30	White porcelain enamel	60-83
Granite	20-25	Wood	
Limestone	35-60	Light birch	35-50
Marble, polished	30-70	Mahogany	6-12
Plaster, white	90-92	Oak, dark	10-15
Sandstone	20-40	Oak, light	25-35
Terra-cotta, white	65-80	Walnut	5-10

2.3 Canyon Daylighting

"Can daylight be the driving force for reshaping the way we design modern urban spaces?"

Sokol & Martyniuk-Peczek (2016)
Gdansk University of Technology

To be able to face the challenge quoted above, first the daylighting factors that have the highest effects on urban spaces need to listed: urban geometry, surface reflectivity and of course the climate conditions of the location. From these, surface reflectivity is the easiest to vary in terms of cost for an already build context. If the reflectance of the materials used on ground and façades were to be increased, the benefits would be higher illuminance at streel level, increased illuminance at adjacent indoor environments and even an improvement on UHI (Nasrollahi & Shokri, 2016). Those were some of the advantages but there are also disadvantages from increasing the reflectance of the mentioned surfaces. The main problem is the high risk of glare or visual discomfort of the pass byers. According to the study of Lopez Besora et al (2016), the main perceived surfaces of pedestrians are the ground and lower parts of the façade (up to 30º from horizontal eye level), while the high areas of buildings and the sky are only perceived when looking far away. Both this study and one carried by F. Rosso et al (2016), concluded that light coloured surfaces have a very high luminance contrast when comparing sun lighted areas and shaded ones. The difference was from 20,000 lux to 100,000 lux in the case of illuminance and 2,000 cd/m2 to higher than 10,000 cd/m2 for luminance. This range of values made surfaces, especially ground level ones, not desired by observers when the reflectance was slightly higher than asphalt, concrete or grass.

2.4 Indoor Thermal Comfort

Thermal comfort is a crucial parameter for occupant productivity and health in workplace, it is important to consider it as key design requirement for buildings. Functionally, buildings are providing shelter and comfort environment for humans (Djongyang, Tchinda, & Njomo, 2010). Thermal comfort gives information of the perceived thermal conditions by the occupants. It is influenced by four physical variables and two personal variables; air temperature, air velocity, relative humidity, mean radiant temperature, clothing insulation and activity level (Djongyang, Tchinda, & Njomo, 2010).

Regarding thermal comfort studies for adaptive façades or adaptive shading systems, the mean radiant temperature and air temperature are the most significant factors for evaluating the performance of a building envelope. Mean radiant temperature could show the effects of blocking direct sunlight. Shaded and unshaded areas could have more than 10 °C difference during a sunny clear day. By using shading devices, the intensive sunlight could be well redistributed, then achieving lower mean radiant temperature, as well as make room temperature more even.

Mean radiant temperature (MRT) expresses the temperature at a certain point in space, due to the exchange of heat with the surrounding surfaces. This exchange between occupants and surroundings include short-wave radiation from direct sunlight, sky reflectance, surrounding buildings' reflection, and long-wave radiation from surrounding surfaces due to the temperature difference between human skin and surrounding surfaces.

When referring to mean radiant temperature, there is still no research that investigated the threshold temperature that will generate heat stress of occupants. Therefore, it is hard to use mean radiant temperature as single factor for assessing indoor thermal comfort. The typical way is combining mean radiant temperature with air temperature to study thermal comfort, in other words operative temperature. Operative temperature is a combination between mean radiant temperature and air temperature, which could represent the perceived temperature by humans. It is often used to study indoor thermal comfort.

The Predicted Mean Vote (PMV) model is a model used worldwide to assess indoor thermal comfort levels, proposed by Fanger (1972). The PMV model was based on experimental results from steady-state laboratory conditions instead of considering an adaptive comfort model based on real building conditions with varying personal behaviour. The studies were performed by the seven-point ASHRAE thermal sensation scale ranges, views from Table 5 (Djongyang, Tchinda, & Njomo, 2010, 14(9)).

Table 5. ASHRAE seven-point thermal sensation scale

Perception	Hot	Warm	Slightly warm	Neutral	Slightly cold	Cool	Cool
Vote	+3	+2	+1	0	-1	-2	-3

Fanger proved that PMV presents the imbalance between the actual heat flow from a human body in a given environment and the heat flow required for optimum comfort at a specified activity by the following equation (Lin Z, 2008).

$$PMV = [0.303\,exp(-0.036M) + 0.028]L = \alpha L \tag{4}$$

L means thermal load on the body, the difference between internal heat production and heat loss to the environment for a person, α is the sensitivity coefficient (Djongyang, Tchinda, & Njomo, 2010, 14(9)).

Based on PMV model, ASHRAE suggests acceptable thermal comfort conditions. During the summer time, the acceptable operative temperature ranges from 23°C to 26°C, while for winter it ranges from 20°C to 23°C. The conditions were as followed.

1. The clothing insulation was assumed as 1 clo during winter and 0.5 clo during summer;
2. The relative humidity was controlled to 50%;
3. Average air velocity was 0.15 m/s;
4. Mean radiant temperature was defined as equal to indoor air temperature;
5. The human metabolic rate was 1.2 met. (Djongyang, Tchinda, & Njomo, 2010, 14(9)).

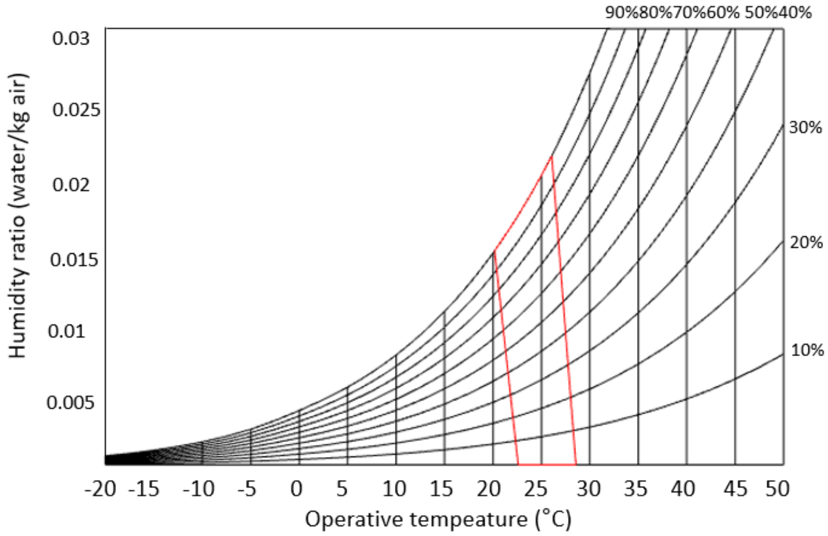


Figure 2. Acceptable range of operative temperature (10% PPD) for 1 met, 0.5 and 1 clothing level

2.5 Outdoor Thermal Comfort

In general, regarding thermal comfort in buildings most studies focus only on indoor environments, but outdoor thermal comfort also needs to be considered. Especially in Nordic countries, people spend long time outdoors during summer. However, this may also increase the risk of getting heat-related illnesses. As one research mentioned, heatstroke is caused when old people are walking in street canyons during hot summer afternoons (Thorsson, o.a., 2014).

The urban canyon is a place surrounded by buildings on both sides. It generates a local microclimate and contributes to an urban heat island effect. One research showed that urban heating is attributable to a large excess in heat from the rapidly heating urban surfaces, such as buildings, façades and ground. In some cases, the temperature inside of a canyon could be about 10°C warmer than nearby woodlands (Kim, 1992).

Studying outdoor thermal comfort becomes meaningful when designing building façades. It indicates that façade design may highly affect human perception about temperature in a street canyon, surrounded by building surfaces. Consequently, materials, geometry and the window to wall ratio are essential parameters for adaptive façades.

Outdoor mean radiant temperature which only considers radiant heat transfer between aa human and surroundings could well present the shading effects by an adaptive façade. However, the mean radiant temperature is just one of the impacting parameters for thermal comfort. Then, a combination index called Universal Thermal Climate Index (UTCI) seems as a good option for studying the thermal comfort impact results from adaptive façades.

The Universal Thermal Climate Index (UTCI) was recently considered as a well-accepted outdoor comfort model. It is an equivalent ambient temperature characterized as the thermal stress influenced by the combined effects about air temperature, radiation, humidity and wind on an equivalent temperature scale (Bröde P. F., 2009). The UTCI was defined in 10 different stress levels: no thermal stress, 4 heat stress levels and 5 cold stress levels, (Sookuk Parka, 2014). It presents the stress level when people were investigated in the certain outdoor condition, view from Table 6.

Table 6.UTCI Assessment Scale: UTCI categorized in terms of thermal stress

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

The calculation could be simplified by the following equation.

$$UTCI = 3.21 + 0.872t + 0.2459MRT - 2.5078V - 0.0176RH \quad (5)$$

Where: t is air temperature (°C), MRT is mean radiant temperature (°C), v is wind speed at 10 m above ground (m/s), RH is relative humidity (%) (Arnfield, 2003).

2.6 Shading Devices

Studied literature of shading systems are describing a large amount of different shading systems and control methods, and have a design and protection focus (Bellia, Marino, Minichiello, & Pedace, 2014). Regarding the most used systems, Dubois studied that venetian blinds, white screens and blue awnings are the most adequate traditional shading systems for office work, in comparison with static overhangs or awnings of other colours (Dubois, 2001). The Venetian blind system is therefore one of the most used and studied systems (Kirimtat, Koyunbaba, Chatzikonstantinou, & Sariyildiz, 2016).

Shading devices can be implemented in order to control the solar gains and with it the daylight exposure. This allows to have high window to wall ratios, compromising the visual comfort less and decreasing the cooling demands compared to completely glazed façades (Dubois, 2001). Also mentioned by Dubois, shading devices have the advantage over other systems due to the flexibility of designs, the reduction of heat losses during night time and the ability to operate them and even retract them from windows.

Given that daylight is related to location, climate and orientation, the way it is controlled and used has been and should be unique to every project. For locations in with clear sky or slightly cloudy conditions, direct sunlight should be addressed in terms of light distribution, glare and the possible need for shading devices. While the contrary, if overcast skies occur more than 2/3 of the time, shading devices have a high risk of reducing the incoming light to the building (Egan & Olgyay, 2002).

With all this in mind, the surface colour of shading devices can be chosen depending on the sky conditions and location. This would turn them into sunlight-redirecting elements that help distribute daylight into the deeper parts of the building/room, while keeping the primary function to stop the direct unwanted light (Egan & Olgyay, 2002).

From studies on the effect of geometry and colour on atria, it can be seen that for horizontal distribution of colours through the vertical surfaces (walls) the daylight factors were more complicated than for vertical patterns. These vertical patterns were simple to understand. The wider the colour bands, especially the light colour ones, the higher DF values were obtained (Jensen Skarning, Hviid, & Svendsen, 2017).

According to studies carried out for Copenhagen and Rome, the use of dynamic shading could increase the amounts of hours with more than 300 lux in 75% of the space on a south facing office room from 750 h to 1000 h (Jensen Skarning, Hviid, & Svendsen, 2017).

2.7 Parametric Design

In order to analyse and explore all the explained options and combinations, a design process was introduced into architecture, Parametric Design. According to a recent study (Eltaweel & SU, 2017) this idea was mentioned for the first time for architecture by Luigi Moretti in 1940 (Moretti, Bucci, & Mulazzani, 2000). Quoting Moretti, parametric architecture is "defining the relationship between the dimensions dependent upon the various parameters". The concept introduces the idea of setting mathematical boundaries between parameters to study. The manual calculation or modelling of changing design ideas like geometry size, location, orientation, etc would be time consuming. But through the use of software not only the calculation and virtual 3D modelling could be carried out but also a mathematical option to change a set of desired values and understand how they would affect the simulations in mind. Taking into consideration all the orientations, geometrical and material factors that affect the perceived daylight, the use of parametric simulation is crucial to anticipate the desired lighting levels.

With the development of the software and computational strength needed for advanced parametric design, numerous studies have been done for daylight assessment. Given that this study is focused on the effect of the façade to the indoor and outdoor environments, the first studies to analyse are the ones assessing the façade design. Cammarano et al. (2015) analysed how weather (Germany, Turin and Catania), WWR, glazing, visual transmittance, external obstruction height affects urban canyon illuminance (Cammarano, Pellegrino, Lo Verso, & Aghemo, 2015). Also following a parametric analysis and adding the thermal related energy demands, Krüger and Suga (2009) studied the effect of the common aspect ratios on urban canyons in Curitiva, Brazil.

2.8 Adaptive Façade

"Many believe that the façade is the real battleground in the fight for a better building sustainability"

Antony Wood
Executive Director
Council on Tall Buildings and Urban Habitat
(Aedas, 2012)]

Although being a concept that was proposed in the 1970s by William Zuk and Roger H. Clark (Ramzy & Fayed, 2011) the technology needed for its operation is very recent. It is important to understand the difference between different categorized types of moving façades and the kind of movement they can have. The façades by typology would be first retractable, convertible, transformable, performative, responsive and finally adaptive (Barozzi, Lienhard, Zanelli, & Monticelli, 2016).

Adaptive façades are the latest implementation to the architectural environment. The advanced mechanical systems, sensors, phase changing materials are among these state-of-the-art solutions. The adaptive façade definition used in this study is the one used by Loonen et al (2015). They stated that the façade can be changed to achieve a better building environment and lower energy use by a multifunctional integrated system. Here the skin of the building (i.e. the elements in contact with the exterior) has the ability to move, react, change its shape or function as an answer to climate conditions (Loonen, et al., 2015). Also, this series of responses should be possible to do as many times as required and in a reversible manner (Aelenei, Aelenei, & Pacheco Vieira, 2016). According to Loonen, eight concepts, including purpose, function, operation, technology, response time, spatial scale, visibility, and dynamism, were taken into account when analysing or designing this kind of façades.

With this in mind, adaptive façades may have a high potential for building energy savings while giving a possibility for response against specific climatic conditions.

3 Methodology

For the development of the indoor-outdoor relation concept of both thermal and visual perceptions through the façade a concrete methodology had to be used. First a clear workflow was prepared to have a map of where to start, where to develop and finally where to conclude. Each one of these phases is then isolated and further developed.

3.1 Introduction – Workflow

The study conducted was divided in three phases, preliminary analysis and definition, shading system simulation and a final variable study.

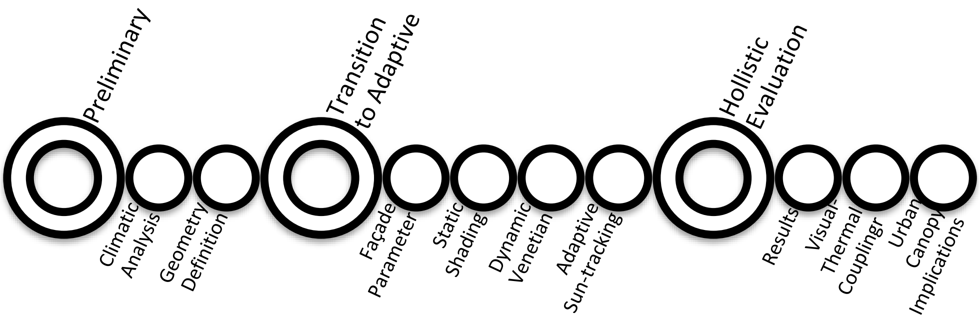


Figure 3. Step by step workflow of the study

For the preliminary phase, first climatic zone of Copenhagen was analysed. The studied geometry was a typical street canyon from Copenhagen that was modelled parametrically using the software Grasshopper for Rhino 5. The study focused only on thermal and visual comfort for the indoor and outdoor environment. Illuminance and illuminance-related measurements were used for daylight assessment, while both operative temperature and UTCI were used for thermal comfort assessment. In terms of energy-efficiency, heating and cooling demand was studied, with the addition of light dependency.

The main phase of this thesis is referred as Transition to Adaptive, and as the name implies, it is the step-by-step workflow to have a full understanding of the savings and improvements on the indoor environment and outdoor environment. A four-step analysis was followed.

The first step was without shading devices, showing how changing the façade's WWR and surface colour affected the studied point in time simulation results. This gave a first confirmation of the effect that the façade design has on the street canyon comfort.

The second step studied the effect of translating the parametric study to a static shading device, varying colour, distance from the façade, width and angle. For this step an optimization needed to be done to obtain an ideal width of the louvers for both thermal and visual comfort. This stage indicated if the previous studied effect still applies using a shading device and the possible limitations of the software.

In step 3, a first dynamic façade system was defined and analysed both for annual performance and point-in-time results on the selected design date. The whole-year performance was used to test if the proposals were efficient in terms of energy demand and comfort indices, while the point-in-time results tested how the possibilities of each design affected the visual and thermal perception. This first dynamic shading was a traditional exterior venetian blind that opened and closed only according to a certain illuminance level. Outside occupancy hours, the system was closed completely, to explore how it influences on the outdoor environment.

Step 4 was the design of an advanced sun-tracking shading system. It consisted of 5 different states which changed from one to the next one according to illuminance levels, outdoor temperature and solar azimuth. The operation of the system was done independent for each floor according to sun altitude, to not take away daylight when there is no possible direct sun due to the urban context (opposite building). Same as with the previous dynamic venetian system, this one also closed completely during non-occupancy hours.

Referring to holistic evaluation, the study has the innovation of assessing not only the indoor but also the outdoor environment and then joining these studies to see the full picture. This combination will be referred to as Holistic Approach. The assessment process was detailly divided in three steps (see Figure 4). The shading system evaluation in result section was used this process.

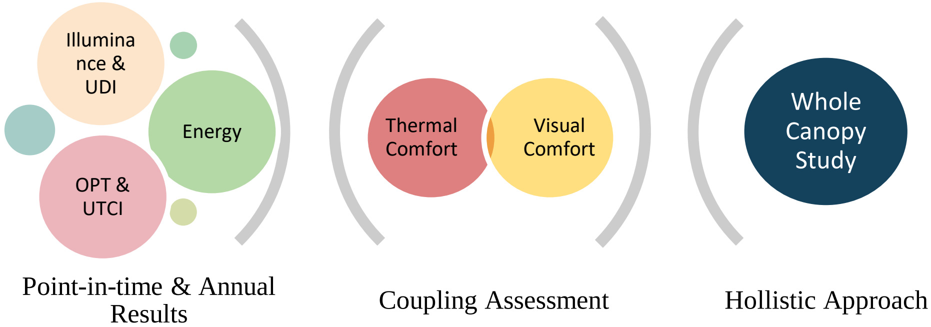


Figure 4. Evaluation workflow for Holistic Approach

3.2 Preliminary Phase

3.2.1 Software

Rhinoceros 5 (McNeel & Associates, 2018) was used as the 3D modeller for visualizing all work and results from the rest of the software.

Grasshopper (2018) (Davidson, 2018) was used to create building geometry. It provides more flexibility, as the dimensions of the buildings and canyon could be iterated parametrically.

Ladybug (Sadeghipour Roudsari & Mackey, Ladybug, 2018) is a plugin for Grasshopper for importing EPW weather files and to analyse different weather conditions, as well as to visualise of results.

The **Honeybee** (Sadeghipour Roudsari & Mackey, Honeybee, 2018) plugin was used as the main interface for defining the daylight and thermal models.

Energy Plus (DOE, 2018) was the thermal comfort and energy simulation engine. It was used to calculate for indoor and outdoor thermal index.

Radiance (Ward & Shakespear) (Fritz & McNeil, 2016) is a daylight rendering package consisting of a suite of programs, using backward raytracing.

Daysim (Reinhart C. , 2018) is a Radiance-based daylight software for annual simulations.

TToolbox (Core Studio, 2017) provided an efficient way to export simulation inputs and outputs to an Excel file.

Octopus (University of Applied Arts Viena & Bollinger+Grohmann Engineers, 2014) is a plug-in for applying evolutionary principles to parametric design and problem solving.

The essential inputs of construction materials properties were taken from **Open studio library** as well as **WUFI pro** material databases. The exterior constructions were built based on ASHRAE standard and Danish building standard. Regarding shading systems, **LunchBox** plugin worked for creating complex geometries.

Software Limitation

Due to the EnergyPlus calculations based on energy balance in the zones, the simulation time is always more than one day and starts from 01:00. It could not start at a specific hour of a day as was expected. This was one of the biggest obstacles for simulating dynamic shading devices. The shading devices changed states many times during a day, and therefore the shadow calculations are crucial for dynamic simulations. However, the time step frequency method is very time-consuming, so average frequency shadow calculation method had to be used for EnergyPlus. At the same time, the amount of context surfaces for Energy Plus calculations were also limited. Therefore, the overlaying surfaces were always simplified as one surface.

When it comes to dynamic shading design, an EP transparent shading schedule was used to make the shading states to change over time. The transparent schedule was based on a few assumptions. Firstly, the shading surface’s visible transmittance was assumed equal to its solar transmittance. Also, the shading is always opaque to long-wave radiation. In other words, shading surfaces still have heat exchange through long-wave radiation when it is transparent. Shading devices only work when the sun is up, which is automatically determined by Energy Plus from latitude and time of year. Therefore, the design for closing the shading during night to avoid long-wave radiation with the sky could not be taken into account (EnergyPlus version 8.7 Documentation, 2016).

For the daylight evaluation, the dynamic shading simulation could not be conducted through the same process as the energy simulation, as Radiance does not “read” the transparency schedule settings of EP for context surfaces. Also, the method for calculating sDA through

Daysim for Honeybee consists of running the daylight simulation without shading devices and then calculates the effect of the shading device. This process is limited to only static shading for the time being therefore sDA could not be accounted for the dynamic and adaptive shading system evaluation.

3.2.2 Base Model Definition

A typical, well-known urban canyon on Østergade in Copenhagen is modelled in Figure 5. The street canyon is 10 meters wide and 68 meters long. The orientation of the canyon is set to East-West to facilitate modelling. The Illum shopping centre was simplified as study case. The building consists of 4 floors, each 4 meters high.

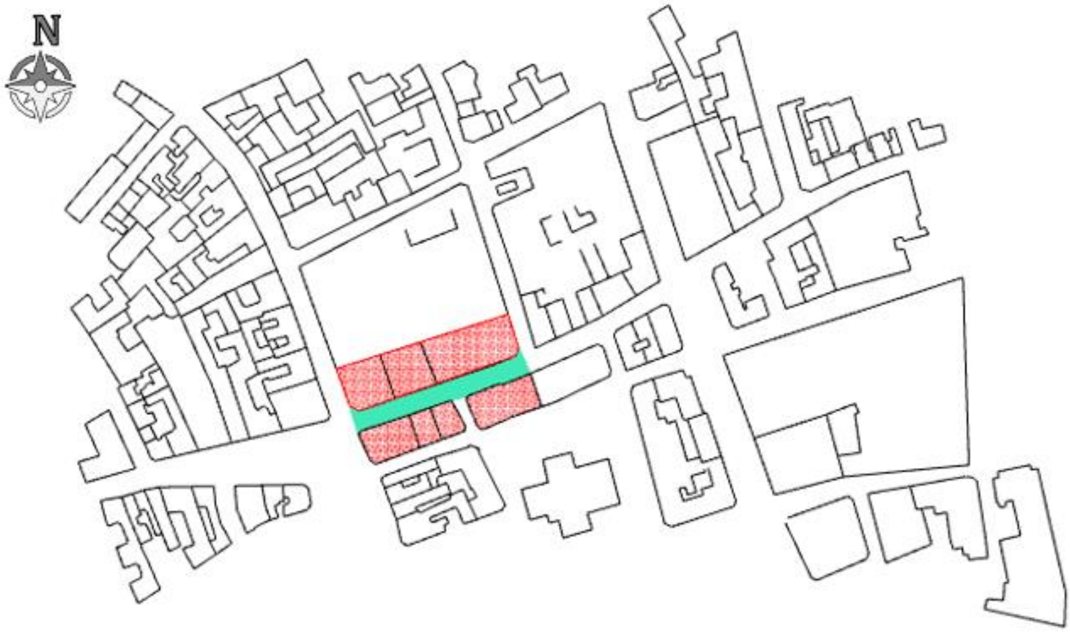


Figure 5. View of the location in Copenhagen.

The WWR was set as a parametric study from 0.1 to 0.9 for the first stage. After that WWR was simplified and defined throughout the whole canyon as 0.9. This was decided as the study analyses the effect of the shading device that covers most of the façade. The higher the WWR, the easier it would be to understand these effects. At work flow stages 3, 4, 5, the shading system was put at the south facing side of the building and covered all the façade, which is outlined in the red-dashed rectangle in figure 8.

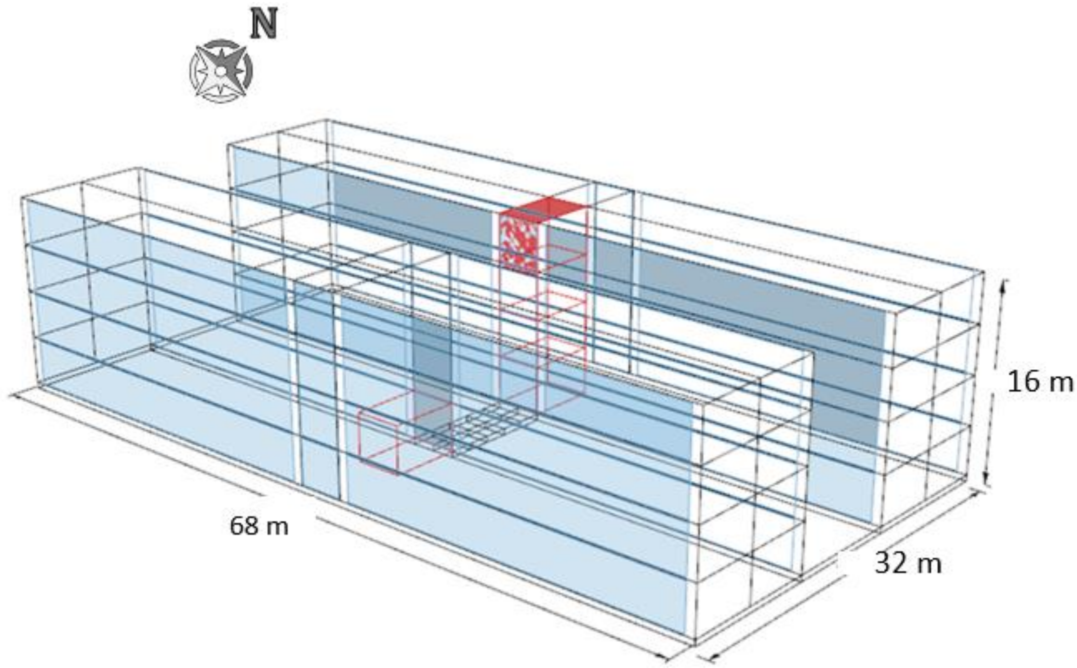


Figure 6. Simplified street canyon and building model from Copenhagen Street Canyon Østergade

One room was modelled at the centre of the canyon for the study (shown in red linework, in Figure 6) and repeated at each floor. The room was 6 meters long, 4 meters wide, and 4 meters high. Test points were selected per square meter with 1.1 meters height for the thermal comfort model, and 0.8 meters height for the visual comfort. For the street canyon the same method was used to put test points, although the height of the visual comfort was at 1.6 meter from the ground, to simulate the walking eye level. Depending on the analysis the number and distribution of points was changed due to a need of higher grid quality. For point-in-time studies the test points were placed on a North-South axis (perpendicular to the canyon) as seen on Figure 7. The room on the building B was chosen to see the effect of reflected light on the neighbouring building.

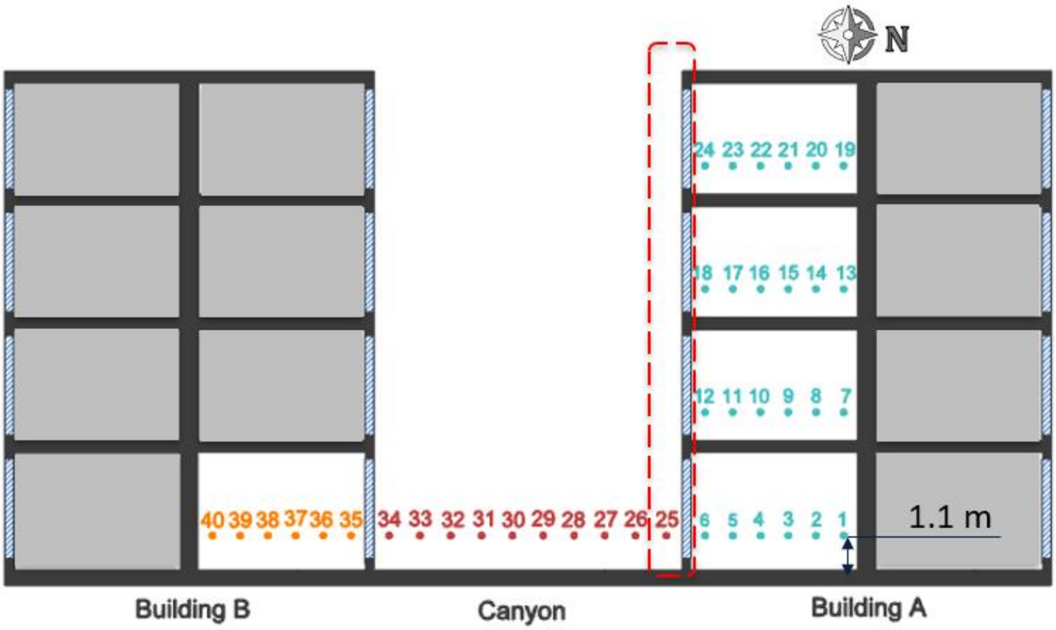


Figure 7. Building test points information (1,1m height, 1m between points)

The illuminance and mean radiant temperatures were tested in the simulations, as input parameters for selecting the optimized shading dimension and the movement states of adaptive façade. The illuminance and mean radiance temperatures were compared to the standard comfort region where the illuminance should be above 300 lux (BR18, 2018) (annually assessed in building code but will be taken as reference), and the comfort thermal zone has operative temperature 20°C to 26°C.

Energy use per square meter was calculated at building level to compare the normal façade with the adaptive façade.

3.2.3 Simulation Inputs

To study the thermal implications of the façade design, all parameters were set as constants. The construction inputs were taken from the ASHRAE construction standard and the Danish Building Code (BR18, 2018). The building envelope U-value was considered as a new building requirement in BR standard. The window construction was also set to 0.5 solar gain coefficient and 0.64 visible transmittance. The ground U-value was also needed for outdoor thermal comfort calculation. The ground exterior surface temperature was calculated through the zone roof temperature of the ground zone.

At the first stage of the study, the wall construction had two variants to compare colour effects. The interior surface was painted as white or black, but the exterior surface was always painted white. However, at other stages of study, the wall construction only used white paint for both interior and exterior building surfaces. More details about building materials can be found in Appendix I.

Table 7. Building construction

Construction	Layers (outside to inside)	U-value (W/m^2K)
Roof	Plywood board, Roof insulation, Gypsum board	0.2
Wall	Plywood board, Wall insulation, Gypsum board	0.3
Window	Fixed Window	0.8
Exterior floor	Insulation, Aerated concrete	0.2
Interior wall	Gypsum board, Wall air space resistance, Gypsum board	2.58
Interior floor	Acoustic tile, Air space resistance, Lightweight concrete	1.45
Outdoor ground	Asphalt	0.27

The surface properties set for the daylight analysis are displayed in Table 8. The “White Paint” material was used as base surface colour for the exterior and interior walls, although it is understood that for the façade, the degradation of the paint by being in contact with a harsh environment would decrease the actual reflectance values. The rest was obtained as the default materials from the Radiance library, even the windows, as they matched the recommended ones from the BR18.

Table 8. Material properties used for daylighting model

Material Name	RAD Primitive	Reflectance (R=G=B)	Transmittance
White Paint	Plastic	0.73	0
Interior_ceiling	Plastic	0.8	0
Interior_floor	Plastic	0.2	0
Exterior_floor	Plastic	0.2	0
Exterior_roof	Plastic	0.8	0
Exterior_window	Glass	0.654	0.346

Table 9 shows the assumed building loads. The occupancy level in the test room was set to 4 people per 24 m^2 of floor area, and light bulbs were set as LED light with 3 W/m^2 density. The room also had a medium equipment load. At the same time, the infiltration rate was combined infiltration and certain air flow rate to guarantee air quality of the buildings. The value was taken from ASHRAE recommended general infiltration rates based on façade area. An average building infiltration rate of 0.0003 m^3/s per m^2 façade area was used. Air flow rate was set based on EN-ISO 7730 air quality requirement, 7 l/s person and 0.35 l/s per m^2. Equipment load was based on EnergyPlus default setting.

Table 9. Building Loads

Equipment load per area (W/m^2)	6.8889
Infiltration rate per area (m^3/m^2)	0.0015
Lighting density per area (W/m^2)	3.0000
Number of people per area (ppl/m^2)	0.1667

The occupancy schedule is not only a parameter for internal heat gain for energy and temperature calculation, but also related to the working period of the heating and cooling system due to occupancy time. During façade parameter study, shading optimization, different shading system comparison, there was not heating and cooling set points to regulate indoor operative temperature. The heating set point was set to 20°C and the cooling set point to 26°C only during energy demand calculation. Since set point cut down all temperatures which were above cooling setpoint and below heating setpoint, in this case, it could not observe the influence from shading system. However, set points were needed during energy simulation, because the energy was calculated by keeping the indoor temperature between the setpoint range.

The occupancy, lighting, and equipment schedule was set similar as the closed office schedule by default from the E+ library. The occupancy schedule was also added for making a dynamic and adaptive shading schedule, meaning shading would only be active during occupancy time, and disabled during non-occupancy periods (view Figure 8). The infiltration rate schedule was more complex with consideration of occupancy rate, day and night infiltration rate, but also the building requirement air flow rate per area. The lighting, equipment, and infiltration schedule can be found in Appendix II.

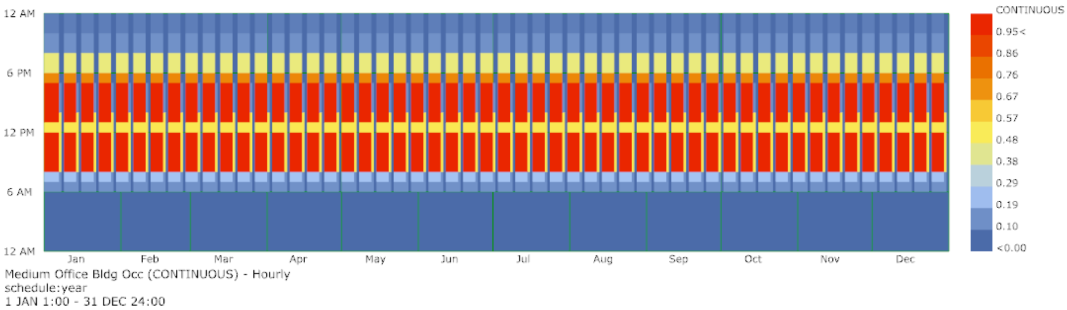


Figure 8. Occupancy rate in typical office building

3.2.4 Design Day

To approach the climate analysis, the software Ladybug for Grasshopper was used. Through it, climate databases were downloaded as .epw files for Copenhagen. Based on Copenhagen weather data, different pre-design studies were done (View from Appendix III). First an outdoor dry-bulb temperature diagram indicated during which time of the year the solar heat gains are a benefit. The same was done for the sky cloud/overcast hourly state, which showed when shading devices are more problematic as they block the low levels of daylight. Particularly, annual outdoor dry bulb temperature, global illuminance, sun azimuth, sun latitude was used for stating the schedule for dynamic shading operation.

The optimal façade was sized according to the worst weather scenario: the hottest day at noon time has intensive solar radiation, the highest temperatures and strong illuminance levels. The .stat files indicated the hottest week as between August 3rd and 9th, so this week was chosen as the analysis period for dimensioning the shading devices for the thermal approach, while August 4th at noon was selected for the point-in-time daylight simulations. The following table (Table 10) show different parameters regarding climatic conditions during August 4th.

Table 10. Climatic data during the hours with solar activity during the 4th of August

Time / hour	**DBTemp** / ºC	**Wind Speed** / m·s	**Global Hor. Illum** / lux	**Sun Altitude** / degrees	**Sun Azimuth** / degrees
05:00:00	17.7	3.8	600	9	62
06:00:00	18	3.9	5800	17	74
07:00:00	18.4	4.1	17900	25	86
08:00:00	20	3.8	33400	34	98
09:00:00	21.6	3.4	49700	42	112
10:00:00	23.2	3.1	64600	49	129
11:00:00	23.3	3.6	75700	55	150
12:00:00	23.5	4.1	81100	57	174
13:00:00	23.6	4.6	82500	56	199
14:00:00	23.7	5.2	80000	52	222
15:00:00	23.9	5.7	71100	45	240
16:00:00	24	6.2	57900	37	255
17:00:00	23.4	5.2	42900	29	269
18:00:00	22.8	4.1	25800	21	281
19:00:00	22.2	3.1	11700	12	292
20:00:00	21.2	2.6	2200	5	304

3.2.5 Comfort Study

Regarding daylight, UDI was calculated for indoor visual comfort and finally illuminance was used as the outdoor metric. The study was narrowed to calculate only operative temperatures and MRT for the indoor thermal comfort, while UTCI and MRT were calculated for outdoor thermal comfort.

3.2.5.1 Visual Comfort

Since visual comfort has many parameters to analyse, specific daylight evaluations were chosen for this study. For the indoor environment, two different values were used for the analysis: point-in-time values and annual values. For point-in-time simulations, illuminance was the main parameter used and was calculated throughout a grid of 24 points spread through each studied room, 0.8 m above floor level. For the annual values of indoor daylight measures, Useful Daylight Illuminance (UDI) and Lighting Dependency (LD) were the chosen metrics for the evaluation, which was done with a grid of test points of 0.375 x 0.375 m distance and 0.8 m height for every floor. UDI was the main measurement to assess comfort, with threshold values ranging from 200 lux to 2000 lux, while LD was used to test the energy-efficiency of the proposals. LD is obtained from the opposite of Daylight Autonomy, which was the simulated value and then subtracted from 100%.

For the outdoor environment, only point-in-time illuminance was considered. This decision was made since the multi-directional and non-constant flow of people made it specific to account for other visual comfort-based metrics such as glare probability. This approach gave the required information of how the dynamic shading system increased or decreased the horizontal illuminance throughout the width of the street.

Due to the thermal-visual coupling approach of this study, daylight glare probability was not assessed for the indoors. This decision was made given that during heating season (outdoor temperatures lower than 10ºC) it was desired to maximize the solar heat gains. An outdoor shading system used for reducing glare would radically limit the solar gains on such an occasion. It is therefore recommended that on such a time of the year, an additional internal shading system (other than the one studied) should be used to avoid probable glare.

3.2.5.2 Thermal Comfort

There were two perspectives for analysing indoor thermal comfort; the zone evaluation and the point evaluation. The overall zone operative temperature is a general temperature measurement during the year, whereas point operative temperature is a specific measurement at a specific time and location.

The zone average operative temperature was the design parameter for shading system optimization. A shading design was considered better if it would sustain the zone average operative temperature within a comfort range as longer time as possible. Test points operative temperature was used to evaluate and compare the cooling effects of different shading system. The test point operative temperature could present how well a shading system could cool down room temperature at near window side or far from window part.

The outdoor conditions assessed only by point-in-time method, mean radiant temperature and UTCI were used for evaluation. Mean radiant temperature well presented the shaded affects and UTCI was an indicator for outdoor thermal comfort.

The annual zone operative temperature was calculated in EnergyPlus, considering construction, zone load, zone schedule, weather condition. It was calculated with a mechanical ventilation system with certain air flow and without active heating and cooling system. Furthermore, when zone air temperature, relative humidity, air flow rate, air heat gain, surface indoor temperature, surface outdoor temperature was retrieved from EnegyPlus engine, the “Indoor climate map” component was used to simulate test points temperature. Outdoor thermal comfort incorporated outdoor building surfaces temperature, ground zone exterior surface temperature to calculate outdoor microclimate.

The Annual zone heating and cooling energy was also simulated by EnergyPlus engine. It has the same building envelope zone load, zone schedule, weather condition, but it was simulated with ideal load air conditioning. The zone air temperature was controlled between heating and cooling setpoints.

3.3 Transition to Adaptive Facade

The main modelling and simulation phase of the thesis and the whole process was divided in four main steps. The first step was a façade study changing two basic parameters, then a regular static venetian blind was added to obtain the optimal angles, sizes, and colours for the most extreme sunny conditions. The third step was dynamic shading study. The studied static shading was turned into an on-off operational blind according to occupancy rate. Finally, this same dynamic venetian blind was modified so it could track the sun position and move in order to have a more active effect on the outdoor environment and hopefully an improvement over the previous dynamic system in terms of energy efficiency and daylight distribution.

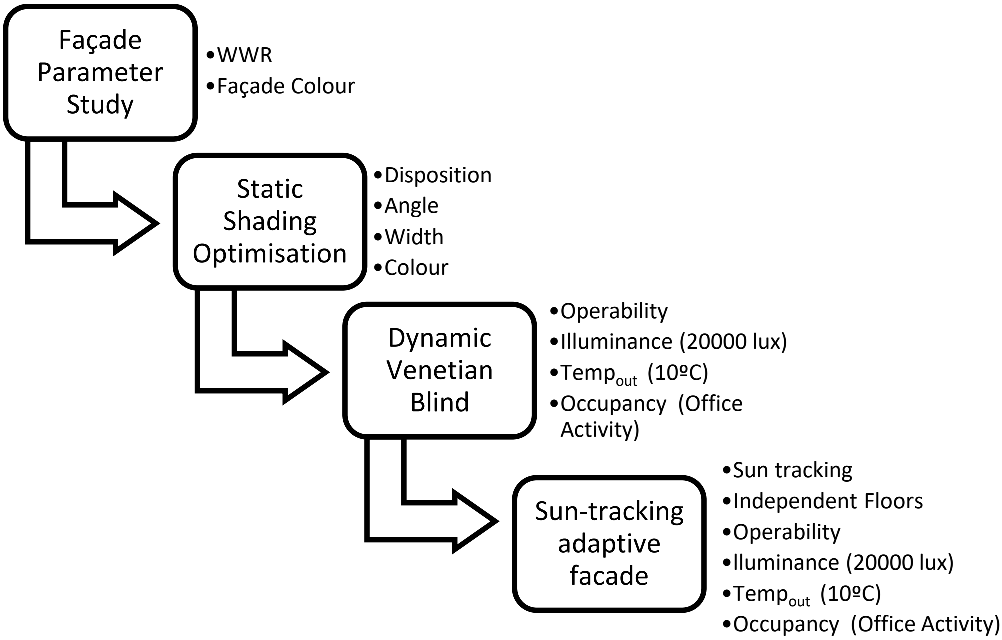


Figure 9. Workflow of the study for shading optimisation and effect on the outdoor comfort.

For every step of the process, the point-in-time simulations were carried out to find the immediate illuminance and thermal impact of every combination of modified parameters. For the annual simulations, 0.9 WWR geometry with shading or without shading were simulated. The following paragraphs describe in detail each one of the four steps.

3.3.1 Façade Parameter Study

To have a full understanding of how the outdoor environment is affected by the façade design, a first study changing the WWR was carried out. To maximize the effect, both buildings' studied parameters were modified simultaneously. This was done by calculating the WWR as a percentage of each floor's façade at each side of the studied buildings, as seen in Figure 6 of section 2.4. This was decided given that the indoors of those side rooms were not studied and the outdoor should not be affected by the breakdown of the window into individual room windows. WWR was studied from 10% to 90% in steps of 10%.

This was done given that this point was not an optimisation but a sensitivity analysis. This analysis monitored how changing those parameters would affect the result and identified the range of values for both illuminance and thermal values. From this stage, the results of the indoor and outdoor environment were separated for independent analysis. This was done especially due to the simultaneous modification of both buildings. In other words, since the WWR of both buildings were being increased, the influence on the outdoor measurements also would affect the indoor ones, these implied that it could not be quantified how much is because of the changes on the opposite façade and how much from the actual WWR change affecting directly the indoor.

Except for the WWR parametric study, the exterior façade colour was also an important study factor. For the change in colour, the same reflectance value was used for the daylight and energy model. As seen in Figure 10, for the energy model a painted layer was added to the wall construction with a fixed average solar and visual reflectance, while for daylight it was set according to generic paint RGB values.

Thermal (Energy+)	Daylight (Radiance)
• *White Paint* • Roughness: Smooth • U-value: 17.0 W/m^{2}K • $Thermal_{abs}$: 0.86 • $Solar_{abs}$: 0.9 • *Black Paint* • Roughness: Smooth • U-value: 17.0 W/m^{2}K • $Thermal_{abs}$: 0.86 • $Solar_{abs}$: 0.9	• *White Paint* • Plastic • RGB: 0.73 • Roughness: 0.2 • Specularity: 0 • *Black Paint* • Plastic • RGB: 0.1 • Roughness: 0.2 • Specularity: 0

Figure 10. Façade colour parameters.

3.3.2 Static Shading Optimization

The optimization was done in three floors of the building. The first floor did not have shading because they are usually shops. Shadings were optimized for all other floors (second, third and fourth).

The first shading system was a static venetian blind. Louvers were placed on all the south windows of building A facing the canyon, but first the louvers parameter had to be defined. To optimize the parameters, a number of louvers were tested for optimal shading angle, distance between shading and window and surface colour (only for daylighting). The main input and output are listed in Table 11 below.

Table 11. Optimization parameters

Input parameters	Louvres numbers in 4m room height	2, 4,6,8,10,12,14,16,18,20
	Louvres angle (0: perpendicular to window, 90: parallel to window)	-90, -75, -60, -45, -30, -15, 0, 15, 30, 45, 60, 75, 90
	Distance between window and shading	0.1, 0.2, 0.3, 0.4, 0.5
	Material colour	White, black, metal
Output goals	Indoor illuminance	24 points in total
	Indoor operative temperature	84 hours in total

The surface colour of the shading system was only tested for illuminance, due to the limitation of using context shading in the Energy Plus simulation. The main input materials for illuminance are shown in Figure 11.

Figure 11. Color settings for shading optimization (daylight)

The desired range for the operative temperature is from 20°C to 26°C, which was also used as goal temperature range for 2nd floor shading optimization. However, the operative temperature at the upper floor of the building was always outside of this thermal comfort zone. Hence, a 20°-30° C temperature range was used for the upper 3rd and 4th floors to optimize the shading. The goal threshold values of illuminance were set between 200 lux and 2000 lux, which correspond to the same values of UDI used later for the annual evaluation.

The number of hours when the test-points achieved the goal operative temperature (inside desired range) was set as an objective for the Octopus simulation. There were 84 daytime hours in one extremely hot week. The thermal part of the assessment was based on how many of the 84 hours were inside the desired range of operative temperature.

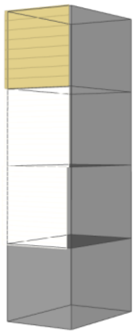
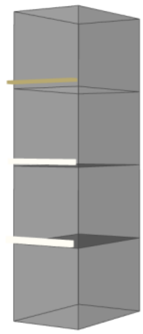
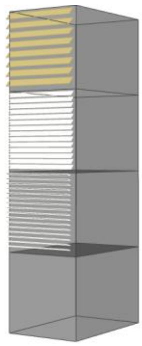
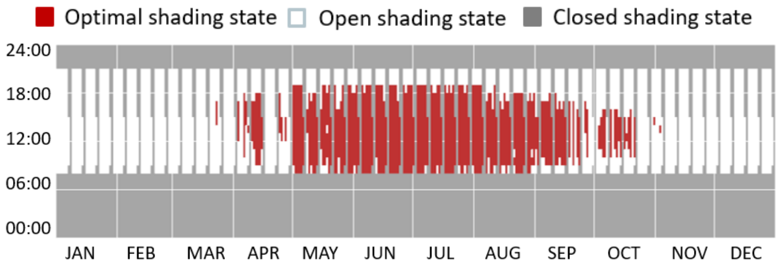
The points of illuminance inside of visual comfort was the second Octopus objective. There were 24 test points for illuminance measurement at 12:00 on August 9th, which was during the hottest week.

The software tries to reach a set goal by minimizing objectives, so hours and points had to be negated to reach the best thermal and visual condition. In Octopus optimization, three sets of generations through evolution were used. Two generations were simulated 400 times, for the 2nd and 4th floor, while a later introduced generation for the 3rd floor included only 100 simulation times with 13 generations; a Pareto Front was generated for each of these cases. A Pareto Front contains a number of optimal shading geometries, and one of the best options was selected.

3.3.3 Dynamic Venetian Blind

The dynamic venetian blind was modelled based on optimization results from the static shading (**Refer to 4.2** Static Shading Optimization**).** It had three shading states, closed, open, and optimal shading geometry. The shading totally covered the façade when it was closed. The louvres were pulled down to the bottom of each floor when it was set as open. The louvres kept the same shaded angle as steady-state shading and named as optimal shading state. Details about the optimal shading geometries can be found in the previous chapter, and the visualization shows in Table 12.

Table 12. Venetian operational blind geometry and schedule

State numbers	**1**	**2**	**3**
Shading name	Closed shading	Open shading	Optimal shading
Shading Geometry for 4 test rooms			
Shading schedule			

The shading was controlled by outdoor dry bulb temperature, global horizontal illuminance and the office occupancy schedule. The shading was closed when the occupancy rate was below 0.2 to reduce the movement of shading. It opened when the outdoor dry bulb temperature was lower than 10 °C, since more solar radiation is needed for passive heating during winter. The shading was open when outdoor illuminance was below 20000 lux and started using steady-state shading when it was equal or above 20000lux.

To set this control or operation schedule, a self-developed component had to be made that would create schedules for each shading state according to these set points. The same logic was used for the point-in-time simulation where another self-developed component that would automatically select the shading state according to the point in time and the schedule was created before.

After analysing hourly weather data and the occupancy rate, a shading schedule was created. The schedule dictated when shading was open, when it was closed, and when it was represented by a shading geometry derived from the steady-state study. Meanwhile, all shading geometries shared one operational schedule, seen in Table 12.

According to Copenhagen climate analysis, Copenhagen is mainly overcast and cold during daytime from November until March, so the shading system was generally off during this period. In April and October, it started to use shading, but not very often. During May and July, the optimal shading or steady-state shading was used almost the whole day. During

August and September, the shading device was open for half of the day. During the other half, it switched to the optimal shading design due to lower illuminance value during autumn. In addition, the shading was designed to close during weekends because of low occupancy rate.

Energy Plus simulated the dynamic system using a transparency schedule. Three shading states geometries were put outside the window, and if one state was active, this shading state would be set as Opaque material. If the other shading states were not used, it would be set as Transparent material.

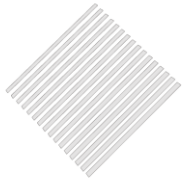
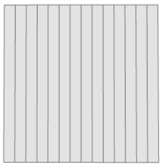
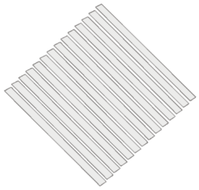
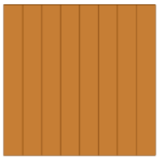
For the daylight annual simulation, three different Radiance runs had to be made, one for each shading state. Then the generated schedule for each shading state was used as "occupancy schedule" for the Daysim annual result reader. Finally, the total UDI and DA were obtained by adding the total hours of UDI or DA of each shading state.

3.3.4 Adaptive Sun-Tracking Shading System

The adaptive sun-tracking system consisted of five shading states: open, closed, optimal (midday), morning and evening. The opening state means shading blind was pulled up. Closing state means shading blind was fully shaded the window which was parallel to the window surface. Optimal (midday) shading states was when the louvres were horizontal at certain angles. The louvre's angle, number and material were determined by shading parameter optimization, which means the louvre parameters were fixed at certain floor. (Refer to Table 16). The morning and evening shading states were rotated the whole panels instead of louvres. The morning shading state was rotated 45° to the east and evening shading state were rotated 45° to the west. (View Table 13).
At the morning and evening states, the panel rotations were basically designed to block direct sun angle. 45° shading angle to east or west was inspired by sun position in the morning and evening. Due to time limitation, the angle of panel was not optimized at shading optimization stage in this thesis.

The distance between shading and window was various due to the rotation of the modules. In case of overlapping at morning and evening states, adjacent modules had 0.2 m distance between each other. When the square module had 45° rotations (morning and evening state), there generated a small opening on the corners of the room. On a real, full modelled building, these corners would be where wall and floor slabs would meet, making the thermal and visual implications smaller than in this case.

Table 13. Sun-tracking adaptive facade geometry per floor

Numbers	**1**	**2**	**3**	**4**	**5**
State conditions	Close shading	Open shading	Morning shading	Optimal /Midday shading	Evening shading
Geometry 2nd floor White colour					
Geometry 3rd floor White colour					
Geometry 4th floor Metal colour					

The operability of the sun-adaptive façade was more complex than the dynamic venetian blind, where operation schedule was separated per floor which correlated to different sun altitudes. As seen in Figure 12, the 2nd and 3rd floor, by increasing the open state duration of their system to get more solar radiation. In other words, sun altitude was a key parameter for distinguishing each floor's opening hours.

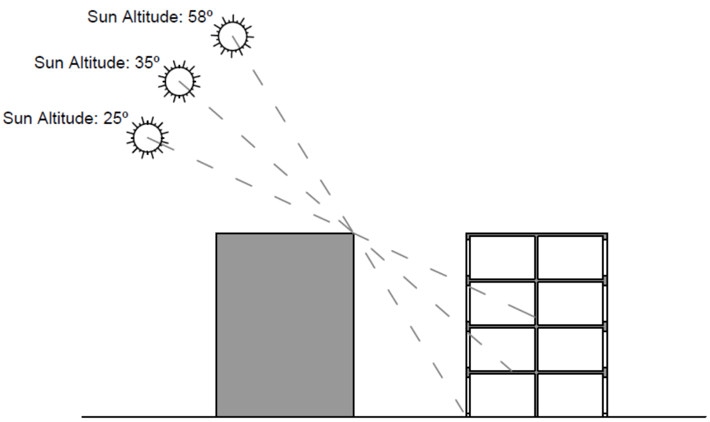


Figure 12. Solar altitude analysis to define floor operability

The next implementation to the shading system was the actual sun-tracking function. Introducing the sun angle into a C# custom component made it possible to follow sun during the day. The fundamental idea was using rotated (Morning and Evening) shading state at lower sun angle to shade from sun direction. Optimal (Midday) shading state was used when sun angle is high.

No shading was used when the outdoor climate was cold or dark, the illuminance value was below 20000 lux or temperature was below 10°C. Shading was closed when occupancy rate was less than 0.2, which means it was only closed at night and weekend.

In total, five weather parameters were used for deciding shading states, including sun altitude, sun angle, illuminance, dry bulb temperature, occupancy rate. The threshold factors are presented in Table 14.

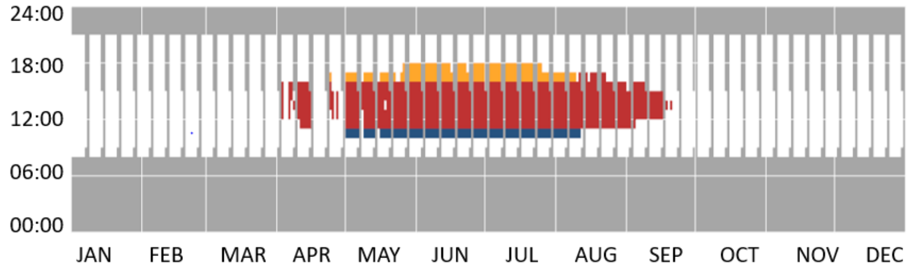
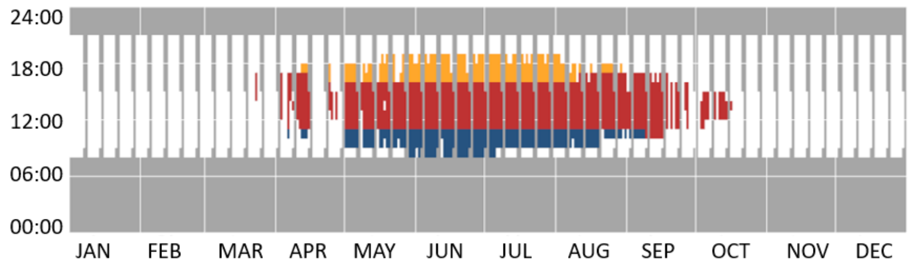
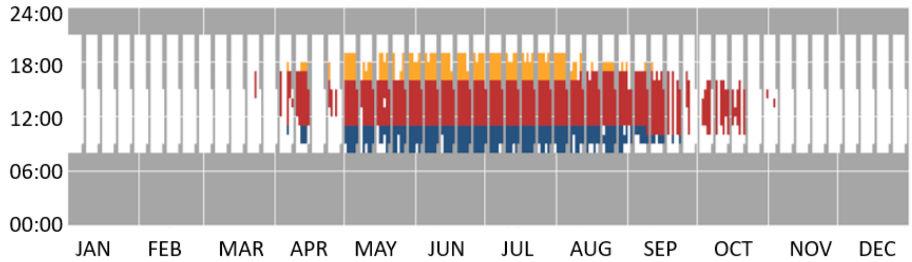
Table 14. Operational settings for Adaptive Sun-Tracking Shading System

Shading State	**2nd Floor**	**3rd Floor**	**4th Floor**
Closed	Occupancy < 0.2	Occupancy < 0.2	Occupancy < 0.2
Open	0 ≤ Illu ≤ 20000 lux or T_{dry} ≤ 10 °C or Sun altitude < 35º	0 ≤ Illu ≤ 20000 lux or T_{dry} ≤ 10 °C or Sun altitude < 25º	0 ≤ Illu ≤ 20000 lux or T_{dry} ≤ 10 °C
Morning	Illu > 20000 lux and 0° < Sun angle < 125°	Illu > 20000 lux and 0° < Sun angle < 125°	Illu > 20000 lux and 0° < Sun angle < 125°
Midday (Optimal)	Illu > 20000 lux or 125° ≤ Sun angle ≤ 235°	Illu > 20000 lux or 125° ≤ Sun angle ≤ 235°	Illu > 20000 lux or 125° ≤ Sun angle ≤ 235°
Evening	Illu > 20000 lux and 235° < Sun angle < 360°	Illu > 20000 lux and 235° < Sun angle < 360°	Illu > 20000 lux and 235° < Sun angle < 360°

The operational schedule was generated based on threshold values from Table 14. Building was mainly shaded from April to October. The second floor had more opening periods compared to the third and fourth floors. The shading system started to be used in April but only for around one week. It stopped shading in September, which was different than other floors. During summer day time, the shading was activated around late morning and shading was open earlier than the third and fourth floors.

The third and fourth floor operational schedules were similar to each other. They worked from April to October and mostly shaded during May to August. The obvious difference between third and fourth floor schedules was the usage of morning and evening shading state. Morning and evening shading were more frequently used on the fourth floor (view from Table 15)

Table 15. Sun-tracking adaptive facade schedule per floor

Shading schedule	Optimal shading state, Morning shading state, Evening shading state, Open shading state, Closed shading state
2nd floor	
3rd floor	
4th floor	

EnergyPlus simulation also used a transparency schedule for sun tracking adaptive façade, which was the same as the method of dynamic shading simulation.
It used five shading geometries put outside of window, if one state was Opaque, others would be Transparent.

For the daylight annual simulation, 11 different runs had to be made using Radiance, one for each shading state. Then the same process was used to obtain UDI and DA as was used for the Dynamic Venetian Blind.

4 Results

The façade parametric study was the first attempt for thermal and visual comfort modelling. The static shading optimization results provided the key geometric parameters for a shading device, which was used for the development of an adaptive façade. The developed adaptive façade was compared and evaluated with three other shading systems, in perspective of visual and thermal comfort, to judge the effectiveness of each system.

4.1 Façade Parameter Study

The first set of results correspond only to the space situated between the two buildings (test points 25 to 34).

4.1.1 Visual Comfort

Observing Figure 13, the results show that the reflective surface area has a high impact on the street illuminance. 0.9 WWR show the lowest values of all the study cases while 0.1 the highest. Also, the observed trend of the results, show a sloped increase the closer the test point was to the northern façade until 1m away. This was expected due to the solar altitude at that time (57º), time when the sun rays don't impact the canyon, but the reflected daylight occur with a high vertical angle, therefore close to the façade.

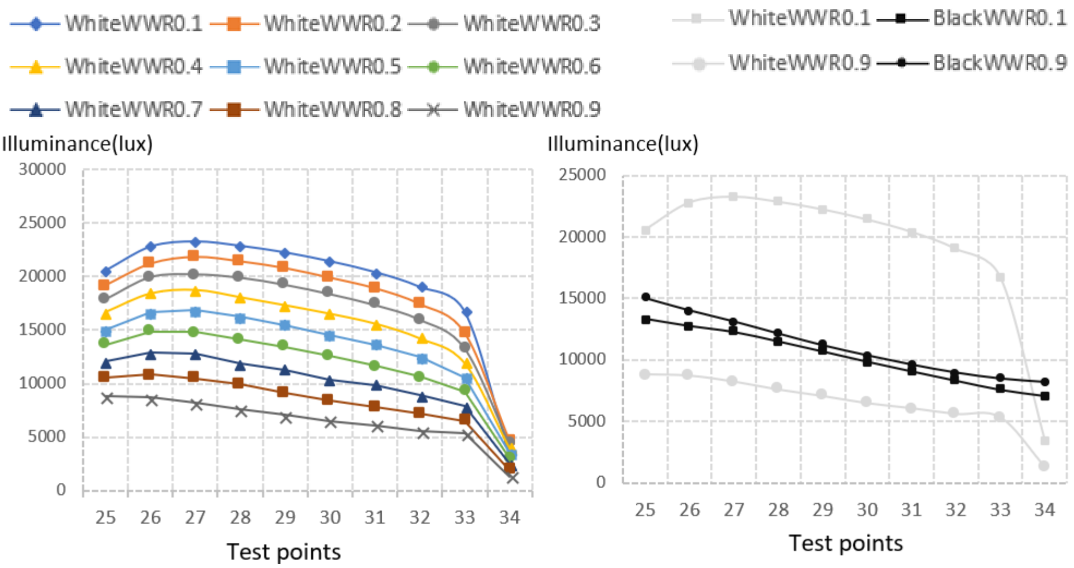


Figure 13. Point-in-time illuminance for the street canyon for different cases from Building A to B

4.1.2 Thermal Comfort

The façade parameter study focused on the heating or cooling effects from different window-to-wall ratios and envelope exterior colors. The results mainly show the impacts on outdoor mean radiant temperature, viewed in Figure 14. More details are in Appendix IV.

When the window-to-wall ratio is 90% or 80%, the outdoor mean radiant temperature is higher than when the window to wall ratio is 10- 70%. Otherwise, the temperatures are similar when the window-to-wall ratio is between 10% and 70%. The temperature range at different window to wall ratio are not so obvious, there are 1.5 °C difference. The window-to-wall ratio did not have a clear relation with temperature change at the corner part of canyon. The temperature variations don't have the same peace as window-to-wall ratio. However, in general the canyon mean radiant temperature is the highest at 90% window-to-wall ratio.

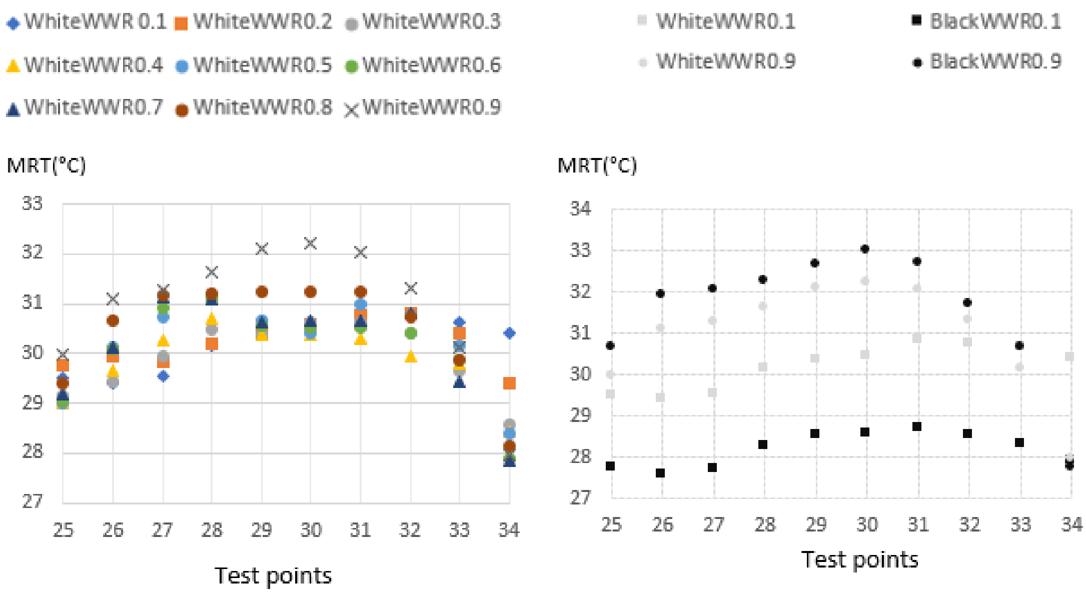


Figure 14.Outdoor mean radiant temperature for different window wall ratios and colors

When the window-to-wall ratio is 10%, white façade leads to higher outdoor temperature than black façade. Due to large area of white painting, it results to high reflectance in the canyon and high temperature. In contrast, when the window is 90% of the wall, outdoor mean radiant temperature of white façade is lower than black façade. It caused by large area of window, black façade has absorbed more heat through sun radiation and makes higher room temperature than white painting façade. Heat transfer through indoor to outdoors warm up outdoor street canyon.

The biggest temperature difference observed between white and black façade was about 3°C.Considering the window-to-wall ratio effects, the gap between highest and lowest mean radiant temperature is around 4.5°C. Hence, different window wall ratio and colors do impact outdoor mean radiant temperature.

4.2 Static Shading Optimization

Through Octopus simulation, it generated a Pareto Front for all cases. On the Pareto Front line, optimized shading parameters were carefully selected for each floor. Those optimized shading parameters were usually a balanced value which have both acceptable thermal comfort and visual comfort.

In general, the best thermal conditions occurred when shading was totally closed due to no solar heat gain, but this also led to no indoor daylight, as illuminance dropped to zero.

Sometimes, all illuminance value of test points was inside the visual comfort zone, but the room operative temperature was mostly outside of thermal comfort zone. The optimized case did not happen simultaneously.

The best selected cases are listed in Table 16. The optimal louvres number are between 8 to 16, so the shading panel was around 25 cm to 50 cm. The outdoor shading system had better performance when the shading panels were not so narrow. The shading material were different between each floor. It was basically depended on the required reflectance of each floor. Certain shading angles performed better, which was -15° and 45° during this simulation. The horizontal shaded condition was not the only option for shading system, the angle was variable at different situation. At the second floor was hard to reach good thermal and visual comfort, the illuminance and operative temperature values were far behind than upper floors. Since second floor was mostly shaded by surroundings, not enough sunlight could reach this floor, so the improvement through shading device was limited.

Those optimized louvres number, angles and distance to window were used as the common geometries for steady-state system, optimal (Midday) state of dynamic venetian blind and Optimal (Midday) state of adaptive façade (refer to 3.3.3 Dynamic Venetian Blind and 3.3.4 Adaptive Sun-Tracking Shading System).

Table 16. The optimal shading parameters, illuminance, operative temperature of black circle points

	Unit	**2nd floor**	**3rd floor**	**4th floor**
Louvres number		16	14	8
Louvres angle	°	-15	45	45
Distance to window	m	0.3	0.1	0.1
Shading colour		white	white	metal
Illumiance	Points	8	20	23
Operative temperature	Hours	12	53	44

4.3 Shading Systems Evaluation

Three different types of shadings systems were compared and evaluated for visual and thermal comfort both for indoor and outdoor. All tests include a control group without a shading system for comparison. The results consist of point-in-time and annual value for both visual and thermal comfort.

4.3.1 Visual Comfort

The values are reported in 3 different units, illuminance, UDI, DA/LD. The results of Building A are all the mentioned. For the outdoor environment simulation only point-in-time illuminance was used, same as for Building B.

4.3.1.1 Point-in-time Simulation Results

From Figure 15, it can be observed that the highest values occur mainly with the no shading solution, as it was expected. Since the global horizontal illuminance from the weather file is lower than 20000 lux until after 8:00 the illuminance values of the no shaded and the dynamic proposals are the same, as it was intended with this kind of operability. After 10:00 and until 17:00 they have similar performance since the shading states are the same (static and dynamic) or very similar (adaptive), having most of the values inside the UDI threshold of 100 lux to 2000 lux. The adaptive façade has fewer uniform values than the other shading systems due to the frontal distance of the modules, necessary for the proper module rotation, that allows daylight to enter to the areas close to the window. In this graph the results from closed shading are disregarded as this state is a simulation for non-office hours.

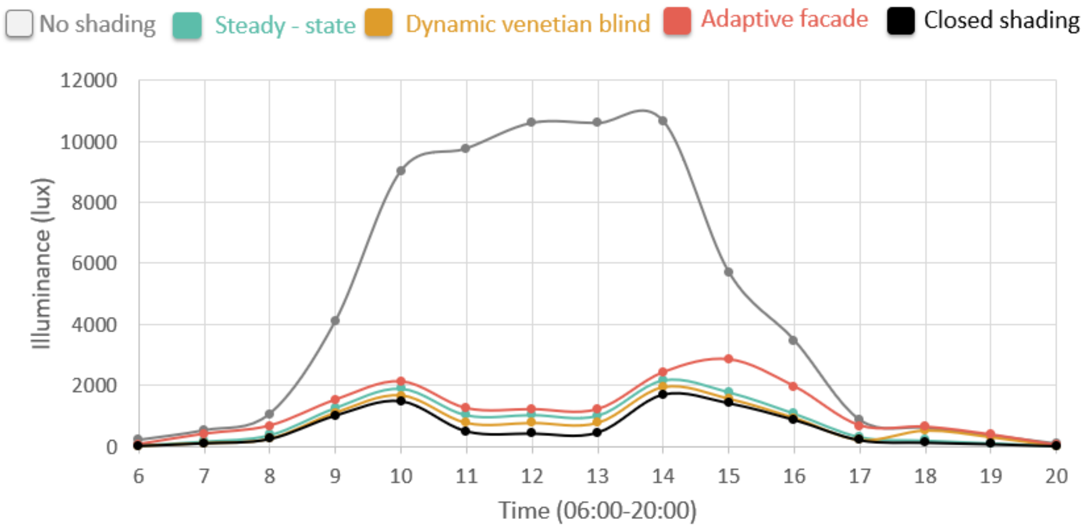


Figure 15.Point-in-Time illuminance for room on Building A

From the next Figure 16, the first effect of the shading system on the surrounding illuminance can be observed. Building A without shading device and other three-shading systems during office hours have very similar results, but, and here comes the first impact, the closed state for the two dynamic systems show an increase of up to 3000 lux, due to its high homogeneous reflectance.

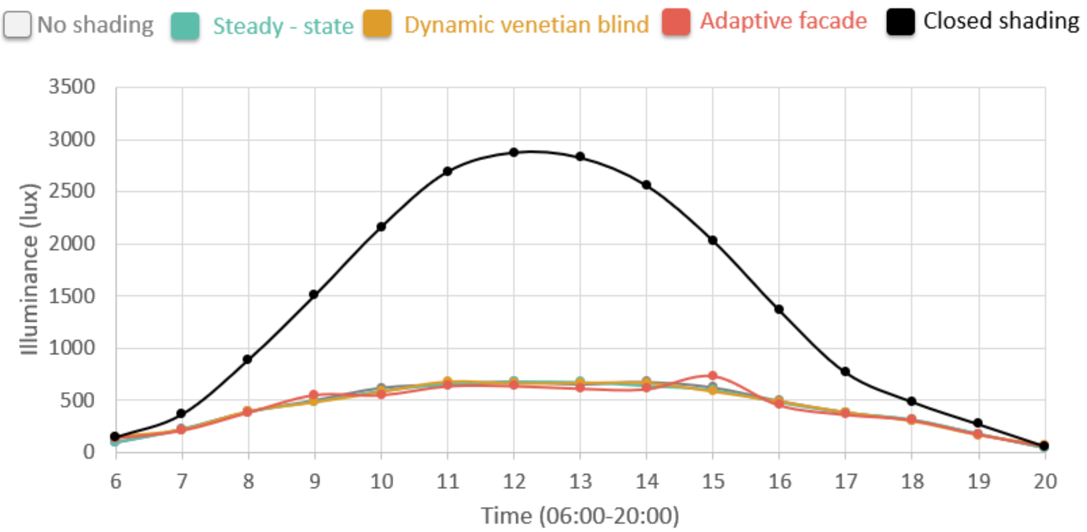


Figure 16. Point-in-Time illuminance for room on Building B

From the final point-in-time set of results Figure 17,a similar effect from the shading systems, to that of the previous figure, can be observed. Then trend of the canyon illuminance is descending from North to South as it is where most of the direct and reflected daylight is received (see explanation from WWR discussion). Here the impact from the closed state of the dynamic shading systems occurs from 8:00 till 17:00 when the sun rays impact the Façade of Building A directly, and the effect is an increase of 3000 lux to 8000 lux.

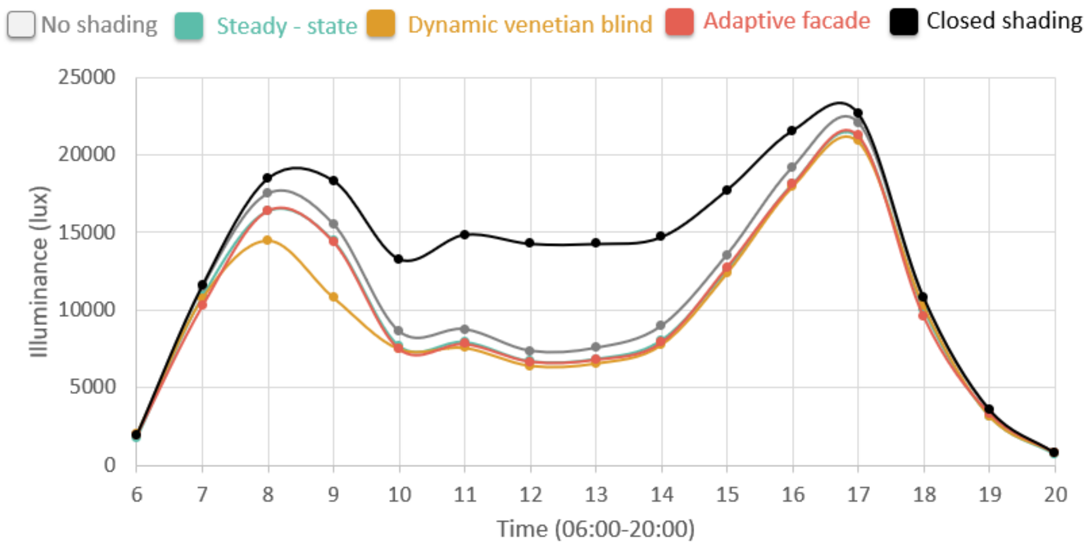


Figure 17.Point-in-Time illuminance for room on the street canyon

The whole canopy study shown in Figure 18, gives an idea of the relationship between each environment. It can be seen how the façade of Building A dictates the difference in results. When the shading system is not with "closed/exterior" mode activated, light enters the rooms of Building A following the previously explained results. At the same time the lowest levels of illuminance are seen on the street and Building B, no matter the studied case. On the other hand, when the "closed/exterior" mode is activated, outdoor illuminance is increased on a factor of 70% and the illuminance of Building B also increases by 150%.

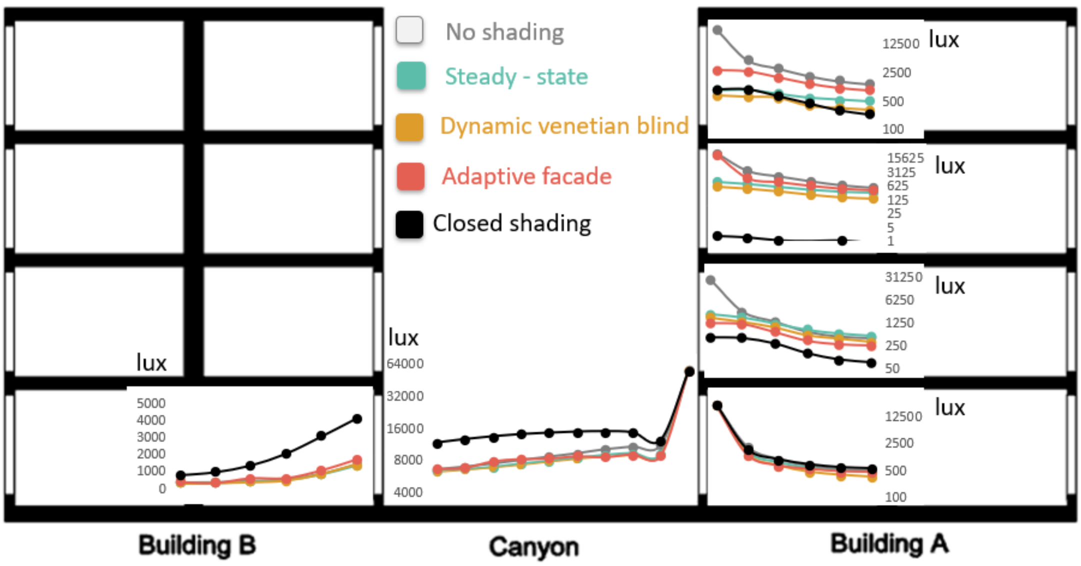


Figure 18. Canopy study for daylight point-in-time values at 15:00 during simulation day

4.3.1.2 Annual Results (UDI)

Finally, from the annual set of results for Visual Comfort, Figure 19 shows that overall, having a shading system does not have a clear effect to the un-shaded ground floor. For both the second and the third floor, the static system has the lower values of all the systems, while for the 4th floor this same system is the most optimal, having almost all the values between 60 % and 75 %. Both the adaptive and the dynamic venetian system have very good values for the 2nd and 3rd floor, having more than 75% of the points above 50% on the 2nd floor and 62% on the 3rd floor.

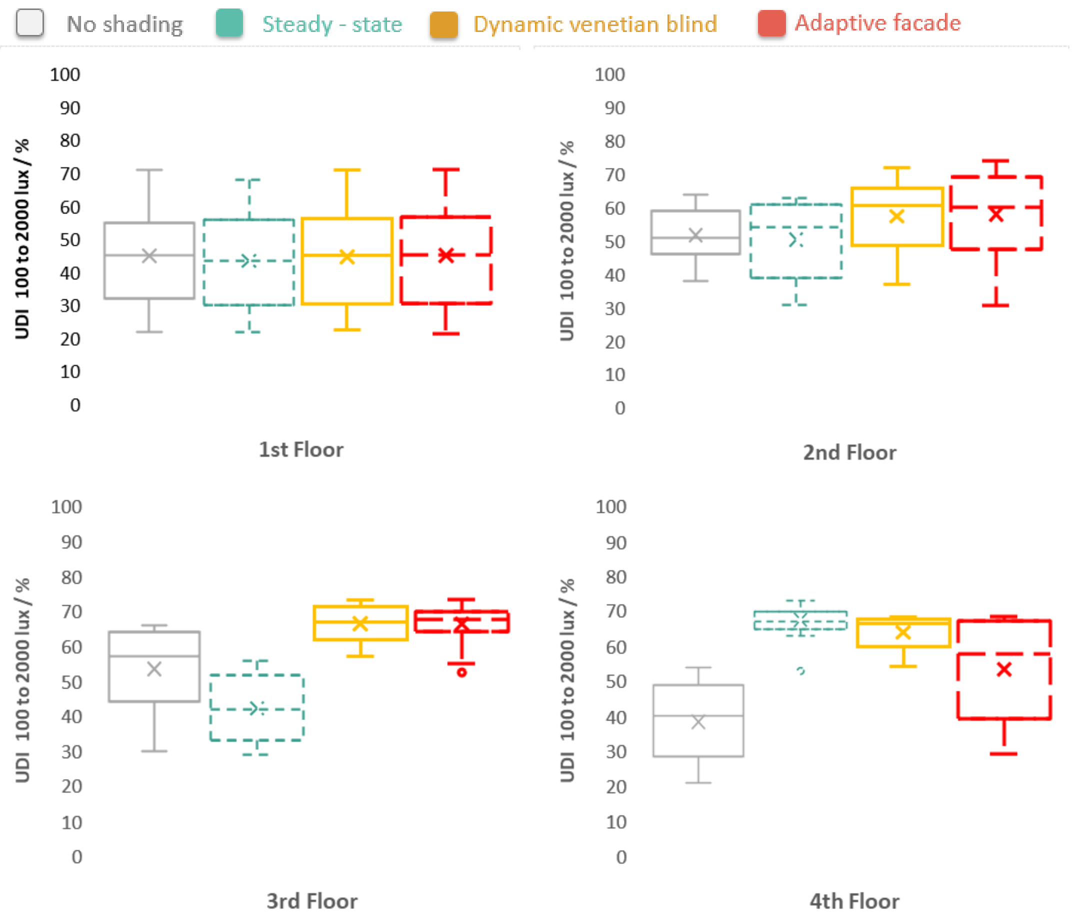


Figure 19. Boxplot for Useful Daylight Illuminance of each floor in Building A

4.3.2 Thermal Comfort

The values are reported in 3 different units, temperature, UTCI, PMV. It depends on if the study was indoor or outdoor. Operative temperature was simulated for the indoors while mean radiant temperature and Universal Thermal Comfort Index (UTCI) were calculated for the outdoors for point-in-time simulation. The annual results were simulated as the Total Operative Temperatures and PMV.

4.3.2.1 Point-in-time Simulation Results

Without a shading system, the indoor operative temperature reached 55°C at certain test points in building A during 14:00 to 15:00, since the building were only taking fresh outdoor air without cooling. The lowest operative temperature was still around 30°C, so the temperature range was far from thermal comfort zone. As shown in Figure 20 shading systems play an important role in decreasing room temperature. Regardless of the type of shading, steady-state shading, dynamic venetian blind shading or adaptive façade, the maximum temperature was reduced to 35°C. The temperature range become narrow than without shading device. The lowest temperature achieved was 25°C.

In general, the maximum temperatures decreased by about 20°C when a shading device was used, with the higher temperatures recorded at the window side. The minimum temperature was recorded far from the window, and the shading system reduced the temperature by 5°C at those test points. (View all data in Appendix V)

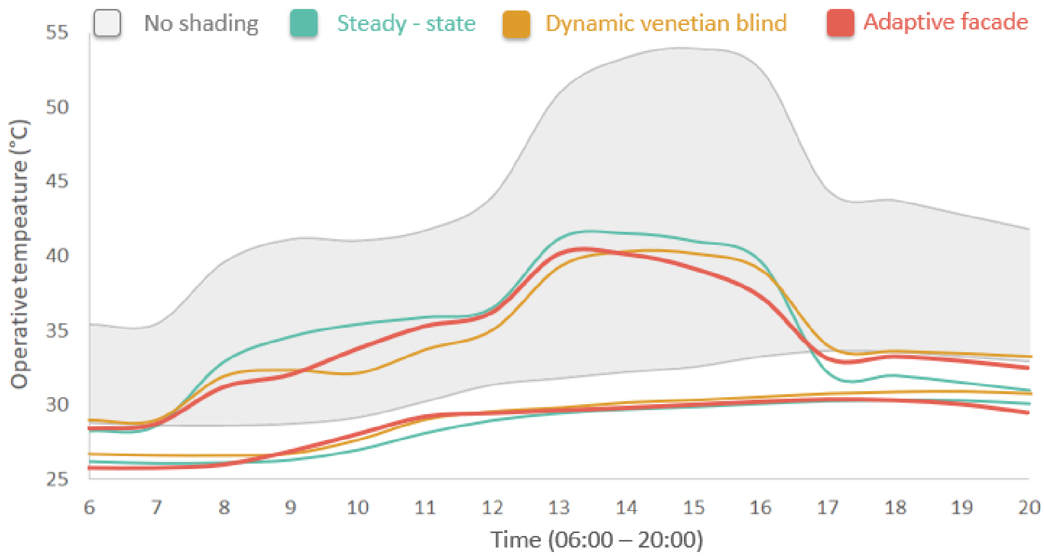


Figure 20. Minimum and maximum operative temperature at building A test points

Furthermore, dynamic venetian blind and adaptive façade work better at high temperature pots during 06:00 to 15:00, for instance, at upper floor window side test points. In Figure 20 ,the red line and yellow line which are lower than the green line during 06:00 to 20:00, which means dynamic venetian blind or adaptive façade cool down the room 1°C or 2°C more. Especially, adaptive façade has more shaded effects during hot afternoon than other shading systems.

Not only the shading reduced the indoor temperature, they also decreased the mean radiant temperature. Figure 21 shows that the highest and lowest temperature among 6 test points at certain hour of the day. (View all data in Appendix VI) Basically, shading devices reduced around 10°C at peak points when it is between 15:00 to 16:00. At those points, there are exposing direct sun light. While, at 10:00 to 14:00, there are not direct sun light in the street canyon. The canyon is fully shaded by surroundings. The shading system cool down street canyon around 10°C.

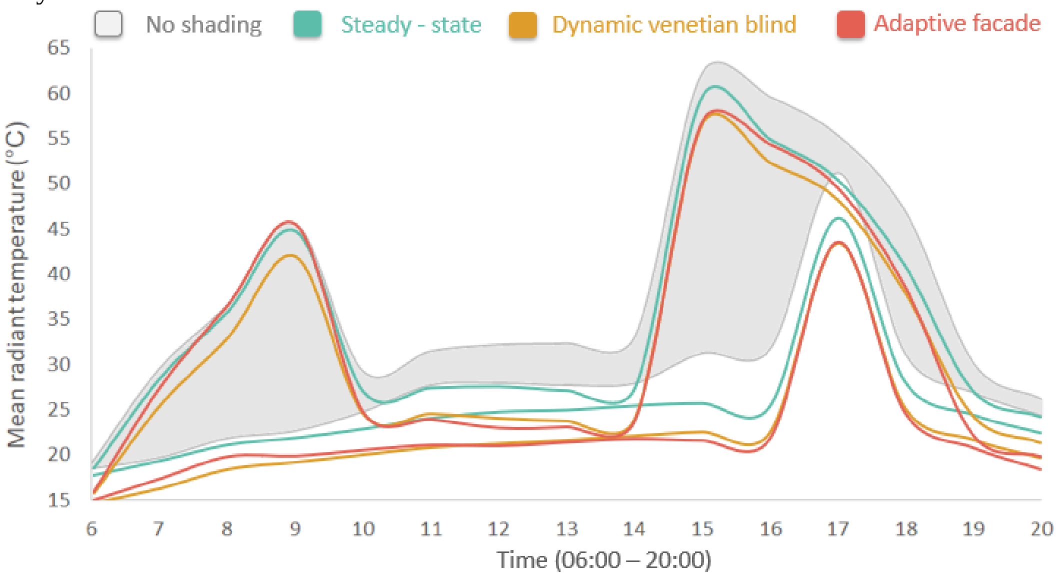


Figure 21. Test points 25-35 outdoor maximum and minimum mean radiant temperature

Furthermore, dynamic venetian blind and adaptive façade have more cooling effects than steady-state shading during 10:00 to 20:00, but their effects are similar with each other at morning time. It is shown that line of dynamic venetian blind and adaptive façade almost approach to each other.

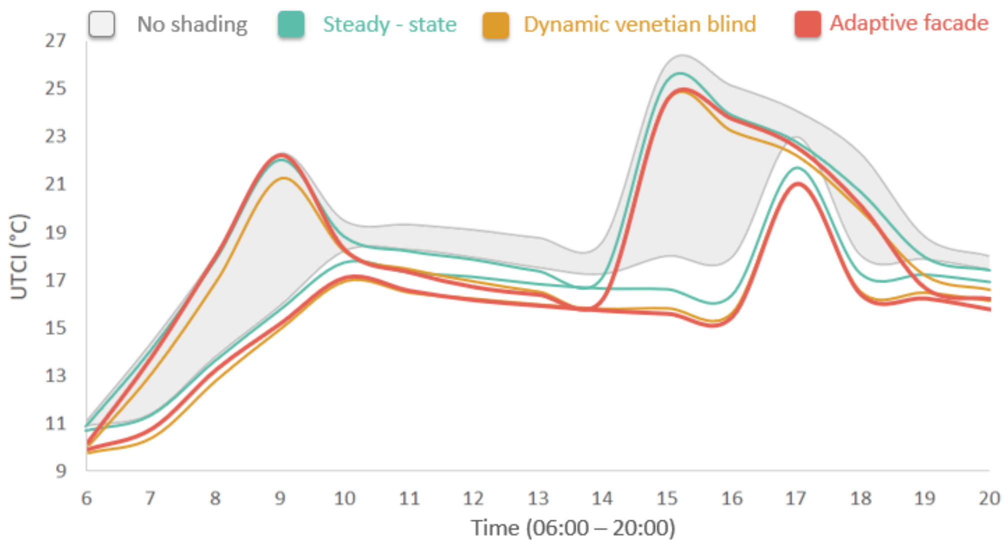


Figure 22. Test points 25-34 outdoor UTCI maximum and minimum value during simulation day

While, the mean radiant temperature is a useful measurement for outdoor temperature, the Universal Thermal Climate Index (UTCI) represents thermal comfort best. UTCI thermal comfort scale would show when UTCI is between +9 to +26, meaning there is no heat stress (see Table 6). Figure 22 shows the canyon UTCI is between 9 to 26, people don't feel heat stress at any test points in the canyon. If there is direct sun light, the short-wave radiation is

the dominant factor for the UTCI value. Otherwise, the wind factor has large effects on outdoor thermal comfort.
Outdoor mean radiant temperature increased from 10:00 to 16:00 (see Figure 22), while UTCI value is decreasing. This decreasing could be because wind speed increased 3.1 m/s to 6.2 m/s during this period. (View all data in Appendix VII).

The last point-in-time simulation results (Figure 23) are drawn from the entire microclimate, where indoor and outdoor values are joined to assess possible relation between environments. In all environments, no shading case had the highest thermal values. The shading system had cooling effects for south facing building and canyon, also affects building B. In other words, the whole thermal condition of the microclimate was influenced. During the study hours, 15:00 to 16:00, there were direct sun rays on the northern building's south facing facade, therefore values close to it were the highest for all solutions. More results about north-facing building could be find in Appendix VIII.

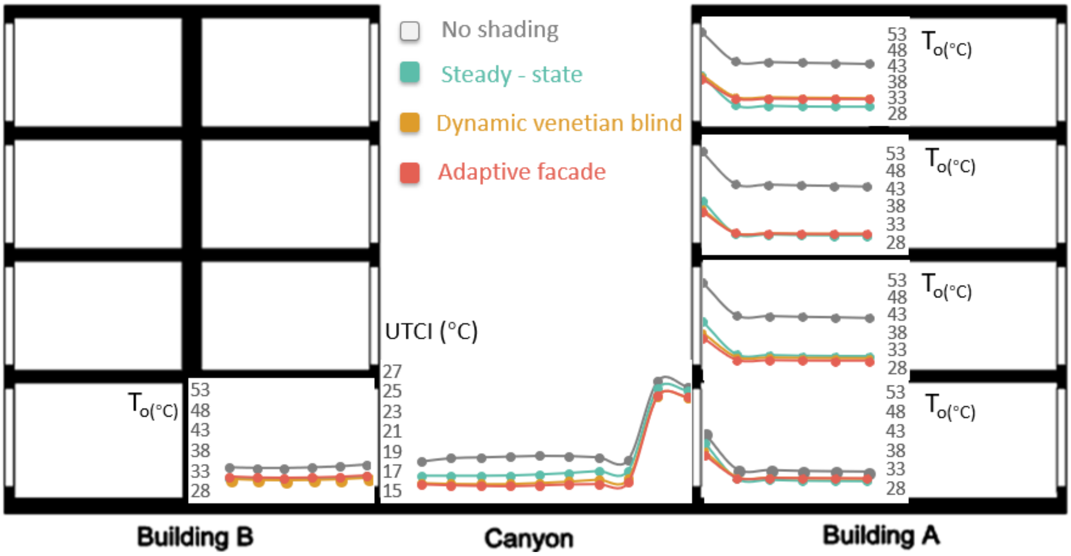


Figure 23.Canopy study for thermal point-in-time values at 15:00-16:00 during simulation day

4.3.2.2 Annual Results

Figure 24 represents the overall range of obtained values of Operative Temperature for every stance in building A. No shading device case have the highest temperatures and the widest range. Static shading has the lowest set of values, while both dynamic systems achieve temperate values.

The average operative temperatures of dynamic venetian blind and adaptive façade are above steady-state shading. It could achieve the goal to get more solar radiant when it is needed. However, the difference between dynamic venetian blind and adaptive façade is not so obvious.

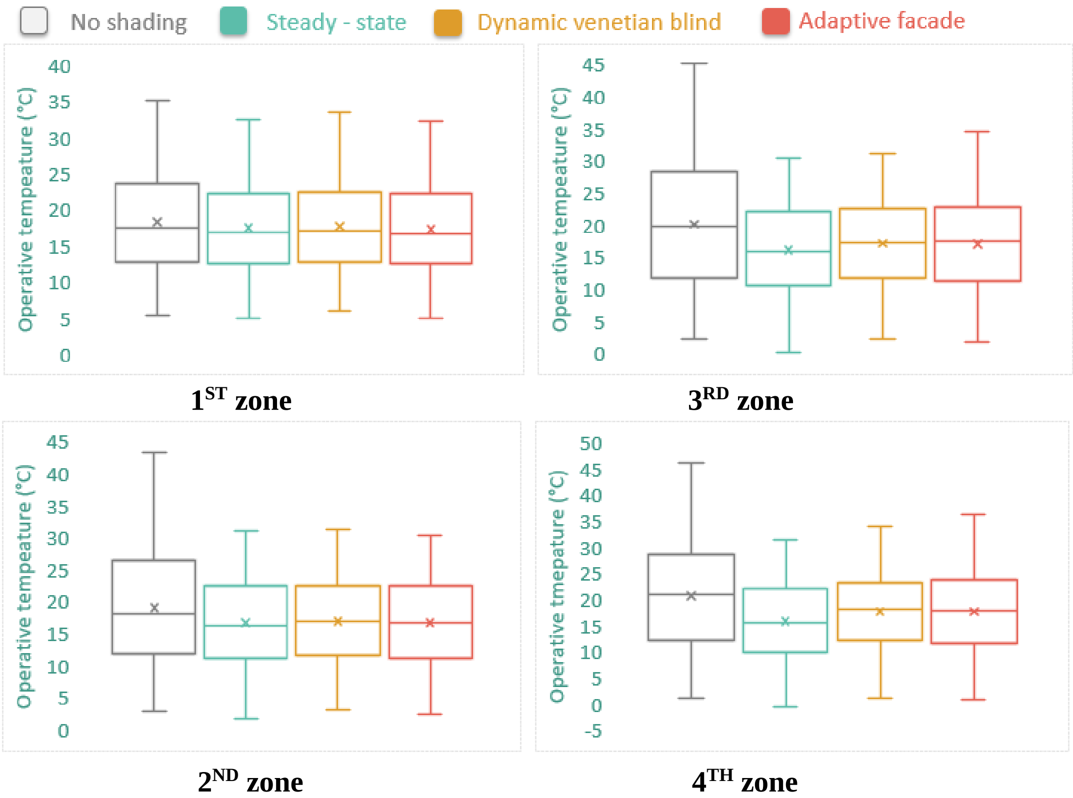


Figure 24. Annual operative temperature of each floor in Building A

4.3.3 Energy Demand

The results obtained from Table 17, indicate that the lowest overall energy demand is for the no shaded solution even with a WWR of 0.9. The cooling demand is also the highest of all, but it could be reduced by the use of passive measures that do not affect the solar heat gains.

The heating demand and light dependence of the static system are the highest of all. The cooling demands are in the order of 1kWh/m^2 for the shaded solutions, making the adaptive and the dynamic proposals interesting systems depending on the COP of the heating and cooling systems of the building. The Dynamic venetian blind has approximately the same heating and cooling demand as the adaptive façade. It is interesting to notice that the desired LD and PMV values are achieved with the non-shaded and the adaptive façade.

Table 17. PMV, light dependence, heating and cooling demands under the four different shaded conditions

		Unit	1ST zone	2ND zone	3RD zone	4TH zone
No shading	PMV	%	32	35	37	36
	LD	%	72	54	37	27
	Heating	kwh/m^2	138	131	122	122
	Cooling	kwh/m^2	3.7	4.2	5.1	6.0
Steady-state shading	PMV	%	31	30	29	29
	LD	%	74	70	81	51
	Heating	kwh/m^2	142	144	149	163
	Cooling	kwh/m^2	2.6	0.7	0.5	0.7
Dynamic venetian blind	PMV	%	32	30	31	35
	LD	%	73	58	55	43
	Heating	kwh/m^2	142	141	136	136
	Cooling	kwh/m^2	2.9	0.7	0.5	1.2
Adaptive facade	PMV	%	33	35	37	36
	LD	%	73	60	43	27
	Heating	kwh/m^2	147	144	139	137
	Cooling	kwh/m^2	2.6	0.4	0.5	1.4

5 Discussion

Throughout the whole thesis study, the idea of actively influencing the outdoor thermal and visual environment by having an active facade was merely a concept to explore. It can now be confirmed, that at least on the design and simulation stage of a project it can be done. This thesis work has shown how designing a façade system both static and dynamic have implications on the outdoor thermal and visual comfort. The fact of making the system dynamic or adaptive would give the designer control over both visual and thermal perception of the users/occupants of the direct vicinity. Due to increasing urban scale concerns (Urban Heat Island and Canyon Daylight), urban planners could also plan for mayor proposals that would translate this concept into bigger scale projects. This opens for a new line of research and experimentation.

Research Question 1: Can daylight and thermal implications of a shading system be accounted for simultaneously and how?
Result: Accomplished.

By coupling thermal and daylight evaluations, it was possible to fully understand the implications one approach has over the other. By the use of optimisation algorithms. it is not only possible but recommended to have both perspectives in mind. An increase in visual comfort by larger windows may have a dangerous effect on thermal stress. To protect from overheating, a thermal approach would limit illuminance levels drastically. Therefore, in this report at least one method to couple both measurements are described.

Research Question 2: Can urban and building design be interlaced through the façade to achieve common human comfort goals?
Result: Accomplished.

The idea of interlacing the analysis for both indoors and outdoors was the topic of the traineeship at KADK. Through Figure 18 and Figure 23, the relationship between the two was appreciated clearly. The outdoor environment and the building façade have an effect on each other, and these two have a direct implication on the indoor environment.

Research Question 3: Can the outdoor environment be affected and/or manipulated by a dynamic/adaptive façade system?
Result: Accomplished.

As seen from the background chapter, dynamic/adaptive façades offer many possibilities, and by including one more shading state, the outdoor could be an additional environment to influence. The fact that it is only one more shading state opens a new range of shading and façade design possibilities.

6 Conclusions

Indoor comfort has been studied for decades, but the combination of indoor and outdoor comfort was gradually draw attentions during current research. The shading system, which is only a small part of a building, still has obvious effects on outdoor thermal and visual comfort. When taking all constructions into account, there could be a big impact on outdoor conditions. In terms of thermal comfort, it smoothens and reduces the temperature of the environment. Regarding daylight, it protects from direct sunlight and gives the option of creating a reflective effect to bring light to dark areas of the street.

The point-in-time study was quite new for building thermal simulations. Usually, simulations only calculate average room temperature as an indicator for thermal comfort. The temperature distributions in the room hardly draw attention for researchers. In this thesis, point-in-time study provides a good view on how the temperature changes at different spots.

Computer programming becomes more and more important for building design. The accuracy of thermal calculation gets improved, because software can consider highly detailed inputs. Software also makes it possible to simulate more complex building structures. However, there are limitations in computer power and on the software itself, therefore simulations are still heavily time consuming for commercial purposes.

The adaptive façade was not fully developed in this thesis and there is still space for improvement and optimizations. The results of overall energy demand show that it makes almost no sense to adopt a shading system even for the south façade in Copenhagen as the heating demand would always increase more than the savings on cooling. If energy demand is not the main purpose but human comfort is, then the adaptive shading is already a big improvement and can be further developed.

As for the static shading system, the high heating and lighting demands are a sufficient explanation of why static systems like this are not common in Nordic countries.

Overall, it was proven possible to design façades for both indoor and outdoor comfort holistically.

7 Summary

The present study includes visual and thermal implications when approaching façade design, especially static and dynamic shading systems. The chosen location was a well-known street in the City of Copenhagen, Østergarde, during a design summer day. A literature review identified a lack of studies of outdoor thermal comfort and daylight depending parameters of the building design. Since the late 80's buildings have been increasingly designed with high window to wall ratios, therefore creating a need of exploring shading systems. Part of the literature review showed an opening for a new line of research; dynamic shading systems that could influence the immediate outdoor environment.

Five cases were simulated with the aid of the parametric modelling tool Grasshopper for Rhino and the integrated running engines in Ladybug tools. First a test was carried out of how the use of different WWR would affect visually and thermally the street canyon. From there with the highest WWR (0.9) the core of the study began, first testing illuminance, and MRT throughout the 4 floor rooms of the building, the street canyon and the ground floor of the opposite building. Then a typical exterior venetian blind, optimized for both visual and thermal, was introduced to the top three floors of the south facing façade. The evolutionary solver Octopus was used for this purpose of optimizing the blinds to achieve both comfort values of Operative Temperature and Illuminance. Then a dynamic venetian shading system was used (opened and closed as extra states) according to hourly outdoor illuminance and dry bulb temperature. The closed state introduced the idea of setting an outdoor comfort approach when the building was not in use (out of office hours). Finally, this dynamic shading system was developed to adapt; it would rotate throughout the façade, "following" the sun. Further optimization was introduced by setting open-close schedules by floor according to solar altitude.

The results showed that for the outdoor environment not only window to wall area ratio but also shading systems have an effect on street level comfort during warm periods. The adaptive system showed the greatest solar mitigation at street level of the solar radiation. For the indoor environment, comfort levels were improved both for the tested day and for overall annual results. On the other hand, the use of the studied shading systems did not result in sufficiently reduced energy use, since the reduction of cooling demand was smaller than the heating losses from blocking direct sun during heating periods. Overall, the study showed a need of further research on both the effects of dynamic shadings and façade design for not only the indoor environment, but the urban context.

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Appendix I: Building construction and materials

Roof constructions from outmost layers to inmost layers					
	Roughness	**Thickness (m)**	**Conductivity (K/m-K)**	**Density (Kg/m^3)**	**Specific heat (J/kg-K)**
Plywood board	Rough	0.02	0.1	500	1400
Roof insulation	Rough	0.18	0.04	70	1400
Gypsum board	Rough	0.015	0.2	850	850

Roof layers from inside to outside

White wall constructions from outmost layers to inmost layers					
	Roughness	**R-value (m^2-K/W)**	**ThermAbsp**	**SolAbsp**	**VisAbsp**
White oil paint	Smooth	0.0588	0.1	0.27	0.7
	Roughness	**Thickness (m)**	**Conductivity (K/m-K)**	**Density (Kg/m^3)**	**Specific heat (J/kg-K)**
Plywood board	Rough	0.02	0.1	500	1400
Wall insulation	Rough	0.12	0.04	70	1400
Gypsum board	Rough	0.015	0.2	850	850
	Roughness	**R-value (m^2-K/W)**	**ThermAbsp**	**SolAbsp**	**VisAbsp**
Interior oil paint	Smooth	0.125	0.9	0.2	0.7

White colour wall for stage I-IV studies

Black wall constructions from outmost layers to inmost layers					
	Roughness	**R-value (m^2-K/W)**	**ThermAbsp**	**SolAbsp**	**VisAbsp**
Black oil paint	Smooth	0.0588	0.86	0.9	0.7
	Roughness	**Thickness (m)**	**Conductivity (K/m-K)**	**Density (Kg/m^3)**	**Specific heat (J/kg-K)**
Plywood board	Rough	0.02	0.1	500	1400
Wall insulation	Rough	0.12	0.04	70	1400
Gypsum board	Rough	0.015	0.2	850	850
	Roughness	**R-value (m^2-K/W)**	**ThermAbsp**	**SolAbsp**	**VisAbsp**
Interior oil paint	Smooth	0.125	0.9	0.2	0.7

Black colour wall for stage I study

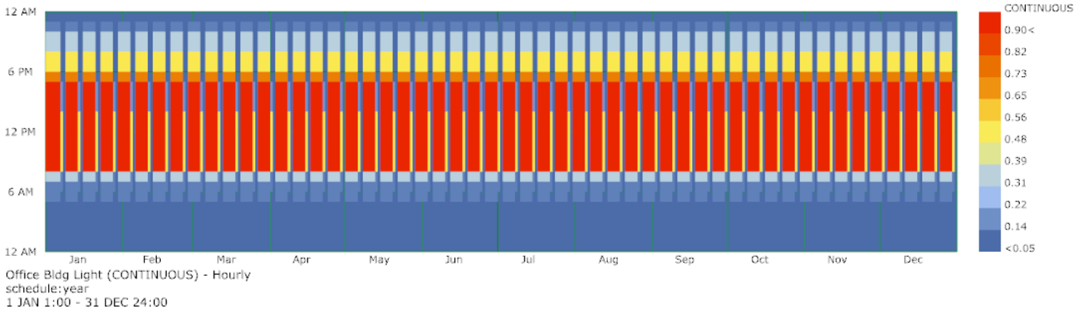
Exterior slab construction from outmost layers to inmost layers					
	Roughness	**Thickness (m)**	**Conductivity (K/m-K)**	**Density (Kg/m^3)**	**Specific heat (J/kg-K)**
Ground insulation	Rough	0.14	0.04	70	1400
Aerated concrete	Rough	0.2	0.14	600	850

Exterior slab construction

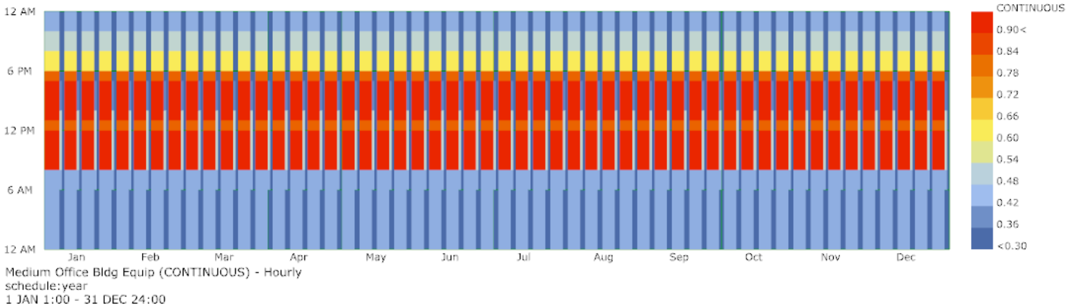
	U-value (W/m^2K)	**SHGC**	**VT**
Fixed window	0.8	0.5	0.64

Appendix II: Energy setting schedule

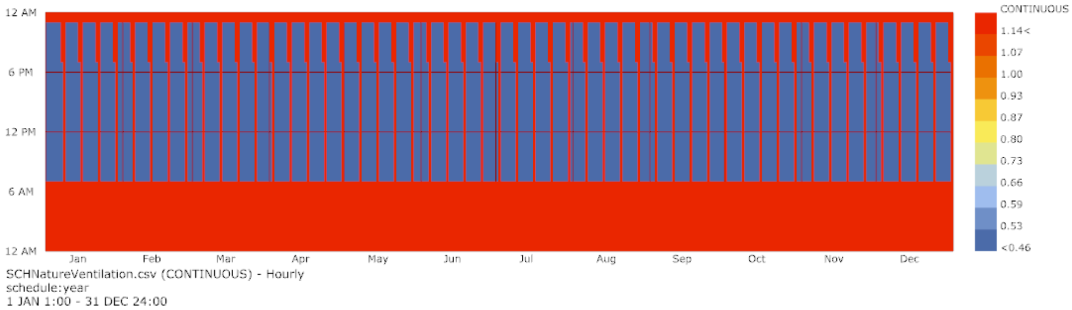
Lighting schedule



Equipment schedule

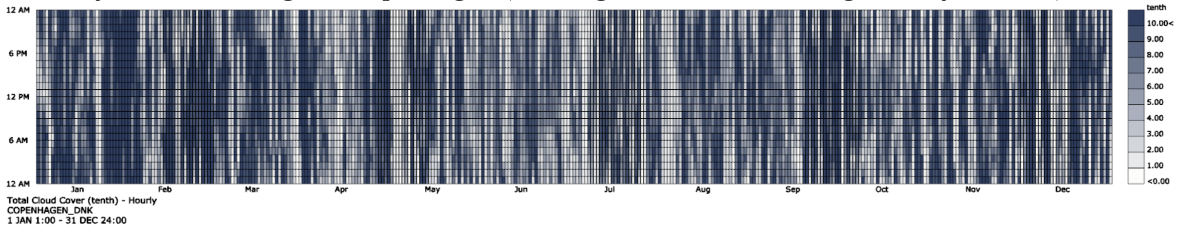


Infiltration and natural ventilation schedule

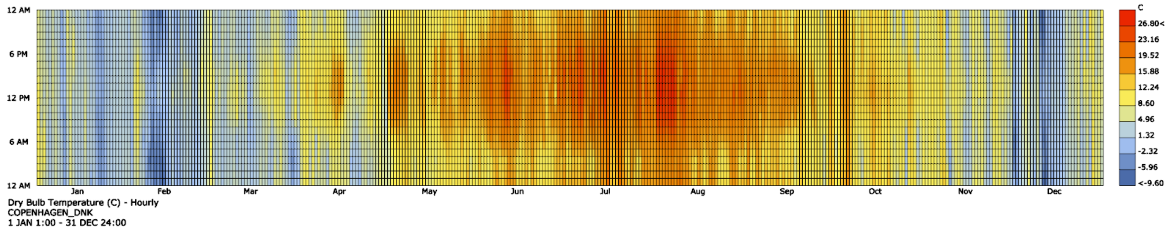


Appendix III: Copenhagen weather analysis

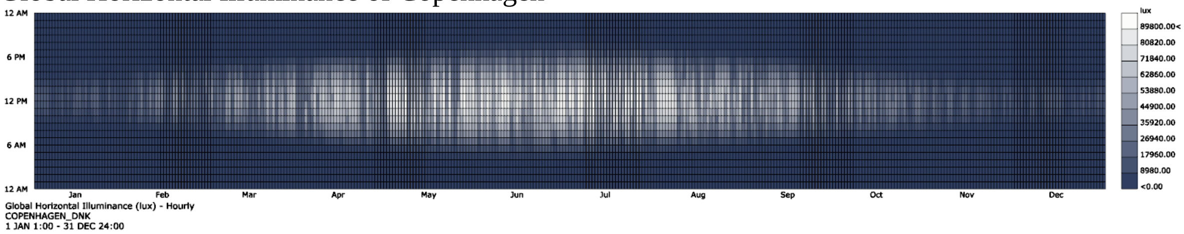
Total Sky Cloud Coverage of Copenhagen (values go from 0 to 10, being 10 fully clouded)



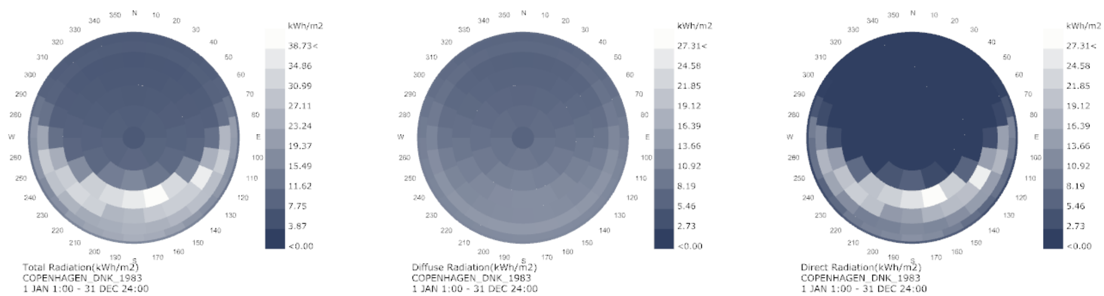
Dry Bulb Temperatures of Copenhagen



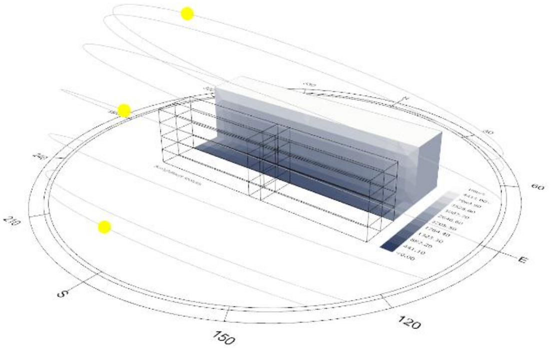
Global Horizontal Illuminance of Copenhagen

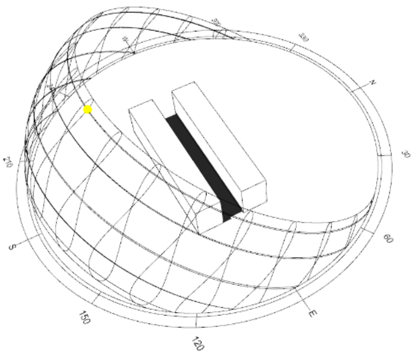


Sky Domes with the radiation patches (Total, Diffuse and Direct radiation from left to right)

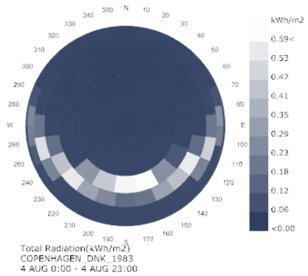


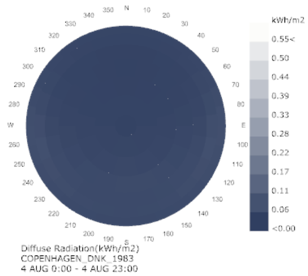
Sun Path and amount of sun hours on the canyon and Building A (left), Sun Altitude (57º) and Shade study at noon for the 4th of August (right)

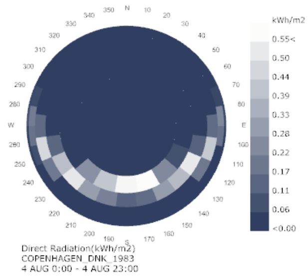




Sky Dome for the 4th of August (Total, Diffuse and Direct radiation from left to right)







Appendix IV: Façade parametric study indoor and outdoor MRT

Test points mean radiant temperature at white façade of different window wall ratios

Test points location	Zones	Test points Numbers	White WWR0.1 °C	White WWR0.2 °C	White WWR0.3 °C	White WWR0.4 °C	White WWR0.5 °C	White WWR0.6 °C	White WWR0.7 °C	White WWR0.8 °C	White WWR0.9 °C
{5.0, 12.5, 1.1}	Zone 0	1	25.881	26.721	27.475	28.348	29.019	29.688	30.316	30.888	31.476
{5.0, 11.5, 1.1}		2	25.88	26.688	27.609	28.335	29.01	29.69	30.325	31.02	31.616
{5.0, 10.5, 1.1}		3	25.874	26.846	27.609	28.457	29.133	29.815	30.605	31.183	31.781
{5.0, 9.5, 1.1}		4	26.037	26.965	27.725	28.604	29.321	30.158	30.79	31.434	32.18
{5.0, 8.5, 1.1}		5	26.163	27.403	28.307	39.26	40.099	41.115	42.082	42.822	43.405
{5.0, 7.5, 1.1}		6	36.651	39.749	40.464	41.146	42.029	42.991	43.589	44.138	45.024
{5.0, 12.5, 5.1}	Zone 1	7	28.262	29.604	30.777	32.009	33.009	33.981	34.889	35.71	36.586
{5.0, 11.5, 5.1}		8	28.308	29.635	30.982	32.079	33.086	34.084	35.007	35.956	36.85
{5.0, 10.5, 5.1}		9	28.313	29.806	31	32.218	33.23	34.232	35.304	36.144	37.042
{5.0, 9.5, 5.1}		10	28.469	29.918	31.108	32.351	33.405	34.558	35.481	36.376	37.412
{5.0, 8.5, 5.1}		11	28.576	30.327	31.644	42.964	44.133	45.454	46.696	47.688	48.564
{5.0, 7.5, 5.1}		12	38.998	42.578	43.682	44.705	45.902	47.148	48.017	48.812	49.97
{5.0, 12.5, 9.1}	zone 2	13	29.007	30.488	31.754	33.055	34.14	35.194	36.167	37.052	37.973
{5.0, 11.5, 9.1}		14	29.068	30.535	31.974	33.144	34.236	35.318	36.308	37.321	38.26
{5.0, 10.5, 9.1}		15	29.074	30.705	31.994	33.284	34.38	35.467	36.604	37.509	38.453
{5.0, 9.5, 9.1}		16	29.227	30.814	32.1	33.411	34.551	35.787	36.777	37.734	38.813
{5.0, 8.5, 9.1}		17	29.329	31.214	32.624	44.014	45.267	46.669	47.974	49.03	49.95
{5.0, 7.5, 9.1}		18	39.726	43.431	44.626	45.715	46.993	48.316	49.247	50.104	51.303
{5.0, 12.5, 13.1}	zone 3	19	28.584	29.999	31.226	32.492	33.532	34.573	35.55	36.439	37.357
{5.0, 11.5, 13.1}		20	28.663	30.067	31.469	32.603	33.652	34.721	35.717	36.736	37.673
{5.0, 10.5, 13.1}		21	28.681	30.252	31.502	32.758	33.813	34.888	36.034	36.945	37.888
{5.0, 9.5, 13.1}		22	28.839	30.366	31.613	32.893	33.991	35.217	36.215	37.181	38.262
{5.0, 8.5, 13.1}		23	28.936	30.764	32.137	43.494	44.705	46.098	47.415	48.478	49.398
{5.0, 7.5, 13.1}		24	39.329	42.982	44.141	45.2	46.438	47.756	48.697	49.561	50.763
{5.0, 6.5, 1.1}	Outdoor	25	30.396	29.409	28.567	28.436	28.389	27.895	27.846	28.128	27.956
{5.0, 5.5, 1.1}		26	30.644	30.4	29.668	29.806	30.142	29.86	29.438	29.868	30.134
{5.0, 4.5, 1.1}		27	30.748	30.799	30.411	29.955	30.77	30.401	30.811	30.72	31.312
{5.0, 3.5, 1.1}		28	30.835	30.769	30.639	30.305	30.996	30.516	30.653	31.257	32.043
{5.0, 2.5, 1.1}		29	30.466	30.592	30.63	30.357	30.402	30.518	30.664	31.227	32.223
{5.0, 1.5, 1.1}		30	30.358	30.364	30.383	30.365	30.649	30.562	30.624	31.242	32.103
{5.0, 0.5, 1.1}		31	30.159	30.209	30.468	30.696	31.115	31.112	31.102	31.188	31.643
{5.0, -0.5, 1.1}		32	29.542	29.843	29.94	30.269	30.731	30.92	31.121	31.185	31.288
{5.0, -1.5, 1.1}		33	29.405	29.935	29.424	29.667	30.111	30.102	30.139	30.653	31.085
{5.0, -2.5, 1.1}		34	29.499	29.75	29.137	29.016	28.987	29.054	29.192	29.383	29.984
{5.0, -3.5, 1.1}	zone 24	35	26.796	28.766	29.401	29.939	30.373	31.089	32.021	32.29	32.829
{5.0, -4.5, 1.1}		36	26.24	27.537	28.349	28.939	29.362	30.075	31.166	31.524	31.91
{5.0, -5.5, 1.1}		37	26.118	27.086	27.732	28.465	28.857	29.571	30.489	30.856	31.419
{5.0, -6.5, 1.1}		38	25.965	26.989	27.649	28.348	28.714	29.27	30.369	30.655	31.058
{5.0, -7.5, 1.1}		39	25.986	26.85	27.69	28.273	28.651	29.215	30.15	30.571	30.982
{5.0, -8.5, 1.1}		40	26.019	26.945	27.639	28.409	28.809	29.396	30.349	30.664	31.093

Test points mean radiant temperature at black façade of different window wall ratios

Test points location	Zones	Test points Numbers	Black WWR0.1 °C	Black WWR0.2 °C	Black WWR0.3 °C	Black WWR0.4 °C	Black WWR0.5 °C	Black WWR0.6 °C	Black WWR0.7 °C	Black WWR0.8 °C	Black WWR0.9 °C
{5.0, 12.5, 1.1}	Zone 0	1	25.979	26.75	27.457	28.284	28.951	29.596	30.222	30.84	31.42
{5.0, 11.5, 1.1}		2	25.981	26.719	27.59	28.273	28.941	29.6	30.232	30.971	31.559
{5.0, 10.5, 1.1}		3	25.98	26.878	27.594	28.396	29.066	29.727	30.509	31.135	31.724
{5.0, 9.5, 1.1}		4	26.153	27.008	27.721	28.549	29.261	30.075	30.705	31.39	32.124
{5.0, 8.5, 1.1}		5	26.29	27.451	28.3	39.209	40.042	41.031	41.991	42.775	43.348
{5.0, 7.5, 1.1}		6	36.797	39.805	40.463	41.095	41.971	42.904	43.498	44.093	44.966
{5.0, 12.5, 5.1}	Zone 1	7	28.422	29.663	30.77	31.941	32.914	33.856	34.77	35.656	36.508
{5.0, 11.5, 5.1}		8	28.472	29.697	30.974	32.012	32.99	33.959	34.889	35.902	36.771
{5.0, 10.5, 5.1}		9	28.482	29.869	30.996	32.152	33.135	34.108	35.183	36.089	36.963
{5.0, 9.5, 5.1}		10	28.648	29.992	31.115	32.291	33.318	34.438	35.369	36.326	37.333
{5.0, 8.5, 5.1}		11	28.765	30.406	31.648	42.907	44.046	45.333	46.577	47.635	48.485
{5.0, 7.5, 5.1}		12	39.205	42.664	43.691	44.647	45.813	47.022	47.898	48.76	49.889
{5.0, 12.5, 9.1}	zone 2	13	29.184	30.549	31.74	32.987	34.039	35.056	36.043	36.991	37.899
{5.0, 11.5, 9.1}		14	29.249	30.599	31.959	33.076	34.134	35.18	36.185	37.259	38.185
{5.0, 10.5, 9.1}		15	29.26	30.77	31.982	33.218	34.279	35.33	36.478	37.446	38.377
{5.0, 9.5, 9.1}		16	29.422	30.889	32.098	33.35	34.457	35.654	36.659	37.675	38.738
{5.0, 8.5, 9.1}		17	29.534	31.294	32.618	43.956	45.173	46.535	47.85	48.968	49.874
{5.0, 7.5, 9.1}		18	39.947	43.517	44.624	45.654	46.896	48.176	49.122	50.044	51.226
{5.0, 12.5, 13.1}	zone 3	19	28.737	30.051	31.216	32.434	33.465	34.471	35.448	36.386	37.289
{5.0, 11.5, 13.1}		20	28.82	30.122	31.457	32.545	33.584	34.619	35.615	36.681	37.603
{5.0, 10.5, 13.1}		21	28.842	30.307	31.494	32.702	33.745	34.787	35.929	36.89	37.817
{5.0, 9.5, 13.1}		22	29.009	30.432	31.616	32.843	33.931	35.12	36.118	37.13	38.192
{5.0, 8.5, 13.1}		23	29.117	30.835	32.136	43.447	44.646	46.001	47.312	48.424	49.328
{5.0, 7.5, 13.1}		24	39.529	43.06	44.145	45.151	46.377	47.653	48.593	49.509	50.691
{5.0, 6.5, 1.1}	outdoor	25	27.93	29.274	28.716	28.659	28.686	28.238	27.926	28.218	27.741
{5.0, 5.5, 1.1}		26	28.33	31.008	30.616	30.868	31.381	31.414	30.215	30.594	30.645
{5.0, 4.5, 1.1}		27	28.53	31.68	31.738	31.264	32.362	32.406	32.502	31.524	31.718
{5.0, 3.5, 1.1}		28	28.69	31.86	32.498	32.219	32.945	32.682	32.29	32.459	32.691
{5.0, 2.5, 1.1}		29	28.57	31.841	32.916	32.649	32.389	32.944	32.743	32.568	33.006
{5.0, 1.5, 1.1}		30	28.55	31.511	32.391	32.764	32.967	32.814	32.378	32.865	32.667
{5.0, 0.5, 1.1}		31	28.29	31.659	32.45	32.715	32.821	32.593	32.278	32.119	32.278
{5.0, -0.5, 1.1}		32	27.71	31	31.466	31.989	31.822	32.043	32.261	32.473	32.061
{5.0, -1.5, 1.1}		33	27.56	31.156	30.598	30.992	31.476	31.64	31.411	32.376	31.919
{5.0, -2.5, 1.1}		34	27.76	31.583	30.904	30.587	30.369	30.792	30.534	30.692	30.675
{5.0, -8.5, 1.1}	zone 24	35	26.431	28.052	28.482	28.863	29.355	30.056	31.09	31.723	32.287
{5.0, -7.5, 1.1}		36	25.891	26.852	27.457	27.892	28.359	29.059	30.244	30.959	31.371
{5.0, -6.5, 1.1}		37	25.774	26.412	26.859	27.424	27.859	28.562	29.575	30.294	30.881
{5.0, -5.5, 1.1}		38	25.628	26.32	26.779	27.315	27.719	28.266	29.456	30.096	30.523
{5.0, -4.5, 1.1}		39	25.653	26.19	26.825	27.247	27.661	28.218	29.246	30.017	30.452
{5.0, -3.5, 1.1}		40	25.694	26.295	26.789	27.393	27.832	28.41	29.459	30.12	30.572

Appendix V: Operative temperature of four shading conditions

Time	Location	Zones	Number	No shading	Steady-state	Dynamic venetian blin	Adaptive façade
				°C	°C	°C	°C
6:00 AM	{5.0, 12.5, 1.1}	Zone 1	1	28.8365	26.2155	26.8155	25.786
	{5.0, 11.5, 1.1}		2	28.867	26.228	26.821	25.786
	{5.0, 10.5, 1.1}		3	28.895	26.247	26.8235	25.792
	{5.0, 9.5, 1.1}		4	28.9335	26.2865	26.8155	25.804
	{5.0, 8.5, 1.1}		5	28.964	26.33	26.801	25.817
	{5.0, 7.5, 1.1}		6	28.994	26.3845	26.746	25.816
	{5.0, 12.5, 5.1}	Zone 2	7	33.484	28.045	28.4485	27.5235
	{5.0, 11.5, 5.1}		8	33.551	28.06	28.4555	27.5225
	{5.0, 10.5, 5.1}		9	33.5845	28.0745	28.4535	27.5235
	{5.0, 9.5, 5.1}		10	33.6145	28.1055	28.437	27.5265
	{5.0, 8.5, 5.1}		11	33.6255	28.1395	28.415	27.5305
	{5.0, 7.5, 5.1}		12	33.591	28.167	28.3355	27.505
	{5.0, 12.5, 9.1}	zone 3	13	35.261	28.131	28.8035	28.208
	{5.0, 11.5, 9.1}		14	35.3435	28.139	28.805	28.205
	{5.0, 10.5, 9.1}		15	35.3795	28.15	28.8015	28.205
	{5.0, 9.5, 9.1}		16	35.405	28.1775	28.7825	28.2045
	{5.0, 8.5, 9.1}		17	35.4075	28.211	28.7575	28.205
	{5.0, 7.5, 9.1}		18	35.344	28.2375	28.676	28.172
	{5.0, 12.5, 13.1}	zone 4	19	34.631	27.6765	29.0605	28.4165
	{5.0, 11.5, 13.1}		20	34.7155	27.6835	29.0715	28.4225
	{5.0, 10.5, 13.1}		21	34.745	27.69	29.066	28.421
	{5.0, 9.5, 13.1}		22	34.7675	27.717	29.047	28.422
	{5.0, 8.5, 13.1}		23	34.7715	27.7535	29.0235	28.4255
	{5.0, 7.5, 13.1}		24	34.6975	27.7785	28.9315	28.3875
7:00 AM	{5.0, 12.5, 1.1}	Zone 1	1	28.667	26.095	26.658	25.78
	{5.0, 11.5, 1.1}		2	28.7205	26.1315	26.6845	25.792
	{5.0, 10.5, 1.1}		3	28.7795	26.182	26.716	25.8195
	{5.0, 9.5, 1.1}		4	28.907	26.311	26.791	25.895
	{5.0, 8.5, 1.1}		5	29.042	26.4585	26.8725	25.983
	{5.0, 7.5, 1.1}		6	29.256	26.697	26.9885	26.117
	{5.0, 12.5, 5.1}	Zone 2	7	33.1815	27.923	28.305	27.5025
	{5.0, 11.5, 5.1}		8	33.2685	27.962	28.333	27.5135
	{5.0, 10.5, 5.1}		9	33.3335	28.0085	28.361	27.5365
	{5.0, 9.5, 5.1}		10	33.452	28.1285	28.4275	27.6025
	{5.0, 8.5, 5.1}		11	33.5675	28.267	28.5005	27.681
	{5.0, 7.5, 5.1}		12	33.719	28.4775	28.591	27.7895
	{5.0, 12.5, 9.1}	zone 3	13	34.9405	28.04	28.684	28.173
	{5.0, 11.5, 9.1}		14	35.043	28.072	28.707	28.1825
	{5.0, 10.5, 9.1}		15	35.1095	28.1155	28.7335	28.204
	{5.0, 9.5, 9.1}		16	35.224	28.2325	28.7965	28.266
	{5.0, 8.5, 9.1}		17	35.3315	28.3695	28.8675	28.3415
	{5.0, 7.5, 9.1}		18	35.4545	28.578	28.9545	28.442
	{5.0, 12.5, 13.1}	zone 4	19	34.251	27.5075	28.793	28.4235
	{5.0, 11.5, 13.1}		20	34.3565	27.54	28.826	28.444
	{5.0, 10.5, 13.1}		21	34.4175	27.5795	28.85	28.466
	{5.0, 9.5, 13.1}		22	34.5305	27.6965	28.914	28.532
	{5.0, 8.5, 13.1}		23	34.64	27.837	28.987	28.6115
	{5.0, 7.5, 13.1}		24	34.755	28.045	29.0655	28.711

8:00 AM	{5.0, 12.5, 1.1}	Zone 1	1	28.6495	26.1345	26.6505	26.005
	{5.0, 11.5, 1.1}		2	28.72	26.188	26.6875	26.017
	{5.0, 10.5, 1.1}		3	28.8065	26.2665	26.738	26.052
	{5.0, 9.5, 1.1}		4	29.014	26.476	26.8705	26.155
	{5.0, 8.5, 1.1}		5	29.243	26.717	27.0205	26.278
	{5.0, 7.5, 1.1}		6	33.551	31.05	30.0685	28.807
	{5.0, 12.5, 5.1}	Zone 2	7	33.0225	27.922	28.2485	27.6265
	{5.0, 11.5, 5.1}		8	33.125	27.9785	28.286	27.636
	{5.0, 10.5, 5.1}		9	33.216	28.0525	28.333	27.6655
	{5.0, 9.5, 5.1}		10	33.4145	28.2525	28.456	27.7555
	{5.0, 8.5, 5.1}		11	33.6245	28.4845	28.5975	27.866
	{5.0, 7.5, 5.1}		12	37.8715	32.7885	31.6185	30.304
	{5.0, 12.5, 9.1}	zone 3	13	34.7655	28.0485	28.6415	28.215
	{5.0, 11.5, 9.1}		14	34.882	28.0985	28.675	28.2245
	{5.0, 10.5, 9.1}		15	34.9745	28.169	28.72	28.2535
	{5.0, 9.5, 9.1}		16	35.169	28.366	28.84	28.3435
	{5.0, 8.5, 9.1}		17	35.371	28.5965	28.979	28.454
	{5.0, 7.5, 9.1}		18	39.5905	32.898	31.996	30.9525
	{5.0, 12.5, 13.1}	zone 4	19	34.0705	27.4585	28.625	28.549
	{5.0, 11.5, 13.1}		20	34.1915	27.51	28.6685	28.5695
	{5.0, 10.5, 13.1}		21	34.2805	27.578	28.7125	28.598
	{5.0, 9.5, 13.1}		22	34.4745	27.7755	28.834	28.684
	{5.0, 8.5, 13.1}		23	34.6795	28.01	28.9755	28.7885
	{5.0, 7.5, 13.1}		24	38.8935	32.312	31.9855	31.14
9:00 AM	{5.0, 12.5, 1.1}	Zone 1	1	28.7755	26.3125	26.7715	26.8725
	{5.0, 11.5, 1.1}		2	28.8315	26.352	26.785	26.866
	{5.0, 10.5, 1.1}		3	28.9075	26.4205	26.8145	26.8705
	{5.0, 9.5, 1.1}		4	29.092	26.608	26.896	26.8845
	{5.0, 8.5, 1.1}		5	29.299	26.828	26.991	26.9015
	{5.0, 7.5, 1.1}		6	35.334	32.891	30.216	29.838
	{5.0, 12.5, 5.1}	Zone 2	7	32.9525	27.98	28.232	28.1905
	{5.0, 11.5, 5.1}		8	33.039	28.022	28.245	28.1835
	{5.0, 10.5, 5.1}		9	33.1185	28.087	28.2695	28.188
	{5.0, 9.5, 5.1}		10	33.294	28.2685	28.3375	28.2085
	{5.0, 8.5, 5.1}		11	33.481	28.4825	28.4185	28.235
	{5.0, 7.5, 5.1}		12	39.455	34.526	31.5195	31.1415
	{5.0, 12.5, 9.1}	zone 3	13	34.6575	28.0935	28.6245	28.6045
	{5.0, 11.5, 9.1}		14	34.757	28.1295	28.639	28.595
	{5.0, 10.5, 9.1}		15	34.838	28.191	28.6675	28.6035
	{5.0, 9.5, 9.1}		16	35.009	28.37	28.7495	28.64
	{5.0, 8.5, 9.1}		17	35.188	28.5835	28.848	28.689
	{5.0, 7.5, 9.1}		18	41.1345	34.625	32.413	31.5855
	{5.0, 12.5, 13.1}	zone 4	19	34.01	27.4845	28.517	28.8755
	{5.0, 11.5, 13.1}		20	34.1165	27.523	28.5335	28.882
	{5.0, 10.5, 13.1}		21	34.196	27.583	28.5495	28.8935
	{5.0, 9.5, 13.1}		22	34.368	27.763	28.6015	28.931
	{5.0, 8.5, 13.1}		23	34.5505	27.9805	28.665	28.9785
	{5.0, 7.5, 13.1}		24	40.494	34.0235	31.3395	31.975

10:00 AM	{5.0, 12.5, 1.1}	Zone 1	1	29.2075	26.9955	27.696	28.0085
	{5.0, 11.5, 1.1}		2	29.2575	27.0285	27.7045	28.0215
	{5.0, 10.5, 1.1}		3	29.3115	27.0785	27.734	28.0395
	{5.0, 9.5, 1.1}		4	29.432	27.2125	27.818	28.082
	{5.0, 8.5, 1.1}		5	35.3625	33.1695	30.813	31.798
	{5.0, 7.5, 1.1}		6	35.8215	33.6905	31.1375	32.011
	{5.0, 12.5, 5.1}	Zone 2	7	32.9315	28.3835	28.5985	28.844
	{5.0, 11.5, 5.1}		8	33.0105	28.4205	28.6065	28.846
	{5.0, 10.5, 5.1}		9	33.0685	28.482	28.6305	28.8735
	{5.0, 9.5, 5.1}		10	33.18	28.661	28.7055	28.9675
	{5.0, 8.5, 5.1}		11	39.093	34.6775	31.7015	32.7885
	{5.0, 7.5, 5.1}		12	39.4955	35.3365	32.001	33.173
	{5.0, 12.5, 9.1}	zone 3	13	34.4875	28.4495	28.886	29.166
	{5.0, 11.5, 9.1}		14	34.58	28.481	28.887	29.164
	{5.0, 10.5, 9.1}		15	34.639	28.5435	28.9065	29.186
	{5.0, 9.5, 9.1}		16	34.747	28.7335	28.974	29.2645
	{5.0, 8.5, 9.1}		17	40.6525	34.7665	31.885	33.005
	{5.0, 7.5, 9.1}		18	41.0295	35.465	32.169	33.3465
	{5.0, 12.5, 13.1}	zone 4	19	33.953	27.886	28.8015	29.477
	{5.0, 11.5, 13.1}		20	34.055	27.921	28.8235	29.493
	{5.0, 10.5, 13.1}		21	34.1165	27.9815	28.845	29.519
	{5.0, 9.5, 13.1}		22	34.227	28.1695	28.909	29.594
	{5.0, 8.5, 13.1}		23	40.1355	34.201	31.959	33.3745
	{5.0, 7.5, 13.1}		24	40.5115	34.89	32.213	33.6855
11:00 AM	{5.0, 12.5, 1.1}	Zone 1	1	30.2835	28.1375	29.0705	29.1635
	{5.0, 11.5, 1.1}		2	30.3515	28.1875	29.0965	29.1965
	{5.0, 10.5, 1.1}		3	30.419	28.2495	29.145	29.2475
	{5.0, 9.5, 1.1}		4	30.5645	28.4055	29.277	29.3905
	{5.0, 8.5, 1.1}		5	36.2815	34.146	32.9785	33.502
	{5.0, 7.5, 1.1}		6	36.8485	34.767	33.4835	34.0455
	{5.0, 12.5, 5.1}	Zone 2	7	33.8625	29.0505	29.1815	29.242
	{5.0, 11.5, 5.1}		8	33.9625	29.09	29.2005	29.247
	{5.0, 10.5, 5.1}		9	34.0305	29.159	29.242	29.288
	{5.0, 9.5, 5.1}		10	34.152	29.36	29.3655	29.429
	{5.0, 8.5, 5.1}		11	39.8305	35.164	33.0705	33.556
	{5.0, 7.5, 5.1}		12	40.2905	35.9375	33.56	34.1265
	{5.0, 12.5, 9.1}	zone 3	13	35.32	28.901	29.2785	29.647
	{5.0, 11.5, 9.1}		14	35.433	28.93	29.2855	29.6495
	{5.0, 10.5, 9.1}		15	35.502	28.9995	29.322	29.688
	{5.0, 9.5, 9.1}		16	35.6195	29.215	29.4415	29.822
	{5.0, 8.5, 9.1}		17	41.291	35.041	33.138	33.934
	{5.0, 7.5, 9.1}		18	41.726	35.8705	33.6265	34.4885
	{5.0, 12.5, 13.1}	zone 4	19	34.8705	28.432	29.4475	30.342
	{5.0, 11.5, 13.1}		20	34.995	28.467	29.497	30.3715
	{5.0, 10.5, 13.1}		21	35.069	28.5365	29.542	30.4195
	{5.0, 9.5, 13.1}		22	35.1915	28.7495	29.657	30.5535
	{5.0, 8.5, 13.1}		23	40.864	34.5715	33.369	34.658
	{5.0, 7.5, 13.1}		24	41.3	35.3875	33.8015	35.182

12:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	31.4055	29.2485	29.782	29.5235
	{5.0, 11.5, 1.1}		2	31.4755	29.299	29.8235	29.5475
	{5.0, 10.5, 1.1}		3	31.5585	29.3735	29.875	29.596
	{5.0, 9.5, 1.1}		4	31.7575	29.577	30.0115	29.742
	{5.0, 8.5, 1.1}		5	37.3695	35.205	34.041	33.903
	{5.0, 7.5, 1.1}		6	38.1785	36.0495	34.6145	34.527
	{5.0, 12.5, 5.1}	Zone 2	7	35.951	29.799	29.6625	29.4075
	{5.0, 11.5, 5.1}		8	36.083	29.83	29.6855	29.4005
	{5.0, 10.5, 5.1}		9	36.1795	29.8955	29.728	29.434
	{5.0, 9.5, 5.1}		10	36.364	30.091	29.853	29.558
	{5.0, 8.5, 5.1}		11	41.9395	35.7175	33.877	33.639
	{5.0, 7.5, 5.1}		12	42.6415	36.561	34.4375	34.2295
	{5.0, 12.5, 9.1}	zone 3	13	37.335	29.271	29.6025	29.832
	{5.0, 11.5, 9.1}		14	37.4785	29.285	29.605	29.8235
	{5.0, 10.5, 9.1}		15	37.5755	29.3435	29.6395	29.856
	{5.0, 9.5, 9.1}		16	37.755	29.5355	29.759	29.98
	{5.0, 8.5, 9.1}		17	43.3225	35.164	33.783	34.1445
	{5.0, 7.5, 9.1}		18	43.9975	36.0155	34.3485	34.7415
	{5.0, 12.5, 13.1}	zone 4	19	36.9605	29.0085	30.3405	31.1145
	{5.0, 11.5, 13.1}		20	37.117	29.0305	30.412	31.1425
	{5.0, 10.5, 13.1}		21	37.222	29.0925	30.468	31.193
	{5.0, 9.5, 13.1}		22	37.407	29.2875	30.596	31.331
	{5.0, 8.5, 13.1}		23	42.974	34.9165	34.61	35.4875
	{5.0, 7.5, 13.1}		24	43.651	35.769	35.13	36.089
1:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	31.8295	29.6055	30.023	29.7225
	{5.0, 11.5, 1.1}		2	31.896	29.6495	30.0815	29.742
	{5.0, 10.5, 1.1}		3	31.9825	29.7245	30.14	29.7895
	{5.0, 9.5, 1.1}		4	32.201	29.9425	30.2855	29.9365
	{5.0, 8.5, 1.1}		5	41.9195	39.672	37.527	37.149
	{5.0, 7.5, 1.1}		6	42.7955	40.5715	38.12	37.786
	{5.0, 12.5, 5.1}	Zone 2	7	38.401	30.36	30.067	29.5895
	{5.0, 11.5, 5.1}		8	38.573	30.3915	30.098	29.579
	{5.0, 10.5, 5.1}		9	38.7015	30.4585	30.144	29.6105
	{5.0, 9.5, 5.1}		10	38.959	30.665	30.2775	29.7335
	{5.0, 8.5, 5.1}		11	48.696	40.3865	37.5335	36.7335
	{5.0, 7.5, 5.1}		12	49.5855	41.2685	38.123	37.3275
	{5.0, 12.5, 9.1}	zone 3	13	39.7915	29.507	29.8505	30.021
	{5.0, 11.5, 9.1}		14	39.9745	29.515	29.851	30.0075
	{5.0, 10.5, 9.1}		15	40.103	29.5705	29.8875	30.038
	{5.0, 9.5, 9.1}		16	40.3555	29.7635	30.0135	30.1625
	{5.0, 8.5, 9.1}		17	50.0835	39.4765	37.244	37.4025
	{5.0, 7.5, 9.1}		18	50.9455	40.3435	37.8425	38.013
	{5.0, 12.5, 13.1}	zone 4	19	39.551	29.487	31.3075	31.9135
	{5.0, 11.5, 13.1}		20	39.7485	29.503	31.401	31.941
	{5.0, 10.5, 13.1}		21	39.8885	29.565	31.4685	31.9935
	{5.0, 9.5, 13.1}		22	40.1465	29.7635	31.61	32.135
	{5.0, 8.5, 13.1}		23	49.8725	39.4795	38.8385	39.354
	{5.0, 7.5, 13.1}		24	50.7375	40.3545	39.3885	39.9715

2:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	32.2595	29.8285	30.4715	30.024
	{5.0, 11.5, 1.1}		2	32.331	29.873	30.546	30.05
	{5.0, 10.5, 1.1}		3	32.4275	29.9555	30.6155	30.101
	{5.0, 9.5, 1.1}		4	32.67	30.195	30.781	30.253
	{5.0, 8.5, 1.1}		5	42.108	39.6445	37.837	37.067
	{5.0, 7.5, 1.1}		6	42.9975	40.5565	38.4365	37.6675
	{5.0, 12.5, 5.1}	Zone 2	7	40.9165	30.9365	30.5815	29.759
	{5.0, 11.5, 5.1}		8	41.1195	30.975	30.623	29.7525
	{5.0, 10.5, 5.1}		9	41.2685	31.0515	30.6775	29.79
	{5.0, 9.5, 5.1}		10	41.5635	31.2815	30.83	29.9295
	{5.0, 8.5, 5.1}		11	51.03	40.7235	37.91	36.72
	{5.0, 7.5, 5.1}		12	51.946	41.617	38.509	37.321
	{5.0, 12.5, 9.1}	zone 3	13	42.341	29.766	30.199	30.2055
	{5.0, 11.5, 9.1}		14	42.5565	29.7765	30.202	30.1945
	{5.0, 10.5, 9.1}		15	42.706	29.8395	30.245	30.23
	{5.0, 9.5, 9.1}		16	42.996	30.0545	30.3875	30.365
	{5.0, 8.5, 9.1}		17	52.454	39.4875	37.3775	37.1805
	{5.0, 7.5, 9.1}		18	53.342	40.3655	37.984	37.776
	{5.0, 12.5, 13.1}	zone 4	19	42.293	29.9815	32.422	32.379
	{5.0, 11.5, 13.1}		20	42.523	29.9985	32.534	32.4065
	{5.0, 10.5, 13.1}		21	42.686	30.0685	32.6135	32.4595
	{5.0, 9.5, 13.1}		22	42.9825	30.2895	32.776	32.6005
	{5.0, 8.5, 13.1}		23	52.4365	39.7235	39.819	39.398
	{5.0, 7.5, 13.1}		24	53.3285	40.611	40.373	39.9675
3:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	32.597	30.094	30.7515	30.6295
	{5.0, 11.5, 1.1}		2	32.6685	30.1365	30.824	30.652
	{5.0, 10.5, 1.1}		3	32.76	30.2125	30.8885	30.6785
	{5.0, 9.5, 1.1}		4	32.98	30.432	31.0405	30.7515
	{5.0, 8.5, 1.1}		5	33.223	30.691	31.207	30.8345
	{5.0, 7.5, 1.1}		6	42.54	40.0385	37.9865	36.8275
	{5.0, 12.5, 5.1}	Zone 2	7	42.198	31.211	30.8395	29.9705
	{5.0, 11.5, 5.1}		8	42.395	31.245	30.877	29.956
	{5.0, 10.5, 5.1}		9	42.523	31.313	30.925	29.9825
	{5.0, 9.5, 5.1}		10	42.7565	31.5215	31.062	30.093
	{5.0, 8.5, 5.1}		11	42.981	31.773	31.2245	30.2375
	{5.0, 7.5, 5.1}		12	52.207	41.1	38.0045	36.4695
	{5.0, 12.5, 9.1}	zone 3	13	43.682	29.9295	30.3665	30.4435
	{5.0, 11.5, 9.1}		14	43.894	29.933	30.3635	30.4235
	{5.0, 10.5, 9.1}		15	44.024	29.9895	30.401	30.4455
	{5.0, 9.5, 9.1}		16	44.253	30.189	30.53	30.544
	{5.0, 8.5, 9.1}		17	44.4695	30.44	30.693	30.6735
	{5.0, 7.5, 9.1}		18	53.668	39.775	37.4915	36.7755
	{5.0, 12.5, 13.1}	zone 4	19	43.914	30.3305	33.026	32.7275
	{5.0, 11.5, 13.1}		20	44.141	30.3395	33.132	32.7405
	{5.0, 10.5, 13.1}		21	44.2865	30.4025	33.206	32.7745
	{5.0, 9.5, 13.1}		22	44.5225	30.6055	33.35	32.8615
	{5.0, 8.5, 13.1}		23	44.7335	30.8535	33.4975	32.9605
	{5.0, 7.5, 13.1}		24	53.936	40.1905	40.219	39.031

4:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	33.3055	30.6695	31.448	30.932
	{5.0, 11.5, 1.1}		2	33.3785	30.7125	31.506	30.9385
	{5.0, 10.5, 1.1}		3	33.453	30.771	31.5595	30.9445
	{5.0, 9.5, 1.1}		4	33.606	30.928	31.6855	30.963
	{5.0, 8.5, 1.1}		5	33.7625	31.108	31.8235	30.9835
	{5.0, 7.5, 1.1}		6	41.456	38.8485	37.065	35.119
	{5.0, 12.5, 5.1}	Zone 2	7	42.357	31.426	31.128	30.179
	{5.0, 11.5, 5.1}		8	42.5315	31.4545	31.155	30.1545
	{5.0, 10.5, 5.1}		9	42.624	31.5115	31.194	30.165
	{5.0, 9.5, 5.1}		10	42.757	31.6875	31.308	30.23
	{5.0, 8.5, 5.1}		11	42.8615	31.901	31.4445	30.322
	{5.0, 7.5, 5.1}		12	50.383	39.7185	36.6915	34.7065
	{5.0, 12.5, 9.1}	zone 3	13	43.917	30.1475	30.596	30.6505
	{5.0, 11.5, 9.1}		14	44.11	30.1465	30.585	30.619
	{5.0, 10.5, 9.1}		15	44.2065	30.1965	30.6145	30.6225
	{5.0, 9.5, 9.1}		16	44.3375	30.379	30.721	30.6675
	{5.0, 8.5, 9.1}		17	44.4345	30.611	30.8575	30.7335
	{5.0, 7.5, 9.1}		18	51.9305	38.483	36.1195	34.8975
	{5.0, 12.5, 13.1}	zone 4	19	44.4525	30.6905	33.482	32.821
	{5.0, 11.5, 13.1}		20	44.6595	30.6925	33.5685	32.8165
	{5.0, 10.5, 13.1}		21	44.771	30.748	33.628	32.8325
	{5.0, 9.5, 13.1}		22	44.9085	30.928	33.74	32.876
	{5.0, 8.5, 13.1}		23	45	31.15	33.852	32.927
	{5.0, 7.5, 13.1}		24	52.501	39.01	39.0465	37.177
5:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	33.69	30.9915	32.222	30.883
	{5.0, 11.5, 1.1}		2	33.7575	31.029	32.2585	30.887
	{5.0, 10.5, 1.1}		3	33.8145	31.0705	32.297	30.913
	{5.0, 9.5, 1.1}		4	33.9135	31.1765	32.3915	31.004
	{5.0, 8.5, 1.1}		5	34.0025	31.2945	32.499	31.117
	{5.0, 7.5, 1.1}		6	34.0585	31.41	32.662	31.29
	{5.0, 12.5, 5.1}	Zone 2	7	41.516	31.434	31.358	30.3325
	{5.0, 11.5, 5.1}		8	41.67	31.4585	31.371	30.3135
	{5.0, 10.5, 5.1}		9	41.7465	31.5095	31.397	30.334
	{5.0, 9.5, 5.1}		10	41.8475	31.671	31.482	30.4305
	{5.0, 8.5, 5.1}		11	41.9155	31.868	31.587	30.5595
	{5.0, 7.5, 5.1}		12	41.881	32.172	31.7455	30.7735
	{5.0, 12.5, 9.1}	zone 3	13	43.169	30.3285	30.824	30.82
	{5.0, 11.5, 9.1}		14	43.3445	30.326	30.803	30.788
	{5.0, 10.5, 9.1}		15	43.4265	30.374	30.821	30.798
	{5.0, 9.5, 9.1}		16	43.5265	30.55	30.8995	30.8635
	{5.0, 8.5, 9.1}		17	43.5885	30.7735	31.0025	30.9565
	{5.0, 7.5, 9.1}		18	43.529	31.1535	31.1775	31.108
	{5.0, 12.5, 13.1}	zone 4	19	43.9605	30.9455	33.623	32.8345
	{5.0, 11.5, 13.1}		20	44.147	30.9435	33.6795	32.823
	{5.0, 10.5, 13.1}		21	44.241	30.9945	33.72	32.8385
	{5.0, 9.5, 13.1}		22	44.3455	31.165	33.7945	32.893
	{5.0, 8.5, 13.1}		23	44.403	31.376	33.8675	32.961
	{5.0, 7.5, 13.1}		24	44.348	31.736	33.945	33.0605

6:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	33.6115	30.9075	32.041	30.4195
	{5.0, 11.5, 1.1}		2	33.6665	30.931	32.0545	30.4155
	{5.0, 10.5, 1.1}		3	33.7315	30.9785	32.072	30.4405
	{5.0, 9.5, 1.1}		4	33.873	31.1225	32.1235	30.5355
	{5.0, 8.5, 1.1}		5	34.0215	31.294	32.1845	30.656
	{5.0, 7.5, 1.1}		6	34.252	31.5685	32.2675	30.851
	{5.0, 12.5, 5.1}	Zone 2	7	40.4895	31.3175	31.3455	30.277
	{5.0, 11.5, 5.1}		8	40.626	31.3305	31.3405	30.256
	{5.0, 10.5, 5.1}		9	40.709	31.3735	31.3485	30.272
	{5.0, 9.5, 5.1}		10	40.847	31.5195	31.3905	30.358
	{5.0, 8.5, 5.1}		11	40.968	31.7	31.4475	30.4745
	{5.0, 7.5, 5.1}		12	41.095	31.9945	31.5225	30.6655
	{5.0, 12.5, 9.1}	zone 3	13	42.218	30.418	30.9445	30.747
	{5.0, 11.5, 9.1}		14	42.378	30.405	30.913	30.718
	{5.0, 10.5, 9.1}		15	42.466	30.4405	30.9185	30.7315
	{5.0, 9.5, 9.1}		16	42.6025	30.5845	30.9645	30.8085
	{5.0, 8.5, 9.1}		17	42.715	30.7715	31.03	30.9145
	{5.0, 7.5, 9.1}		18	42.813	31.092	31.1385	31.091
	{5.0, 12.5, 13.1}	zone 4	19	43.135	31.0655	33.534	32.8315
	{5.0, 11.5, 13.1}		20	43.301	31.051	33.557	32.8235
	{5.0, 10.5, 13.1}		21	43.396	31.0895	33.577	32.8475
	{5.0, 9.5, 13.1}		22	43.5335	31.232	33.616	32.9275
	{5.0, 8.5, 13.1}		23	43.642	31.4125	33.654	33.0275
	{5.0, 7.5, 13.1}		24	43.7395	31.728	33.686	33.188
7:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	33.305	30.5475	31.5775	30.011
	{5.0, 11.5, 1.1}		2	33.335	30.5455	31.5845	29.992
	{5.0, 10.5, 1.1}		3	33.381	30.573	31.601	29.999
	{5.0, 9.5, 1.1}		4	33.481	30.67	31.655	30.0485
	{5.0, 8.5, 1.1}		5	33.5855	30.791	31.719	30.1155
	{5.0, 7.5, 1.1}		6	33.7615	30.995	31.808	30.2175
	{5.0, 12.5, 5.1}	Zone 2	7	39.657	31.125	31.275	30.138
	{5.0, 11.5, 5.1}		8	39.7675	31.1195	31.2665	30.106
	{5.0, 10.5, 5.1}		9	39.832	31.14	31.273	30.1065
	{5.0, 9.5, 5.1}		10	39.9275	31.226	31.3115	30.144
	{5.0, 8.5, 5.1}		11	40.003	31.3375	31.3655	30.203
	{5.0, 7.5, 5.1}		12	40.075	31.5145	31.4325	30.29
	{5.0, 12.5, 9.1}	zone 3	13	41.446	30.3955	30.974	30.6215
	{5.0, 11.5, 9.1}		14	41.5815	30.3655	30.9425	30.5835
	{5.0, 10.5, 9.1}		15	41.6515	30.378	30.9465	30.583
	{5.0, 9.5, 9.1}		16	41.7445	30.459	30.986	30.6165
	{5.0, 8.5, 9.1}		17	41.8115	30.5725	31.043	30.6725
	{5.0, 7.5, 9.1}		18	41.8525	30.764	31.1335	30.7565
	{5.0, 12.5, 13.1}	zone 4	19	42.3715	31.0545	33.418	32.7475
	{5.0, 11.5, 13.1}		20	42.509	31.021	33.4265	32.7285
	{5.0, 10.5, 13.1}		21	42.581	31.036	33.4395	32.736
	{5.0, 9.5, 13.1}		22	42.673	31.1155	33.47	32.773
	{5.0, 8.5, 13.1}		23	42.736	31.224	33.503	32.8225
	{5.0, 7.5, 13.1}		24	42.771	31.413	33.5305	32.891

8:00 PM	{5.0, 12.5, 1.1}	Zone 1	1	32.99	30.1895	31.1845	29.5665
	{5.0, 11.5, 1.1}		2	32.9885	30.1565	31.1675	29.528
	{5.0, 10.5, 1.1}		3	32.9965	30.147	31.157	29.5085
	{5.0, 9.5, 1.1}		4	32.9985	30.1465	31.14	29.485
	{5.0, 8.5, 1.1}		5	32.991	30.155	31.123	29.468
	{5.0, 7.5, 1.1}		6	32.97	30.1625	31.071	29.4205
	{5.0, 12.5, 5.1}	Zone 2	7	39.0465	30.9865	31.209	29.954
	{5.0, 11.5, 5.1}		8	39.124	30.9545	31.1825	29.9075
	{5.0, 10.5, 5.1}		9	39.151	30.9405	31.165	29.8835
	{5.0, 9.5, 5.1}		10	39.1495	30.93	31.1375	29.85
	{5.0, 8.5, 5.1}		11	39.1145	30.9295	31.114	29.8255
	{5.0, 7.5, 5.1}		12	38.996	30.91	31.046	29.763
	{5.0, 12.5, 9.1}	zone 3	13	40.9125	30.2815	30.9795	30.45
	{5.0, 11.5, 9.1}		14	41.0145	30.227	30.9325	30.398
	{5.0, 10.5, 9.1}		15	41.047	30.205	30.911	30.3725
	{5.0, 9.5, 9.1}		16	41.0435	30.1885	30.8795	30.3365
	{5.0, 8.5, 9.1}		17	40.9995	30.1885	30.8545	30.3085
	{5.0, 7.5, 9.1}		18	40.849	30.1775	30.798	30.2425
	{5.0, 12.5, 13.1}	zone 4	19	41.6785	30.9345	33.314	32.428
	{5.0, 11.5, 13.1}		20	41.7805	30.8755	33.3015	32.392
	{5.0, 10.5, 13.1}		21	41.812	30.8535	33.2905	32.372
	{5.0, 9.5, 13.1}		22	41.8035	30.835	33.262	32.336
	{5.0, 8.5, 13.1}		23	41.754	30.8305	33.2285	32.3015
	{5.0, 7.5, 13.1}		24	41.5895	30.8165	33.14	32.217

Appendix VI: Outdoor MRT of four shading conditions

Time	Location	Numbers	No shading	steady-state	Dynamic venetian blind	Adaptive facade
			°C	°C	°C	°C
6:00 AM	{5.0, 6.5, 1.1}	25	18.507	18.256	15.648	15.838
	{5.0, 5.5, 1.1}	26	18.734	18.318	15.484	15.701
	{5.0, 4.5, 1.1}	27	18.903	18.173	15.218	15.371
	{5.0, 3.5, 1.1}	28	19	18.076	15.023	15.18
	{5.0, 2.5, 1.1}	29	18.975	17.885	14.819	15.072
	{5.0, 1.5, 1.1}	30	18.957	17.777	14.691	14.975
	{5.0, 0.5, 1.1}	31	18.921	17.746	14.655	14.95
	{5.0, -0.5, 1.1}	32	18.811	17.705	14.703	15.005
	{5.0, -1.5, 1.1}	33	18.679	17.698	14.796	15.125
	{5.0, -2.5, 1.1}	34	18.475	17.709	15.013	15.296
7:00 AM	{5.0, 6.5, 1.1}	25	19.666	19.408	16.837	17.348
	{5.0, 5.5, 1.1}	26	19.906	19.487	16.689	17.455
	{5.0, 4.5, 1.1}	27	20.092	19.381	16.465	17.412
	{5.0, 3.5, 1.1}	28	20.198	19.306	16.295	17.486
	{5.0, 2.5, 1.1}	29	29.518	28.472	25.446	27.021
	{5.0, 1.5, 1.1}	30	29.515	28.387	25.344	27.198
	{5.0, 0.5, 1.1}	31	29.373	28.247	25.202	27.312
	{5.0, -0.5, 1.1}	32	29.261	28.201	25.25	27.414
	{5.0, -1.5, 1.1}	33	29.144	28.2	25.355	27.556
	{5.0, -2.5, 1.1}	34	28.888	28.148	25.524	27.326
8:00 AM	{5.0, 6.5, 1.1}	25	35.811	35.454	32.969	35.966
	{5.0, 5.5, 1.1}	26	36.203	35.678	32.975	36.549
	{5.0, 4.5, 1.1}	27	36.577	35.81	32.974	36.58
	{5.0, 3.5, 1.1}	28	22.27	21.346	18.411	22.006
	{5.0, 2.5, 1.1}	29	22.617	21.564	18.614	22.013
	{5.0, 1.5, 1.1}	30	22.74	21.627	18.658	21.67
	{5.0, 0.5, 1.1}	31	22.614	21.51	18.539	20.966
	{5.0, -0.5, 1.1}	32	22.49	21.449	18.566	20.584
	{5.0, -1.5, 1.1}	33	22.327	21.403	18.614	20.226
	{5.0, -2.5, 1.1}	34	21.809	21.08	18.484	19.791
9:00 AM	{5.0, 6.5, 1.1}	25	44.616	44.039	41.47	44.576
	{5.0, 5.5, 1.1}	26	45.613	44.596	41.812	45.366
	{5.0, 4.5, 1.1}	27	25.734	24.05	21.209	23.253
	{5.0, 3.5, 1.1}	28	25.944	23.991	21.073	22.456
	{5.0, 2.5, 1.1}	29	25.826	23.773	20.844	21.496
	{5.0, 1.5, 1.1}	30	25.384	23.416	20.474	20.599
	{5.0, 0.5, 1.1}	31	24.355	22.861	19.9	20.048
	{5.0, -0.5, 1.1}	32	23.731	22.505	19.613	19.854
	{5.0, -1.5, 1.1}	33	23.265	22.194	19.377	19.936
	{5.0, -2.5, 1.1}	34	22.627	21.828	19.181	19.977

10:00 AM	{5.0, 6.5, 1.1}	25	27.034	25.974	24.11	23.976
	{5.0, 5.5, 1.1}	26	29.005	26.848	24.43	24.62
	{5.0, 4.5, 1.1}	27	29.199	25.337	22.761	22.733
	{5.0, 3.5, 1.1}	28	29.304	24.743	21.967	22.004
	{5.0, 2.5, 1.1}	29	28.855	24.105	21.284	21.571
	{5.0, 1.5, 1.1}	30	28.09	23.459	20.595	20.975
	{5.0, 0.5, 1.1}	31	26.87	22.994	20.125	20.524
	{5.0, -0.5, 1.1}	32	26.1	22.818	20.003	20.518
	{5.0, -1.5, 1.1}	33	25.502	22.831	20.046	20.726
	{5.0, -2.5, 1.1}	34	24.767	22.824	20.161	20.971
11:00 AM	{5.0, 6.5, 1.1}	25	27.707	26.365	24.268	23.715
	{5.0, 5.5, 1.1}	26	30.047	27.319	24.51	23.921
	{5.0, 4.5, 1.1}	27	30.776	26.227	22.882	22.637
	{5.0, 3.5, 1.1}	28	31.354	25.754	22.179	22.073
	{5.0, 2.5, 1.1}	29	31.505	25.144	21.785	21.865
	{5.0, 1.5, 1.1}	30	31.201	24.577	21.257	21.459
	{5.0, 0.5, 1.1}	31	30.491	24.098	20.817	21.068
	{5.0, -0.5, 1.1}	32	29.916	23.984	20.814	21.117
	{5.0, -1.5, 1.1}	33	29.245	24.07	20.945	21.292
	{5.0, -2.5, 1.1}	34	28.218	24.205	21.235	21.569
12:00 PM	{5.0, 6.5, 1.1}	25	27.953	26.665	23.656	22.975
	{5.0, 5.5, 1.1}	26	30.121	27.477	24.023	23.002
	{5.0, 4.5, 1.1}	27	31.303	27.226	23.258	22.098
	{5.0, 3.5, 1.1}	28	32.033	26.854	22.775	21.657
	{5.0, 2.5, 1.1}	29	32.213	25.946	22.177	21.552
	{5.0, 1.5, 1.1}	30	32.093	25.309	21.642	21.268
	{5.0, 0.5, 1.1}	31	31.633	24.856	21.233	20.966
	{5.0, -0.5, 1.1}	32	31.279	24.696	21.227	21.046
	{5.0, -1.5, 1.1}	33	31.071	24.713	21.349	21.194
	{5.0, -2.5, 1.1}	34	29.981	24.822	21.67	21.467
1:00 PM	{5.0, 6.5, 1.1}	25	27.718	26.256	23.301	23.1
	{5.0, 5.5, 1.1}	26	29.814	27.001	23.732	23.051
	{5.0, 4.5, 1.1}	27	31.225	27.032	23.531	22.297
	{5.0, 3.5, 1.1}	28	32.094	26.788	23.204	21.91
	{5.0, 2.5, 1.1}	29	32.396	26.034	22.561	21.892
	{5.0, 1.5, 1.1}	30	32.317	25.443	22.019	21.664
	{5.0, 0.5, 1.1}	31	31.911	25.009	21.604	21.379
	{5.0, -0.5, 1.1}	32	31.554	24.887	21.605	21.484
	{5.0, -1.5, 1.1}	33	31.228	24.902	21.719	21.616
	{5.0, -2.5, 1.1}	34	30.082	25.061	22.07	21.894
2:00 PM	{5.0, 6.5, 1.1}	25	27.912	26.41	23.513	23.723
	{5.0, 5.5, 1.1}	26	29.963	27.114	23.906	23.709
	{5.0, 4.5, 1.1}	27	31.429	27.203	23.84	22.769
	{5.0, 3.5, 1.1}	28	32.413	27.027	23.569	22.335
	{5.0, 2.5, 1.1}	29	33.003	26.421	23.011	22.317
	{5.0, 1.5, 1.1}	30	32.97	25.861	22.488	22.059
	{5.0, 0.5, 1.1}	31	32.518	25.453	22.074	21.742
	{5.0, -0.5, 1.1}	32	32.129	25.377	22.101	21.856
	{5.0, -1.5, 1.1}	33	31.678	25.408	22.206	22.012
	{5.0, -2.5, 1.1}	34	30.395	25.503	22.575	22.329

3:00 PM	{5.0, 6.5, 1.1}	25	60.167	58.738	56.007	56.51
	{5.0, 5.5, 1.1}	26	62.276	59.454	56.427	56.685
	{5.0, 4.5, 1.1}	27	31.871	27.667	24.533	23.007
	{5.0, 3.5, 1.1}	28	32.895	27.518	24.283	22.42
	{5.0, 2.5, 1.1}	29	33.374	26.742	23.51	22.274
	{5.0, 1.5, 1.1}	30	33.458	26.177	22.972	21.899
	{5.0, 0.5, 1.1}	31	33.178	25.771	22.545	21.569
	{5.0, -0.5, 1.1}	32	32.867	25.654	22.518	21.694
	{5.0, -1.5, 1.1}	33	32.574	25.667	22.6	21.923
	{5.0, -2.5, 1.1}	34	31.271	25.682	22.916	22.307
4:00 PM	{5.0, 6.5, 1.1}	25	55.622	53.966	51.855	53.881
	{5.0, 5.5, 1.1}	26	58.013	54.784	52.183	54.203
	{5.0, 4.5, 1.1}	27	59.613	54.505	51.721	51.433
	{5.0, 3.5, 1.1}	28	33.435	27.056	24.112	23.24
	{5.0, 2.5, 1.1}	29	33.825	26.325	23.382	22.754
	{5.0, 1.5, 1.1}	30	33.94	25.78	22.838	22.077
	{5.0, 0.5, 1.1}	31	33.726	25.377	22.441	21.743
	{5.0, -0.5, 1.1}	32	33.384	25.279	22.426	21.839
	{5.0, -1.5, 1.1}	33	33.063	25.34	22.537	22.096
	{5.0, -2.5, 1.1}	34	31.726	25.451	22.859	22.451
5:00 PM	{5.0, 6.5, 1.1}	25	51.223	49.434	47.891	48.822
	{5.0, 5.5, 1.1}	26	53.754	50.304	48.097	49.426
	{5.0, 4.5, 1.1}	27	54.452	48.549	46.051	47.917
	{5.0, 3.5, 1.1}	28	55.106	47.854	45.112	47.017
	{5.0, 2.5, 1.1}	29	55.334	47.208	44.457	45.942
	{5.0, 1.5, 1.1}	30	55.119	46.54	43.76	44.872
	{5.0, 0.5, 1.1}	31	54.625	46.109	43.346	43.912
	{5.0, -0.5, 1.1}	32	53.954	46.051	43.362	43.558
	{5.0, -1.5, 1.1}	33	52.954	46.189	43.529	43.537
	{5.0, -2.5, 1.1}	34	51.592	46.359	43.874	43.629
6:00 PM	{5.0, 6.5, 1.1}	25	31.036	29.212	27.012	24.76
	{5.0, 5.5, 1.1}	26	33.027	29.999	27.476	25.278
	{5.0, 4.5, 1.1}	27	33.404	28.72	25.998	24.76
	{5.0, 3.5, 1.1}	28	33.557	27.971	25.102	24.593
	{5.0, 2.5, 1.1}	29	46.81	40.756	37.851	38.487
	{5.0, 1.5, 1.1}	30	46.089	39.823	36.89	38.183
	{5.0, 0.5, 1.1}	31	45.344	39.182	36.254	37.79
	{5.0, -0.5, 1.1}	32	44.448	38.843	36	37.546
	{5.0, -1.5, 1.1}	33	43.327	38.793	36.037	37.265
	{5.0, -2.5, 1.1}	34	42.159	38.731	36.181	36.852
7:00 PM	{5.0, 6.5, 1.1}	25	27.89	26.354	23.856	22.11
	{5.0, 5.5, 1.1}	26	29.248	27	24.294	22.23
	{5.0, 4.5, 1.1}	27	29.787	26.727	23.871	21.517
	{5.0, 3.5, 1.1}	28	30.117	26.565	23.597	21.228
	{5.0, 2.5, 1.1}	29	29.913	26.075	23.07	21.064
	{5.0, 1.5, 1.1}	30	29.666	25.69	22.649	20.89
	{5.0, 0.5, 1.1}	31	29.367	25.424	22.359	20.845
	{5.0, -0.5, 1.1}	32	28.768	25.101	22.11	20.853
	{5.0, -1.5, 1.1}	33	27.971	24.791	21.892	20.963
	{5.0, -2.5, 1.1}	34	26.87	24.374	21.67	20.774

8:00 PM	{5.0, 6.5, 1.1}	25	24.642	23.749	21.16	19.807
	{5.0, 5.5, 1.1}	26	25.523	24.109	21.331	19.857
	{5.0, 4.5, 1.1}	27	25.916	23.776	20.842	19.209
	{5.0, 3.5, 1.1}	28	26.179	23.59	20.55	18.916
	{5.0, 2.5, 1.1}	29	26.017	23.106	20.033	18.619
	{5.0, 1.5, 1.1}	30	25.956	22.875	19.769	18.403
	{5.0, 0.5, 1.1}	31	25.975	22.909	19.791	18.38
	{5.0, -0.5, 1.1}	32	25.625	22.758	19.731	18.378
	{5.0, -1.5, 1.1}	33	25.197	22.691	19.766	18.455
	{5.0, -2.5, 1.1}	34	24.338	22.372	19.658	18.465

Appendix VII: Outdoor UTCI of four shading conditions

Time	Location	Numbers	No shading	Steady-state	Dynamic venetian blind	Adaptive façade
			°C	°C	°C	°C
6:00 AM	{5.0, 6.5, 1.1}	25	10.911733	10.836221	10.05176	10.108894
	{5.0, 5.5, 1.1}	26	10.980023	10.854874	10.002448	10.067697
	{5.0, 4.5, 1.1}	27	11.030865	10.811252	9.922472	9.968472
	{5.0, 3.5, 1.1}	28	11.060046	10.78207	9.863848	9.911047
	{5.0, 2.5, 1.1}	29	11.052525	10.72461	9.802525	9.878579
	{5.0, 1.5, 1.1}	30	11.04711	10.69212	9.76405	9.849419
	{5.0, 0.5, 1.1}	31	11.03628	10.682794	9.753229	9.841903
	{5.0, -0.5, 1.1}	32	11.003188	10.67046	9.767657	9.858437
	{5.0, -1.5, 1.1}	33	10.963477	10.668354	9.795611	9.894512
	{5.0, -2.5, 1.1}	34	10.902106	10.671663	9.860842	9.945922
7:00 AM	{5.0, 6.5, 1.1}	25	11.406778	11.330189	10.567083	10.718723
	{5.0, 5.5, 1.1}	26	11.478023	11.353641	10.523168	10.750478
	{5.0, 4.5, 1.1}	27	11.533238	11.322174	10.456707	10.737716
	{5.0, 3.5, 1.1}	28	11.564703	11.29991	10.406272	10.759678
	{5.0, 2.5, 1.1}	29	14.325558	14.016659	13.121343	13.587632
	{5.0, 1.5, 1.1}	30	14.324672	13.991542	13.091127	13.639997
	{5.0, 0.5, 1.1}	31	14.282757	13.95017	13.049057	13.673719
	{5.0, -0.5, 1.1}	32	14.249693	13.936575	13.063278	13.703889
	{5.0, -1.5, 1.1}	33	14.215149	13.936279	13.094386	13.745885
	{5.0, -2.5, 1.1}	34	14.13955	13.92091	13.144449	13.67786
8:00 AM	{5.0, 6.5, 1.1}	25	17.788461	17.687582	16.983743	17.83224
	{5.0, 5.5, 1.1}	26	17.899158	17.750885	16.985446	17.996804
	{5.0, 4.5, 1.1}	27	18.004704	17.788178	16.985162	18.00555
	{5.0, 3.5, 1.1}	28	13.926269	13.66069	12.816176	13.850407
	{5.0, 2.5, 1.1}	29	14.025961	13.723363	12.874623	13.852418
	{5.0, 1.5, 1.1}	30	14.061293	13.741473	12.887291	13.753834
	{5.0, 0.5, 1.1}	31	14.0251	13.707839	12.85303	13.551422
	{5.0, -0.5, 1.1}	32	13.989478	13.690302	12.860804	13.441555
	{5.0, -1.5, 1.1}	33	13.942647	13.677077	12.874623	13.338569
	{5.0, -2.5, 1.1}	34	13.793788	13.584205	12.837195	13.213407
9:00 AM	{5.0, 6.5, 1.1}	25	22.011867	21.854909	21.154102	22.000991
	{5.0, 5.5, 1.1}	26	22.282686	22.006429	21.247583	22.215638
	{5.0, 4.5, 1.1}	27	16.797973	16.326583	15.529802	16.103236
	{5.0, 3.5, 1.1}	28	16.856703	16.310054	15.491618	15.879745
	{5.0, 2.5, 1.1}	29	16.823704	16.248975	15.427317	15.610369
	{5.0, 1.5, 1.1}	30	16.700062	16.148926	15.323404	15.358512
	{5.0, 0.5, 1.1}	31	16.412013	15.99333	15.162154	15.203735
	{5.0, -0.5, 1.1}	32	16.237206	15.893489	15.081509	15.149229
	{5.0, -1.5, 1.1}	33	16.1066	15.806246	15.015186	15.172269
	{5.0, -2.5, 1.1}	34	15.927707	15.703549	14.960099	15.183788

10:00 AM	{5.0, 6.5, 1.1}	25	18.85302	18.5628	18.051964	18.01522
	{5.0, 5.5, 1.1}	26	19.392046	18.80211	18.139702	18.191788
	{5.0, 4.5, 1.1}	27	19.445054	18.388294	17.681936	17.674253
	{5.0, 3.5, 1.1}	28	19.47374	18.225504	17.464035	17.474191
	{5.0, 2.5, 1.1}	29	19.351055	18.050593	17.276541	17.355333
	{5.0, 1.5, 1.1}	30	19.141919	17.873427	17.087355	17.191701
	{5.0, 0.5, 1.1}	31	18.808132	17.745865	16.95828	17.067858
	{5.0, -0.5, 1.1}	32	18.597309	17.697576	16.924772	17.06621
	{5.0, -1.5, 1.1}	33	18.433502	17.701143	16.936583	17.123328
	{5.0, -2.5, 1.1}	34	18.232083	17.699222	16.968167	17.190603
11:00 AM	{5.0, 6.5, 1.1}	25	18.29312	17.931265	17.365586	17.216376
	{5.0, 5.5, 1.1}	26	18.923648	18.188516	17.430878	17.27196
	{5.0, 4.5, 1.1}	27	19.119947	17.894047	16.991601	16.925488
	{5.0, 3.5, 1.1}	28	19.275535	17.76647	16.801897	16.773292
	{5.0, 2.5, 1.1}	29	19.316173	17.601922	16.695575	16.717163
	{5.0, 1.5, 1.1}	30	19.234355	17.448955	16.553094	16.607603
	{5.0, 0.5, 1.1}	31	19.043213	17.319718	16.434363	16.502093
	{5.0, -0.5, 1.1}	32	18.888366	17.288958	16.433553	16.515315
	{5.0, -1.5, 1.1}	33	18.707614	17.312163	16.468902	16.562539
	{5.0, -2.5, 1.1}	34	18.430863	17.348588	16.547157	16.637287
12:00 PM	{5.0, 6.5, 1.1}	25	17.963582	17.6222	16.824772	16.644347
	{5.0, 5.5, 1.1}	26	18.538155	17.83742	16.922016	16.6515
	{5.0, 4.5, 1.1}	27	18.851347	17.770892	16.719323	16.412037
	{5.0, 3.5, 1.1}	28	19.044739	17.672294	16.591365	16.295241
	{5.0, 2.5, 1.1}	29	19.09242	17.431634	16.432961	16.267434
	{5.0, 1.5, 1.1}	30	19.060633	17.262809	16.291268	16.19223
	{5.0, 0.5, 1.1}	31	18.938775	17.142756	16.182962	16.112266
	{5.0, -0.5, 1.1}	32	18.844989	17.100355	16.181373	16.133447
	{5.0, -1.5, 1.1}	33	18.78988	17.10486	16.213678	16.172635
	{5.0, -2.5, 1.1}	34	18.501056	17.133746	16.298684	16.244925
1:00 PM	{5.0, 6.5, 1.1}	25	17.539824	17.157269	16.384645	16.332126
	{5.0, 5.5, 1.1}	26	18.088514	17.35219	16.497277	16.319324
	{5.0, 4.5, 1.1}	27	18.457996	17.360301	16.444747	16.122364
	{5.0, 3.5, 1.1}	28	18.68558	17.296456	16.359299	16.021301
	{5.0, 2.5, 1.1}	29	18.764675	17.099195	16.191317	16.016601
	{5.0, 1.5, 1.1}	30	18.743984	16.944612	16.049764	15.957071
	{5.0, 0.5, 1.1}	31	18.637652	16.831115	15.941407	15.882669
	{5.0, -0.5, 1.1}	32	18.544156	16.799214	15.941668	15.910079
	{5.0, -1.5, 1.1}	33	18.458782	16.803136	15.971431	15.94454
	{5.0, -2.5, 1.1}	34	18.158686	16.844713	16.063082	16.017124
2:00 PM	{5.0, 6.5, 1.1}	25	17.267869	16.879657	16.131914	16.186067
	{5.0, 5.5, 1.1}	26	17.798478	17.061574	16.233265	16.182457
	{5.0, 4.5, 1.1}	27	18.178054	17.084577	16.216242	15.940125
	{5.0, 3.5, 1.1}	28	18.432958	17.039089	16.146354	15.828298
	{5.0, 2.5, 1.1}	29	18.585843	16.882499	16.002496	15.823661
	{5.0, 1.5, 1.1}	30	18.577291	16.737846	15.867716	15.757202
	{5.0, 0.5, 1.1}	31	18.460164	16.632489	15.761065	15.675563
	{5.0, -0.5, 1.1}	32	18.359378	16.612866	15.76802	15.70492
	{5.0, -1.5, 1.1}	33	18.242548	16.62087	15.795066	15.745096
	{5.0, -2.5, 1.1}	34	17.910306	16.645399	15.890133	15.826752

3:00 PM	{5.0, 6.5, 1.1}	25	25.491595	25.119637	24.40962	24.540312
	{5.0, 5.5, 1.1}	26	26.041143	25.305967	24.518744	24.58579
	{5.0, 4.5, 1.1}	27	18.17561	17.098376	16.297733	15.908733
	{5.0, 3.5, 1.1}	28	18.438496	17.060262	16.233965	15.759256
	{5.0, 2.5, 1.1}	29	18.561528	16.861836	16.03689	15.722092
	{5.0, 1.5, 1.1}	30	18.583107	16.717447	15.899818	15.626662
	{5.0, 0.5, 1.1}	31	18.51118	16.613736	15.791079	15.542716
	{5.0, -0.5, 1.1}	32	18.431305	16.583856	15.784205	15.57451
	{5.0, -1.5, 1.1}	33	18.356068	16.587176	15.805083	15.632769
	{5.0, -2.5, 1.1}	34	18.021661	16.591007	15.885554	15.730492
4:00 PM	{5.0, 6.5, 1.1}	25	24.100275	23.670971	23.124444	23.648949
	{5.0, 5.5, 1.1}	26	24.721047	23.882966	23.209308	23.73238
	{5.0, 4.5, 1.1}	27	25.137086	23.810646	23.089779	23.015286
	{5.0, 3.5, 1.1}	28	18.388961	16.764774	16.018688	15.798172
	{5.0, 2.5, 1.1}	29	18.488564	16.579297	15.834067	15.675368
	{5.0, 1.5, 1.1}	30	18.51794	16.441108	15.696588	15.50442
	{5.0, 0.5, 1.1}	31	18.463277	16.338977	15.596315	15.420134
	{5.0, -0.5, 1.1}	32	18.375939	16.314148	15.592528	15.444356
	{5.0, -1.5, 1.1}	33	18.293986	16.329602	15.620558	15.509215
	{5.0, -2.5, 1.1}	34	17.952888	16.357727	15.701894	15.598841
5:00 PM	{5.0, 6.5, 1.1}	25	23.011517	22.543627	22.140114	22.383577
	{5.0, 5.5, 1.1}	26	23.673574	22.771157	22.193983	22.541535
	{5.0, 4.5, 1.1}	27	23.856184	22.312185	21.658973	22.146913
	{5.0, 3.5, 1.1}	28	24.027296	22.130438	21.413451	21.911567
	{5.0, 2.5, 1.1}	29	24.086953	21.961511	21.242194	21.630472
	{5.0, 1.5, 1.1}	30	24.030697	21.786837	21.059962	21.3507
	{5.0, 0.5, 1.1}	31	23.901446	21.674139	20.951725	21.099702
	{5.0, -0.5, 1.1}	32	23.725896	21.658973	20.955908	21.00715
	{5.0, -1.5, 1.1}	33	23.464295	21.695057	20.999569	21.00166
	{5.0, -2.5, 1.1}	34	23.108031	21.739509	21.089767	21.025713
6:00 PM	{5.0, 6.5, 1.1}	25	18.059891	17.568771	16.976144	16.36936
	{5.0, 5.5, 1.1}	26	18.595647	17.780704	17.101152	16.508935
	{5.0, 4.5, 1.1}	27	18.697047	17.436259	16.702938	16.36936
	{5.0, 3.5, 1.1}	28	18.738194	17.234503	16.461512	16.324361
	{5.0, 2.5, 1.1}	29	22.288769	20.67058	19.891757	20.062386
	{5.0, 1.5, 1.1}	30	22.096416	20.4206	19.633816	19.980835
	{5.0, 0.5, 1.1}	31	21.897555	20.248769	19.463031	19.875388
	{5.0, -0.5, 1.1}	32	21.658246	20.157867	19.394809	19.809907
	{5.0, -1.5, 1.1}	33	21.358628	20.144458	19.404747	19.734486
	{5.0, -2.5, 1.1}	34	21.046199	20.12783	19.443425	19.623613
7:00 PM	{5.0, 6.5, 1.1}	25	18.178666	17.749493	17.050323	16.560889
	{5.0, 5.5, 1.1}	26	18.557569	17.930066	17.173013	16.594544
	{5.0, 4.5, 1.1}	27	18.707808	17.853768	17.054525	16.394546
	{5.0, 3.5, 1.1}	28	18.799748	17.808484	16.977756	16.313459
	{5.0, 2.5, 1.1}	29	18.742916	17.671473	16.830061	16.267439
	{5.0, 1.5, 1.1}	30	18.674089	17.563781	16.712037	16.218609
	{5.0, 0.5, 1.1}	31	18.590746	17.489356	16.630721	16.20598
	{5.0, -0.5, 1.1}	32	18.423702	17.39896	16.560889	16.208225
	{5.0, -1.5, 1.1}	33	18.201281	17.312181	16.499744	16.239096
	{5.0, -2.5, 1.1}	34	17.893736	17.195417	16.437469	16.186054

8:00 PM	{5.0, 6.5, 1.1}	25	17.543852	17.285269	16.533916	16.140385
	{5.0, 5.5, 1.1}	26	17.798645	17.389551	16.583612	16.154937
	{5.0, 4.5, 1.1}	27	17.912198	17.293092	16.441473	15.966283
	{5.0, 3.5, 1.1}	28	17.988151	17.239196	16.35656	15.880943
	{5.0, 2.5, 1.1}	29	17.94137	17.098887	16.206156	15.794416
	{5.0, 1.5, 1.1}	30	17.923751	17.031892	16.129324	15.731474
	{5.0, 0.5, 1.1}	31	17.929239	17.041754	16.135728	15.724771
	{5.0, -0.5, 1.1}	32	17.828123	16.997951	16.118264	15.724188
	{5.0, -1.5, 1.1}	33	17.7044	16.978513	16.128451	15.746628
	{5.0, -2.5, 1.1}	34	17.455859	16.885943	16.097014	15.749542

Appendix VIII: North facing room T_o at four shading conditions

Time	Location	Number	No shading	Steady-state	Dynamic venetian blind	Adaptive façade
			°C	°C	°C	°C
6:00 AM	{5.0, -8.5, 1.1}	35	29.186	28.4125	28.598	28.1095
	{5.0, -7.5, 1.1}	36	28.7755	27.992	28.479	27.89
	{5.0, -6.5, 1.1}	37	28.748	27.961	28.507	27.8985
	{5.0, -5.5, 1.1}	38	28.737	27.9495	28.5515	27.917
	{5.0, -4.5, 1.1}	39	28.744	27.9585	28.587	27.934
	{5.0, -3.5, 1.1}	40	28.7895	28.0115	28.6735	27.9845
7:00 AM	{5.0, -8.5, 1.1}	35	29.0825	28.3495	28.677	28.3475
	{5.0, -7.5, 1.1}	36	28.879	28.136	28.592	28.2825
	{5.0, -6.5, 1.1}	37	28.753	28.007	28.537	28.2385
	{5.0, -5.5, 1.1}	38	28.655	27.9085	28.5075	28.2105
	{5.0, -4.5, 1.1}	39	28.6295	27.884	28.515	28.21
	{5.0, -3.5, 1.1}	40	28.6465	27.908	28.575	28.2475
8:00 AM	{5.0, -8.5, 1.1}	35	29.589	28.8965	28.848	29.1375
	{5.0, -7.5, 1.1}	36	29.208	28.5065	28.7335	28.8805
	{5.0, -6.5, 1.1}	37	28.984	28.279	28.6635	28.7305
	{5.0, -5.5, 1.1}	38	28.8005	28.095	28.621	28.613
	{5.0, -4.5, 1.1}	39	28.743	28.039	28.6215	28.5815
	{5.0, -3.5, 1.1}	40	28.735	28.0375	28.677	28.5985
9:00 AM	{5.0, -8.5, 1.1}	35	29.589	28.9325	29.1865	29.478
	{5.0, -7.5, 1.1}	36	29.225	28.5595	28.968	29.2305
	{5.0, -6.5, 1.1}	37	29.0135	28.3455	28.8405	29.0895
	{5.0, -5.5, 1.1}	38	28.844	28.1755	28.7495	28.983
	{5.0, -4.5, 1.1}	39	28.7935	28.126	28.734	28.9585
	{5.0, -3.5, 1.1}	40	28.796	28.1345	28.779	28.988
10:00 AM	{5.0, -8.5, 1.1}	35	29.9945	29.3935	29.5485	29.984
	{5.0, -7.5, 1.1}	36	29.577	28.968	29.288	29.698
	{5.0, -6.5, 1.1}	37	29.3405	28.7285	29.1405	29.5385
	{5.0, -5.5, 1.1}	38	29.1515	28.539	29.035	29.4215
	{5.0, -4.5, 1.1}	39	29.0975	28.487	29.016	29.398
	{5.0, -3.5, 1.1}	40	29.105	28.5005	29.065	29.4395
11:00 AM	{5.0, -8.5, 1.1}	35	30.834	29.9425	30.0195	30.4875
	{5.0, -7.5, 1.1}	36	30.3405	29.456	29.7105	30.164
	{5.0, -6.5, 1.1}	37	30.0675	29.1865	29.54	29.988
	{5.0, -5.5, 1.1}	38	29.8535	28.9775	29.4175	29.8655
	{5.0, -4.5, 1.1}	39	29.7945	28.923	29.398	29.8495
	{5.0, -3.5, 1.1}	40	29.812	28.949	29.4545	29.917
12:00 PM	{5.0, -8.5, 1.1}	35	31.8285	30.192	30.2725	30.7205
	{5.0, -7.5, 1.1}	36	31.3695	29.7555	29.996	30.439
	{5.0, -6.5, 1.1}	37	31.124	29.519	29.848	30.2905
	{5.0, -5.5, 1.1}	38	30.9435	29.349	29.7535	30.2045
	{5.0, -4.5, 1.1}	39	30.906	29.3185	29.752	30.215
	{5.0, -3.5, 1.1}	40	30.9615	29.3855	29.8415	30.3315

1:00 PM	{5.0, -8.5, 1.1}	35	32.7375	30.568	30.5965	31.2265
	{5.0, -7.5, 1.1}	36	32.2805	30.1265	30.316	30.9405
	{5.0, -6.5, 1.1}	37	32.0375	29.892	30.1695	30.794
	{5.0, -5.5, 1.1}	38	31.8715	29.737	30.089	30.7235
	{5.0, -4.5, 1.1}	39	31.852	29.7265	30.105	30.7525
	{5.0, -3.5, 1.1}	40	31.946	29.8385	30.235	30.914
2:00 PM	{5.0, -8.5, 1.1}	35	33.954	31.3625	31.1915	31.63
	{5.0, -7.5, 1.1}	36	33.4575	30.8645	30.873	31.308
	{5.0, -6.5, 1.1}	37	33.193	30.6035	30.709	31.145
	{5.0, -5.5, 1.1}	38	33.019	30.4395	30.628	31.071
	{5.0, -4.5, 1.1}	39	33.007	30.4385	30.6575	31.11
	{5.0, -3.5, 1.1}	40	33.1285	30.59	30.83	31.3035
3:00 PM	{5.0, -8.5, 1.1}	35	34.637	31.867	31.435	31.91
	{5.0, -7.5, 1.1}	36	34.176	31.4045	31.1365	31.61
	{5.0, -6.5, 1.1}	37	33.933	31.165	30.989	31.4615
	{5.0, -5.5, 1.1}	38	33.7855	31.03	30.9335	31.404
	{5.0, -4.5, 1.1}	39	33.793	31.051	30.9855	31.4545
	{5.0, -3.5, 1.1}	40	33.948	31.241	31.2025	31.668
4:00 PM	{5.0, -8.5, 1.1}	35	34.798	32.0795	31.7455	32.1485
	{5.0, -7.5, 1.1}	36	34.3785	31.6485	31.4645	31.866
	{5.0, -6.5, 1.1}	37	34.157	31.4275	31.3285	31.7265
	{5.0, -5.5, 1.1}	38	34.0355	31.3135	31.29	31.6755
	{5.0, -4.5, 1.1}	39	34.0595	31.348	31.355	31.727
	{5.0, -3.5, 1.1}	40	34.2405	31.5585	31.5965	31.9375
5:00 PM	{5.0, -8.5, 1.1}	35	34.352	32.2575	32.026	32.3055
	{5.0, -7.5, 1.1}	36	33.9495	31.8275	31.7465	32.0295
	{5.0, -6.5, 1.1}	37	33.7345	31.606	31.611	31.89
	{5.0, -5.5, 1.1}	38	33.618	31.4915	31.573	31.8335
	{5.0, -4.5, 1.1}	39	33.644	31.5245	31.638	31.8765
	{5.0, -3.5, 1.1}	40	33.8255	31.733	31.8795	32.066
6:00 PM	{5.0, -8.5, 1.1}	35	33.7995	32.079	31.999	32.13
	{5.0, -7.5, 1.1}	36	33.4775	31.731	31.781	31.9615
	{5.0, -6.5, 1.1}	37	33.307	31.5535	31.6775	31.8795
	{5.0, -5.5, 1.1}	38	33.222	31.4705	31.6625	31.864
	{5.0, -4.5, 1.1}	39	33.2535	31.5095	31.7315	31.9145
	{5.0, -3.5, 1.1}	40	33.427	31.7085	31.9645	32.0925
7:00 PM	{5.0, -8.5, 1.1}	35	34.4875	32.9785	32.377	32.6305
	{5.0, -7.5, 1.1}	36	33.017	31.483	31.603	31.781
	{5.0, -6.5, 1.1}	37	32.9205	31.38	31.579	31.754
	{5.0, -5.5, 1.1}	38	32.891	31.3525	31.6265	31.7775
	{5.0, -4.5, 1.1}	39	32.9355	31.4035	31.712	31.835
	{5.0, -3.5, 1.1}	40	33.102	31.5945	31.9435	32
8:00 PM	{5.0, -8.5, 1.1}	35	32.4405	31.0615	31.4145	31.157
	{5.0, -7.5, 1.1}	36	32.476	31.0745	31.459	31.2085
	{5.0, -6.5, 1.1}	37	32.5	31.0925	31.4985	31.2425
	{5.0, -5.5, 1.1}	38	32.5675	31.1605	31.593	31.3135
	{5.0, -4.5, 1.1}	39	32.6395	31.239	31.6885	31.382
	{5.0, -3.5, 1.1}	40	32.8105	31.432	31.9125	31.541

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