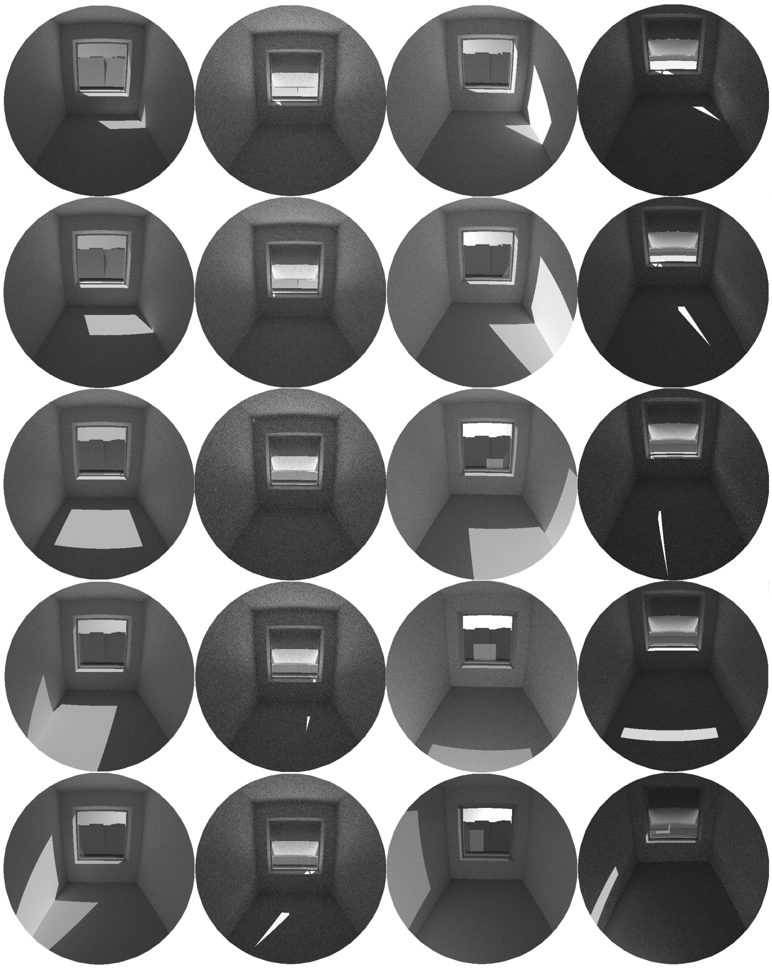

Energy renovation and healthy indoor environment in green buildings

Impact of dynamic shading and demand controlled ventilation on occupant health and comfort

Master's thesis in Master's Program Structural engineering and building technology

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Department of Architecture and Civil Engineering

CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS

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Cover:
Diurnal variation of luminance distribution in rooms
with and without shading at equinox and midsummer.
Images extracted from AcceleradRT software.

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Abstract

A number of measures exist that can help to reduce the energy use of existing buildings, such as demand controlled ventilation and dynamic shading. However, when they are implemented they can also have an on impact the comfort and health of the building's occupants. Discomfort in the domains of thermal comfort, visual comfort and air quality can cause health issues ranging from mild to severe and can significantly impact the performance of office workers with resulting economical losses for employers. Increased awareness of occupant comfort in the design and operation of office buildings can have both health-related and economical benefits.

A case study was carried out for a newly renovated office building where occupants have reported some amount of thermal and visual discomfort. A possible explanation for the discomfort was found in imbalances in the implementation and operation of the demand controlled ventilation and dynamic shading systems. The case study building, which has been awarded a Miljöbyggnad Silver certification, was studied in detail and it was found that thermal discomfort was likely to arise due to the intricate interplay between heat added by the sun and the occupants and heat taken away by the ventilation air flow. Since occupants are also a source of air pollution, ventilation and shading needs to be carefully balanced to ensure that thermal and visual comfort and acceptable air quality are maintained under all circumstances. The geometry of the shading device and the colour of the shading fabric can also be configured to further improve visual comfort and thermal performance.

In general it was found that occupant comfort can be improved by detailed and holistic study of the building, how it behaves and how conditions vary in both space and time. The more time and effort is spent on identifying issues and customizing the building, the better the outcome for occupant comfort. However, increased customization means increased complexity and cost, making it more difficult to successfully implement the intended design. If significant causes of occupant discomfort are identified more clearly and methods are developed to address them in a streamlined and efficient way, it is more likely that the health, comfort and well-being of occupants will be put into focus when designing office buildings.

Keywords: Demand controlled ventilation, dynamic shading, indoor environmental quality, thermal comfort, visual comfort, air quality, energy efficiency, building renovation, health

Contents

1 Introduction

1.1 Background

Reducing emissions of greenhouse gases is of crucial importance for global sustainability. The building sector accounts for 17% of CO_2 emissions and 32% of energy use in Sweden (Boverket, 2020; Boverket, 2021). 30% of emissions from the sector are due to heating while 50% are due to construction. Conversely, 74% of energy use is for heating while only 17% is for construction. The discrepancy is due to the high proportion of renewable energy used for heating, at 64%. Even though a large proportion of the energy used in buildings in Sweden already comes from renewable and non-fossil sources, there is still a potential for reduction of emissions through increased energy efficiency.

In 2020, the European Union launched what it calls a "Renovation wave" or "The European Green Deal", a program which aims to renovate 35 million buildings within the union by 2030 (European Commission, 2020). 85% to 95% of buildings currently existing in the union are expected to still be standing in 2050, which presents an opportunity for large reductions of emissions and energy use by careful and focused renovation.

An important aspect which is closely related to the energy consumption of a building is the comfort and health of its occupants. Air quality, thermal comfort, daylight and lighting have a significant impact on the physical and mental well-being, as well as the productivity, of human beings. This is especially true in spaces where people spend large amounts of time, such as an office. The World Green Building Council (2014) claims that staff costs account for 90% of the operating costs of a typical business and that employers lose billions annually due to absent employees and poor working performances due to medical issues.

When designing buildings for energy efficiency, care needs to be taken to consider the interplay between different measures and parameters and how they impact the indoor environmental quality (IEQ) and the resulting comfort and health of the building's occupants. Large efforts are currently being made to address energy inefficiency in buildings by the means of certification schemes such as LEED, BREEAM and Miljöbyggnad. Many of these schemes include occupant health and comfort parameters but studies show that these aspects are often overlooked or that the results are not necessarily superior to buildings that have not been designed according to the certification schemes (Borgstein et al., 2018; Geng et al. 2018; Lee, 2019).

1.2 Aim and Objectives

The aim of the project is to study energy renovation strategies for office buildings and their influence (positive and negative) on indoor environment comfort and health, as well as to examine the performance of green buildings with regards to energy efficiency, indoor comfort and health. Solutions for some selected aspects such as solar shading, heating and ventilation systems will be analyzed and their influence on energy consumption, indoor comfort and health will be quantified and compared through simulations. Ultimately, recommendations for energy-efficient and healthy office building development will be made.

1.3 Method

A literature review will be conducted to identify common energy renovation strategies and technologies and their influence on the indoor environment. The associated parameters and indicators that are relevant to energy efficiency, indoor environment and human health will be identified and the impact from the renovation technologies will be assessed. With a focus on solar shading and demand controlled ventilation, a case study office building will be analyzed and different scenarios will be defined to investigate how these technologies affect energy efficiency and indoor environment. Ultimately, the findings from the literature will be synthesised with the findings from simulations and recommendations will be made on how to achieve healthy indoor environments and energy efficiency in renovated buildings.

The research questions being investigated in the literature review are the following:

- What technologies are used in renovation of office buildings?
- How do these technologies influence energy efficiency and a healthy indoor environment?
- What are the issues associated with these technologies in green buildings?
- What are the associated parameters, indicators and strategies (e.g., methods of ventilation, shading)?
- What is Miljöbyggnad and what aspects/domains and parameters does it consider regarding energy, indoor environmental quality and occupant comfort and health?

1.4 Scope and limitations

The thesis is focused on office buildings. For the case study, the main energy renovation strategies considered will be solar shading and ventilation.

1.5 Outline of thesis

The thesis consists of two main parts. The first part is the literature study, presented in chapters 2 to 4, and the second part is the case study which is presented in chapters 5 and 6. The findings are then analyzed and discussed in chapter 7 and finally the conclusions are presented in chapter 8.

2 Indoor environmental quality

Indoor environmental quality (IEQ) is a term that encompasses all factors that impact the health and comfort of humans in the built environment. Lee (2019) indicates that three of the most commonly used metrics are **thermal comfort**, **visual comfort** and **air quality**. Visual comfort refers both to provision of sufficient daylight and protection from uncomfortable visual phenomena such as glare. CIBSE (2006) emphazises that there will always be a certain amount of dissatisfaction with the indoor environment due to subjective individual preferences and perceptions. The aim should not be to eliminate dissatisfaction but to minimize it.

Indoor environmental quality has a significant impact on the physical and mental well-being, as well as the productivity, of human beings. This is especially true in spaces where people spend large amounts of time, such as an office. The World Green Building Council (2014) claims that staff costs account for 90% of the operating costs of a typical business and that employers lose billions annually due to absent employees and poor working performances due to medical issues. They suggest three categories of metrics for measuring and quantifying the impact of IEQ on health, wellbeing and productivity. They are financial, perceptual and physical metrics. Financial metrics include absenteeism, staff turnover and medical costs and complaints. Perceptual metrics can be, for example, surveys where occupants report their perceived health and productivity. Physical metrics refers to direct measurements of parameters such as temperature, humidity or particle concentration.

2.1 Thermal comfort

2.1.1 Definitions and calculation methods

ASHRAE (2010) defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment". The human body strives to maintain an internal temperature of approximately 37°C (Parsons, 2014). There are several physiological mechanisms in the human body that allow regulation of heat production and heat transfer to the surroundings, like shivering and sweating. The regulation can also be seen in the behaviour of the skin. When it is cold, the blood vessels in the skin contract to keep blood away from the surface of the body, in order to reduce heat transfer. This gives the skin a pale appearance. Conversely, blood vessels can dilate in warmer conditions to increase heat transfer, causing a reddening of the skin.

Apart from physiological mechanisms, human behaviour is also an important aspect of thermoregulation. We move both instinctively and consciously to escape uncomfortable thermal conditions. If movement away from the source of discomfort is not possible, a change of clothing or the use of heating, cooling or shading can help increase our comfort. The human body is also capable of significant acclimatisation to the surrounding conditions.

Parsons (2014) defines the heat balance of the body as follows. Energy is brought into the body through food which is metabolized (M), enabling the body to perform work (W). The remaining energy (M - W) is released as heat. The mechanisms of heat transfer are conduction (K), convection (C), radiation (R) and evaporation (E). If more heat is gained than lost, it will be stored (S) and the internal temperature will increase, and vice versa. The heat balance of the body can then be described by an equation where heat gains are set equal to heat losses:

$$M - W = E + R + C + K + S$$

If the body temperature is maintained at 37°C, storage (S) is 0, yielding

$$M - W - E - R - C - K = 0$$

In order to quantify thermal comfort, it is neither possible nor adequate to strive for the maintainance of a specific heat balance for every person. Since every person is different, there needs to be a statistical measure of the thermal comfort of a group of people (Parsons, 2014). The thermal comfort of each individual ranges between two extremes: too hot and too cold. In between lies a scale where the optimal condition is thermal neutrality, feeling neither too cold nor too warm. This scale does not include thermal pleasure, such as the sensation of entering a warm building on a cold day, since this is a temporary sensation and the scale is meant to apply to steady-state conditions. The scale of thermal sensation is commonly divided in seven levels, ranging from -3 to 3. By asking each member of a group to rate their thermal sensation on this scale, an average rating is aquired which can be used as a measure of thermal comfort.

−3	−2	−1	0	1	2	3
Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

An important milestone in the study of thermal comfort was the book Thermal Comfort by Fanger (1970). Fanger's version of the heat balance is

$$H - E_d - E_{sw} - E_{re} - L = K = R + C$$

where

H is the internal heat production in the human body

E_d is the heat loss by water diffusion through skin

E_{sw} is the heat loss by evaporation of sweat from skin surface

E_{re} is the latent respiration heat loss

L is the dry respiration heat loss

K is the heat transfer from skin to outer surface of clothing

R is the heat transfer by radiation from clothing surface

C is the heat transfer by convection from clothing surface

Fanger provided ways of expressing the terms of the heat balance equation using the basic parameters of air temperature (t_a), mean radiant temperature ($\bar{t}_r$), relative humidity (RH), air velocity (v), clothing factor (clo) and metabolic rate (Met). He then related this heat balance to the thermal sensation scale, rendering an equation which can be used to determine the **predicted mean vote** (PMV) of a group of humans rating their thermal sensation. This equation has also been adapted in the ISO standard 7730:2005. The equation is

$$PMV = [0.303 \cdot exp(-0.036 \cdot M) + 0.038] \cdot \left\{ \begin{array}{c} (M-W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M-W) - p_a] - 0.42 \cdot [(M-W) - 58.15] \\ -1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) \\ -3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{array} \right\}$$

$$t_{cl} = 35.7 - 0.028 \cdot (M-W) - I_{cl} \cdot \left\{ 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \right\}$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for} \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{for} \quad 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} & \text{for} \quad I_{cl} \leq 0.078 m^2 \cdot \text{K/W} \\ 1.05 + 0.645 \cdot I_{cl} & \text{for} \quad I_{cl} > 0.078 m^2 \cdot \text{K/W} \end{cases}$$

where

M is the metabolic rate [W/m^2]

W is the effective mechanical power [W/m^2]

I_{cl} is the clothing insulation [$m^2 \cdot K/W$]

f_{cl} is clothing surface area factor
t_a is the air temperature [°C]
$\bar{t}_r$ is the mean radiant temperature [°C]
v_{ar} is the relative air velocity [m/s]
p_a is the water vapour partial pressure [Pa]
h_c is the convective heat transfer coefficient [W/m^2·K]
t_{cl} is clothing surface temperature [°C]

The clothing insulation I_{cl} can be measured in m^2·K/W or in clo with 1 clo = 0.155 m^2·K/W (ASHRAE, 2017). A value of clo = 1 corresponds approximately to typical winter indoor clothing while clo = 0.5 corresponds to summer clothing.

The **mean radiant temperature** $\bar{t}_r$ is a way of simplifying radiative heat exchange calculations (ASHRAE, 2017). All surfaces that have a view of each other exchange energy through radiation. If all surfaces in view of a point had the same temperature, the mean radiant temperature would be the temperature that caused the same amount of radiative heat exchange as in the real case. **Operative temperature** t_0 is the average of the mean radiant temperature $\bar{t}_r$ and the air temperature t_a, weighted by their respective heat exchange coefficients. For normal office working conditions, the operative temperature can be simplified to the following equation (ASHRAE, 2010):

$$t_0 = \frac{t_a + \bar{t}_r}{2}$$

If PMV is known, the **predicted percentage dissatisfied** (PPD) can be calculated by

$$\text{PPD} = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2)$$

The relationship between PMV and PPD is shown in figure 1.

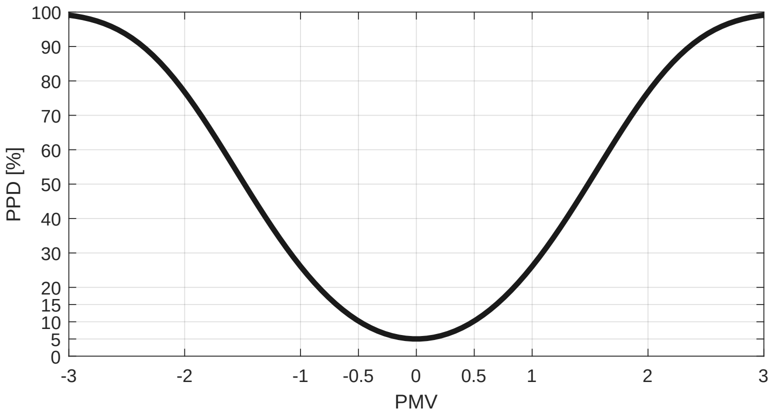


Figure 1: Relation between PMV and PPD

ASHRAE standard 55 (ASHRAE, 2010) defines a range of acceptable PMV values between -0.5 and 0.5, corresponding to PPD values of less than 10%. For a given set of conditions this corresponds to a specific range of operative temperatures, as shown in figure 2.

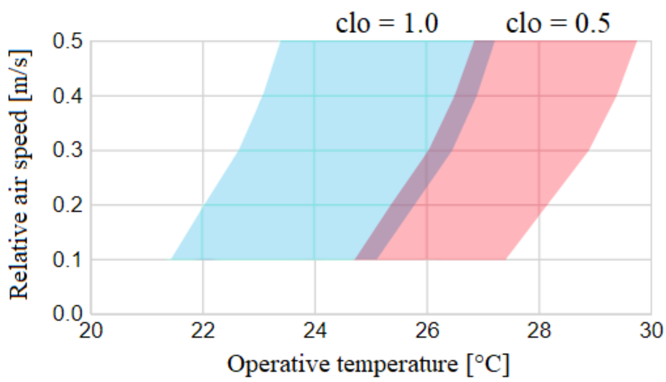


Figure 2: Range of acceptable operative temperatures (-0.5 < PMV < 0.5) for different clothing levels (blue = 1.0, red = 0.5, purple = overlapping) and air speeds. RH = 50%, metabolic rate = 1 met. Image adapted from CBE Thermal Comfort Tool (Tartarini et al., 2020)

2.1.2 Health aspects

The human body has a range of responses to thermal stress and discomfort (Parsons, 2014). In cases of severe hypo- or hyperthermia, thermal stress can pose a significant danger to an individual's health but for everyday conditions in an office, the more likely outcomes are fatigue, discomfort and loss of performance.

REHVA (2010) refers to studies that show reduced performance due to both too high and too low temperatures in offices, with a suggested optimal range of 20°C to 24°C. They also report loss of dexterity in hands and increased sensitivity to draughts at low temperatures.

2.2 Indoor air quality

2.2.1 Definitions and calculation methods

Fanger (2006) defines Indoor air quality (IAQ) as the extent to which human requirements are met. He writes that humans have a desire for fresh, pleasant air which does not negatively impact their health or productivity. The quality of the air is decreased by the presence of substances which may be harmful on their own or in conjunction with others.

The Public Health Agency of Sweden recommends air flow rates to ensure sufficient provision of fresh air and removal of pollution (FoHMFS 2014:18). The recommendation in non-residential buildings is 7 l/s per occupant. In addition to this, 0.35 l/s per m^2 of floor area is recommended to account for pollution from other sources than humans. If carbon dioxide concentration regularly exceeds 1000 ppm during normal use, ventilation is generally considered insufficient.

The concentration of particles of a certain substance within an enclosed space can be modelled using a box model, as shown in figure 3. In this example the substance considered is carbon dioxide, which is generated through human respiration. It is assumed that the room air is well mixed, i.e. that the concentration (C) is uniform. It is also assumed that the concentration in the outside air (C_{ext}) is constant, that the rate of generation by occupants (m) is known and that there are no sinks in the room. The volume of the room is V_r and the air flow through the room is $\dot{V}$.

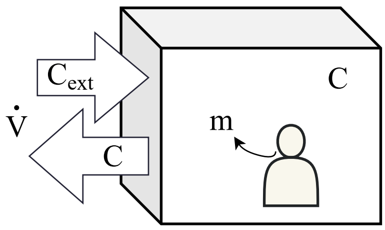


Figure 3: Box model for concentration of CO_2.

Using the box model, the rate of change of concentration in the room can be mathematically described by a differential equation, as for example in Franco & Schito (2020). The equation is

$$V_\mathrm{r} \cdot \frac{C(t)}{dt} = \dot{V} \cdot (C_\mathrm{ext} - C(t)) + \mathrm{m}$$

where

C(t) is the concentration in the room at time t [g/m^3]

C_{ext} is the concentration in the outside air [g/m^3]

V_r is the volume of the room [m^3]

$\dot{V}$ is the volume rate of air flow through the room [m^3/s]

m is the rate of generation in the room [g/s]

The solution to this equation is

$$C(t) = C(0) \cdot \exp\left(-\frac{\dot{V}}{V_{\mathrm{r}}}t\right) + \left(C_{\mathrm{ext}} + \frac{m}{\dot{V}}\right) \cdot \left(1 - \exp\left(-\frac{\dot{V}}{V_{\mathrm{r}}}t\right)\right)$$

Once the system has stabilized at steady state, the concentration can be determined by

$$C = C_{\mathrm{ext}} + \frac{m}{\dot{V}}$$

The steady state concentration thus depends on both the rate of generation inside the room and the airflow through it. If the rate of generation is known, the airflow rate can be varied to achieve a desired concentration. The requisite airflow is then

$$\dot{V} = \frac{m}{C_{\mathrm{ext}} - C}$$

The generation rate of CO_2 in human respiration varies depending on body size and level of physical activity (Li et al., 2011). The generation rate per person [l/s] can be expressed as

$$m_{CO_2} = \frac{0.00276 \cdot A_D \cdot M}{(0.23 \cdot RQ + 0.77)} \cdot RQ$$

where
RQ is the respiratory quotient [-]
M is the level of physical activity [W/m^2]
A_D is the DuBois surface area [m^2]

The respiratory quotient RQ is the ratio between the production of CO_2 to the consumption of oxygen in the body. For a person of height H [m] and body mass W [kg], the DuBois surface area can be calculated by

$$A_D = 0.203 \cdot H^{0.725} \cdot W^{0.425}$$

2.2.2 Health aspects

The quality of the air we breath has a significant impact on the well-being, comfort and health of human beings (Fanger, 2006). Air is polluted by airborne contaminants. Quantifying their harmful impact is difficult due to the large variety of substances and the lack of knowledge regarding their impact on humans. Threshold values for what levels of concentration are detectable by human smell or what levels cause irritation are available for many chemicals but these values are averaged across the population and do not account for those with the highest sensitivity. Adhering to these threshold values may therefore create conditions that the majority of people find acceptable but which cause discomfort and illness to the most sensitive part of the population. If the goal is to minimize dissatisfaction, a strictly quantifiable approach can only go so far.

Indeed, Fanger (2006) claims that standards and guidelines are written with the knowledge that the most sensitive 15-30% of people will not find the IAQ acceptable.

Airborne contaminants can enter a building either through the air brought from outside or from sources present inside (World Green Building Council, 2014). Due to the large number of pollutants that can be found in air, not all of them can be measured and monitored (González-Martín et al., 2021). It is therefore necessary to identify single pollutants that can serve as representatives for whole categories of pollutants. Sofuoglu & Moschandreas (2003) have developed an index for characterising the indoor air quality of office buildings through measurement of a number of key indicator pollutants, chosen by a committee of experts. The pollutants can be categorized as either gases or particles. The gases can be categorized as either organic (formaldehyde and VOC) or inorganic (carbon oxide, carbon dioxide and radon) while the particles measured are biological particles such as fungi and bacteria as well as the total particulate matter in the categories PM_{10} and $PM_{2.5}$.

Carbon dioxide (CO_2) can severely impact and harm the human body at extreme concentrations but normal indoor concentrations do not have lasting health impacts (Satish et al., 2012). Many temporary health issues such as headaches, irritation of mucous membranes, tiredness and reduced performance are commonly attributed to excessive CO_2 concentration since the occurrence of symptoms seems to correlate with the magnitude of the concentration. However, it is now widely believed that these effects are actually caused by other pollutants which have concentrations that correlate with the concentration of CO_2. Regardless of the impact of CO_2 itself, it serves as a useful indicator of air quality because of this correlation and due the ease of measuring it.

VOC stands for Volatile Organic Compounds and refers to gases emitted from carbon-based materials (Environmental Protection Agency, 2021). The word volatile refers to the high tendency of the materials to transfer to the gas phase at relatively low temperatures, due to their high vapour pressure. One defintion of VOCs is that they have vapour pressure higher than 10 Pa at 25°C and a boiling point of lower than 260°C (Koppmann, 2007). VOCs are emitted when fossile fuels are burned but also from many products used in buildings such as paint, glue, solvents, pesticides, cleaners and wood preservatives (Environmental Protection Agency, 2021). Many building materials and furnitures emit VOCs. The levels of emissions are greatest when a product is new and will decline with time. Symptoms of exposure to VOCs include irritation of skin and mucous membranes, tiredness and shortness of breath, headaches and fatigue as well as allergic skin reactions. Some VOCs can damage the liver, kidneys and the central nervous system. Some, like benzene, are known to be carcinogenic while others, like methylene chloride, are suspected to be.

Particulate matter is commonly categorized according to particle size (González-Martín et al., 2021). PM_{10} and $PM_{2.5}$ means that the particles have a mean diameter size of less than 10 μm and 2.5 μm, respectively. Particles that are small enough can enter the human respiratory system and deposit there (ASHRAE, 2017). PM_{10} particles can enter the respiratory airways while PM_4 particles can enter the parts of the lungs where gas is exchanged. $PM_{2.5}$ particles are considered the most harmful to public health and also the dominant pollutant in residences.

Immediate effects of exposure to $PM_{2.5}$ are shortness of breath, irritation of eyes and lungs, nausea, light-headedness and allergies. In the longer run, asthma and other respiratory issues can occur.

Bioaerosols are airborne biological particles such as fungi or mould, bacteria, viruses, mites and plants, as well as their by-products (ASHRAE, 2017). If temperature and moisture conditions are suitable and there is a food source, these particles can proliferate in a building and pose a threat to its occupants. Viruses and bacteria can be released from humans and transmitted to others.

Odour is another aspect of IAQ which pertains to many pollutants. Many substances are perceived as malodorous by humans and foul-smelling air is often assumed to be unhealthy (ASHRAE, 2017). Regardless of whether or not the air is actually toxic, humans are sensitive to perception of bad odours.

2.3 Light and visual comfort

Humans depend on light for health, comfort and productivity. The European standard EN 12464-1:2011 describes important parameters that influence the visual comfort of indoor spaces. They are illuminance, glare, flicker and luminance distribution, as well as directionality, variability and colour rendering of light. REHVA (2010) also emphasizes the importance of having visual contact with the outside world.

2.3.1 Definitions and calculation methods

The solar radiation that reaches the earth surface has wavelengths in the electromagnetic spectrum between 280 and 2500 nm (BBSA, 2015). The radiation carries energy as heat throughout the spectrum while visible radiation, or light, only occupies a small part of the spectrum. IESNA (2000) defines light as "radiant energy that is capable of exciting the human retina and creating a visual sensation". Physically, this means radiation with wavelengths between 380 nm and 780 nm. According to Roos (1994), 50 % of the heat radiation in sunlight sits within the visible spectrum. Another 40% of heat radiation is within the invisible short wave infrared spectrum between 780 nm and 2500 nm, while the remaining 10% comes from UV light below 380 nm. Between 2500 nm and 10000 nm is the longwave infrared spectrum. Heat in this spectrum is emitted by thermal vibration of objects.

The amount of visible light emitted by a light source per unit of time is measured in the unit lumen [lm] (IESNA, 2000). The amount of light from the light source that falls on a particular surface is referred to as **illuminance** and measured in lm/m^2 or [lux]. European standard EN 12464-1:2011 recommends levels of illumination for various task, areas and activities. For typical office work, a minimum illumination of 500 lux is recommended. If a sphere around the light source is imagined, each steradian of the sphere receives an amount of light which can be measured in lumens per steradian, or candela [cd]. Candela is therefore a measure of how much light is emitted by the light source in a particular direction. **Luminance**, measured in [cd/m^2], denotes how much light is emitted from a surface.

Daylight refers to light that comes from the sun rather than from electric or other sources. Indoor illumination requirements can be fulfilled with electric lighting but it is generally desirable to utilize available daylight as much as possible, especially since it is free. There are many ways of quantifying the availability of daylight. A common measure of daylight levels is the **daylight factor** (DF). It relates the illuminance level inside the room to the illuminance outside, as a percentage (Mandalaki & Tsoutsos, 2020). This can be described as

$$\mathrm{DF} = \frac{\text{Illumination outside}}{\text{Illumination inside}} \quad [\%]$$

Since the light levels outside vary significantly, an overcast sky is used. If the illuminance outside is 10000 lux, an indoor illuminance of 100 lux would correspond to a daylight factor of 1%. This is also the recommended lowest level in the Swedish building code (BFS 2011:6).

Glare is described in the european standard EN 12464-1:2011 as a sensation produced by parts of the field of view being overly bright. IESNA (2000) describes two types of glare: disability glare and discomfort glare. Disability glare impairs visual performance, while discomfort glare causes annoyance or pain without affecting visual performance. If discomfort glare is minimized, disability glare is unlikely to be an issue. Two causes of glare are described. The first is simply too much light entering the eye, causing the viewer to reflectively avert their gaze from the light source. Examples of this are direct sunlight or reflection in specular surfaces such as glass or metal, referred to as reflected glare or veiling reflections. A reflection of the sun in a metallic part of a window frame can cause uncomfortable glare at a workplace situated by a window.

The other cause of glare is an overly large range of luminance within the field of view, causing difficulty in making out details in dimmer areas due to contrast being too high. For example, REHVA (2010) recommends that when performing a visual task such as reading from a paper on a desk, the luminance of the desk should not have more than 3 times the luminance of the paper and the desk's surroundings not more than 10 times.

One way of quantifying glare is by calculating the **daylight glare probability** (DGP) [%] as defined in EN 17037:2018. This method considers how much light reaches the eyes as well as the geometry and luminance of objects in view. The equation is

$$DGP = 5.87 \cdot 10^{-5} \cdot E_V + 9.18 \cdot 10^{-2} \cdot \log\left(1 + \sum_i \frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_v^{1.87} \cdot P_i^2}\right) + 0.16$$

where
E_V is illuminance at eye level [lx]
L_S is the luminance of the glare source [cd/m^2]
P is a position index [-]
ω_s is the solid angle subtended by the glare source [sr]
i is the number of glare sources

2.3.2 Health aspects

Humans prefer daylight to electric light (REHVA, 2010). For example, studies have shown that humans strongly prefer working and sitting close to windows, although the reasons are unclear (Aries et al., 2013). Having a view to the outside provides the brain with dynamic stimuli due to the constantly changing nature of light in the outdoor environment. Electric light sources usually have relatively narrow distributions of wavelengths, concentrated around one or a few peaks (Boubekri, 2008). Daylight, on the other hand, has a more even distribution across the spectrum. In conjunction with the dynamic nature of daylight, this means that far more visual variety can be offered than is possible with conventional artificial light sources.

Light plays a large role in human physiology (Mandalaki & Tsoutsos, 2020). Light of varying intensities and wavelengths helps to activate and regulate various processes in the human body. One important example is the production of the sleep hormone melatonin, which is regulated by the variation of light exposure throughout the day. The human body has evolved to follow the natural variations of sunlight but modern humans spend a majority of their time indoors (Boubekri, 2014). A lack of light of sufficient quality can cause problems with circadian rhythms and sleeping as well as vitamin D deficiency and depression. Seasonal Affective Disorder (SAD) is a type of depression which is caused by an imbalance between melatonin and the hormone serotonin which causes alertness. Since these hormones are regulated by light exposure, their daily cycle of production can be disrupted by a lack of light.

By designing buildings so that ample amounts of daylight is provided to occupants, their bodies can better follow the natural cycles of light. The symptoms of SAD have been shown to decrease when sufferers spend more time outside and receive more daylight (Boubekri, 2014). Artificial bright lights can also improve the symptoms at levels of 2500 lux or more, compared to a common indoor illumination of approximately 500 lux. Achieving such high illumination levels through artificial lighting requires significant electrical energy, while windows can easily provide such levels through daylight.

REHVA (2010) has reviewed academic studies on the influence of daylight on the productivity and health of workers and students. They report several findings of productivity increases of 4% to 25% and decrease of 15% to 25% in absenteeism and health complaints. The World Green Building Council (2014) reports that office workers with access to windows slept an average of 46 minutes longer per night and that inadequate daylight and view quality in one case corresponded to a 6.5% increase in sick leave. Boubekri (2014) refers to studies that show shorter hospital stays and lower mortality for patients staying in sunny hospital rooms with views, particularly of nature.

Another important role of light in the human body is as a trigger for production of Vitamin D. Vitamin D deficiency can cause a number of health issues and is a significant cause of illness globally (Boubekri, 2008). Vitamin D is produced in the skin when it is exposed to UV-B radiation. However, glass filters out 95% of UV-B radiation which means that exposure to sunlight through windows is not sufficient to stimulate adequate Vitamin D production.

3 Renovation measures

There is a growing awareness about the impacts and benefits of renovating existing buildings rather than building new ones. For example, the European Union in 2020 launched what it calls a "Renovation wave" or "The European Green Deal", a program which aims to renovate 35 million buildings within the union by 2030 (European Commission, 2020). 85% to 95% of the current building stock in the union is expected to still be standing in 2050, which presents an opportunity for large reductions of emissions and energy use by careful and focused renovation.

The 2010 EU directive on the energy performance of buildings (European Parliament, 2021) lays down minimum requirements for calculation of building energy performance within the union. The directive includes a list of which aspects of a building need to be accounted for in these calculations. This list gives an idea of which aspects of a building impact it's energy use and where potential energy savings can be found. The items on the list can be approximately grouped into the categories thermal characteristics, installations, physical conditions, lighting and intended design.

Thermal characteristics include thermal capacity, insulation, air tightness, thermal bridges, passive heating and cooling elements. Installations include HVAC, district heating and cooling as well as heating or electricity generated on-site. Physical conditions are the position and orientation of the building as well as the prevailing outdoor climate, for example the outdoor temperature and solar exposure profiles. Lighting refers to the provision of both natural and artificial light in the building and the use of solar protection or passive solar systems. Intended design is the intended indoor climate and the internal loads of the building.

Felis (2020) defines three general ways of improving the energy-efficiency of a building. They are, in preferred order of implementation: reducing energy demand, reducing energy consumption, and finally monitoring and controlling energy use. Energy demand can be reduced by improving the thermal characteristics of the envelope. Energy consumption can be reduced by increasing the efficiency and automation of HVAC systems. The energy use can then be monitored and controlled through automated control systems, commissioning and through user interaction.

From an energy use perspective, the focus of this thesis is on reducing energy consumption through automation and control of ventilation systems and solar shading. The thermal properties of windows and the physical conditions of the building will be taken into account and the energy use will be weighed against daylight demands and the optimal utilization of shading technologies.

3.1 Solar shading

Implementing solar shading as part of a renovation of a building is not necessarily significantly more complicated than for a new building. Solar shading devices are often small and can easily be installed in connection to windows. Once a building has been constructed, however, it is not possible to alter many of it's basic physical features and characteristics and so renovation measures have to work with the existing limitations. Designing a building from scratch for optimal provision of daylight and visual comfort will likely give superior results than trying to achieve these goals in an existing buildings with added measures.

The purpose of solar shading is to prevent electromagnetic radiation, in the form of heat and light, from entering through the windows of a building. Bellia et al. (2014) categorizes shading devices as positioned either internally, externally or intermediately between windows. ISO 15099:2003 defines two different categories of shading devices: ones that are parallel to the window pane, like screens or blinds, and ones that stand out significantly from the window, like awnings and overhangs. Shading devices can be either fixed or dynamic and dynamic shading can be either manual or automatic. REHVA (2010) states that since the amount of available daylight varies enormously both daily and annually, dynamic shading is the only way to manage the competing demands on light and energy while avoiding glare and maintaining visual comfort.

3.1.1 Parameters and indicators

EN 14500:2008 describes the possible transmission paths that light can take through a shading device. Incident light can be either normal to the device surface or fall at some angle. The transmitted light can pass through in the same direction or it can be diffused. For light which is not diffused, the term hemispherical transmittance is used, since the light can fall on a hemisphere centered at the point of incidence. The transmitted radiation is referred to as τ_v for light in the visual spectrum and τ_e or τ_s for heat radiation. The transmittance angles are referred to as n for normal incidence, dir for directional, h for hemispherical and dif for diffuse.

The amount of radiation that enters through a window depends on many factors. The location and orientation of the building, the size and shading of the window, the position of the sun as well as the amount of cloud cover all determine how much radiation hits the surface of a window. The portion of this radiation that is then transmitted through the window is again τ_v and τ_e. Some heat radiation will be absorbed in the glass and then emitted as long wave infrared radiation into the room. This is referred to as q_i. The total amount of heat energy that enters the room is referred to as g-value and is the sum of the directly transmitted radiation and the secondary emitted radiation desribed by

$$g = \tau_e + q_i.$$

Bülow-Hübe et al. (2003) defines a g-value for the system of window and shading device combined, which is

$$g_{system} = g_{shading} \cdot g_{window}$$

The amount of radiation that is transmitted through a window is highly dependent on the angle of incidence (Karlsson, 2001). As the sun hits the window more and more from the side, the reflectance increases while the transmittance decreases. At very small angles the transmittance decreases dramatically. Relative transmittance values for angles smaller than 20° are shown in table 1.

Table 1: Approximate transmittance of windows for light incident at various angles from facade, adapted from Karlsson (2001)

Angle from facade	90°	20°	10°	5°
Relative transmittance	± 0	-30%	-65%	-80%

As the radiation goes through the window and enters a room, it will affect the indoor environment in a number of ways. The heat radiation will raise both the air temperature and the temperatures of surfaces. The warm surfaces will then also heat the air and depending on the thermal balance of the building, the room might need to be cooled. Conversely, if heating is needed, the solar heat can be utilized to offset heating demands. Heating the surfaces in the room will increase the mean radiant temperature, which will impact the thermal comfort, measured through PMV or PPD. The surface of the window may get especially warm and any direct sunlight on a person will likely cause significant thermal discomfort.

Radiation in the visible spectrum will propagate through the room and illuminate surfaces. IESNA (2000) describes how daylight can reach a certain point inside the room in three ways: directly from the sun, reflected from external objects or reflected from internal objects. The geometry of the room and the reflective and absorptive properties of the surfaces will determine how the light is spread and what illumination levels [lux] are reached throughout the space. Each surface will have a resulting luminance [cd/m^2] and large differences in luminance between surfaces may cause glare or visual discomfort. Direct sunlight is likely to cause glare due to the large difference in luminance between the sun and the surfaces of the room. Shading will also decrease the view to the outside.

EN 14501:2005 describes how the total transmitted light radiation through a shading device, τ_{V}, can be represented by the $\tau_{\text{dir-h}}$ transmission path and divided in the two components $\tau_{\text{dir-dir}}$ and $\tau_{\text{dir-dif}}$, mathematically described by

$$\tau_{\text{V}} = \tau_{\text{dir-h}} = \tau_{\text{dir-dir}} + \tau_{\text{dir-dif}}$$

$\tau_{\text{dir-dir}}$ can be regarded as a measure of how much direct light passes through holes in the fabric. A higher value makes it easier to see outside and to recognise shapes through the fabric, while also making it easier to see inside from the outside during the night. It also makes glare more likely due to a larger chance of getting a direct view of the sun. Additionally, it increases the likelihood that patches of sunlight will be visible on surfaces inside the room, reducing the uniformity of illuminance.

$\tau_{\text{dir-dif}}$ is the portion of the light which is diffused as it goes through the fabric. This diffusion serves to illuminate the shading device itself, making it act as a light source with a high luminance. An excessive luminance of the screen can either be a glare source in itself or due to uncomfortably large contrasts with the surrounding surfaces.

Konstantzos et al. (2015) have developed a metric called View Clarity Index (VCI) for evaluating the clarity of the view through a shading fabric. It considers the openness factor (OF) and the visible transmittance τ_V. The openness factor (OF) is a measure of what fraction of the fabric consists of holes. τ_V includes both direct and diffuse transmission. The View Clarity Index is calculated by

$$VCI = 1.43 \cdot \mathrm{OF}^{\,0.48} + 0.64 \cdot \left(\frac{\mathrm{OF}}{\tau_V}\right)^{1.1} - 0.22$$

VCI ranges from 0 to 1, where 1 equals having no shading on the window and 0 equals no light transmission. A higher value of OF gives a higher view clarity while the inverse is true for τ_V. This shows the impact of the diffusing fraction of transmission, since a higher light transmission would intuitively be assumed to make it easier to see through the shading.

3.1.2 Influence on energy efficiency

Bülow-Hübe et al. (2003) investigated a selection of shading products to determine their g_{shading} values. They found that external shadings are better at reducing heat loads through windows since the heat absorbed by the shading will dissipate outside of the building. External shadings with high absorptance and low reflectance, meaning dark colours, also provide lower g-values than light-coloured ones. Conversely, if internal shadings are used it is preferable for them to have high reflectance, i.e. light colours, since it is desirable to reflect as much light as possible back to the outside.

REHVA (2010) shows measurements of peak cooling loads and window surface temperatures for office buildings with and without solar shadings. In the studied case, shading reduces the windows temperatures by 5°C to 10°C and the cooling loads by 50% to 100%. They also refer to studies where the use of electric energy was reduced by 50% to 75% by designing buildings for ample light daylight provision, although the studies included measures such as light shelves which are not commonly used in Sweden. Bülow-Hübe (2007) also carried out a study where the use of venetian blinds led to annual electricity savings of 50%.

Dubois (1999) studied the impact of adding a textile awning to shade a south-facing window. It was found that the energy savings obtained during the summer season were approximately the same as the added energy use during the colder season. This illustrates the benefit of seasonal or dynamic shadings.

3.1.3 Influence on indoor environment

The most energy efficient sunlight management strategy would be to completely block all windows when the solar heat is not needed. Obviously this would not create a comfortable indoor environment. Bülow-Hübe et al. (2003) stresses that the heat deflecting performance of the shading device always has to be weighed against the remaining transmittance of visible light and the obstruction of views to the outside. These aspects also need to be consider if shading is deployed to manage glare or visual discomfort.

The surfaces of windows can have significantly different temperatures than the surrounding surfaces and the room air (REHVA, 2010). In the summer this can cause thermal discomfort through increased heat radiation. Warm windows can also cause convective air flows that lead to draught and high local air flows. Solar shading can mitigate these effects by reducing the amount of heat that reaches the windows. Areas inside the building that are reached by direct sunlight will also be heated much more than adjacent areas, which can cause severe local thermal discomfort as well as glare. Shading can be utilized to address these issues as well.

Dubois (2001) studied the impact of shading devices on a number of indicators that characterise the quality of daylight. Apart from daylight factor and glare indices, the illuminance levels on a desk were studied, as well as the distribution of illuminance on the desk surface. The luminance of the surfaces in the room where also studied, as well as the ratios between luminances of different surfaces. The study concluded that different shading devices have different benefits and drawbacks and are suited for different types of activities and work tasks. For example, when working with paper, high illuminance is desired, while a computer screen may be hard to see if there is too much light. Only a few shading devices were studied but the large number of indicators involved show how complex the choice of shading device is, due to the intricate interplay between the factors involved.

Overall, the study by Dubois (2001) found that venetian blinds performed well on all indicators, with the added benefit of being highly adjustable, which is useful for adapting to shifting light conditions and resulting glare issues. It was also found that a white screen performed better than a grey screen, due to the diffusing effect that the white screen has on the light. On the downside, the white screen was described to become self luminous under direct sunlight, effectively making it a glare source and impossible to see through. The study argues that a dark-coloured screen is preferable when using a computer while also having the shaded window in view, whereas a light-coloured screens will perform better when doing paper tasks and not having a direct view of the shaded window.

Dubois (2001) also brings attention to the fact that the sun sits low above the horizon during winter in northerly locations. The choice of shading also needs to take this annual variation into account. From this perspective, a device like a marquisolette which combines a screen and an awning may be problematic since direct sunlight can enter below the awning if the sun is low enough. Covering the whole window with a screen is more fool-proof although this also has drawbacks that a marquisolette would not have. Since irradiation levels are low in winter and since dynamic shading devices can be damaged if they are used during conditions that are too cold or windy, they are likely to not be in use during many of the times during the year when the sun is low enough to reach below an awning.

3.1.4 Strategies for dynamic shading

Any strategy for the operation of dynamic shading devices has to balance the competing goals of maximising visual light radiation while minimizing unwanted heat radiation. No objectively optimal strategy exists, depending instead on the priorities of the actors involved. Aggressive shading can mean large economic savings for a landlord at the expense of uncomfortable occupants. Van Moeseke et al. (2007) attempted to find a strategy that would minimize both the number of hours during a year where shades are drawn and the number of hours where overheating occurs. It was found that a combination of setpoints based on indoor temperature and facade irradiation allowed for simultaneous reduction of both overheating hours and closed hours. The temperature setpoint of was 23°C or 24°C while the irradiation setpoint was between 200 W/m^2 and 300 W/m^2.

3.2 Demand controlled ventilation

In order to fulfill demands on fresh air provision, pollution removal and cooling, outside air needs to be provided to rooms through ventilation systems. The requisite volume of air depends on the number of occupants, posing the issue of how to manage variations in occupancy. By tailoring the supply of air to the demand, large amounts of energy can be saved. Ventilation systems can either provide constant air volume (CAV) or variable air volume (VAV) (REHVA, 2012). If CAV is used, the ventilation can be turned off completely if a room is unoccupied to save energy but more granular control is not possible. If VAV is used, air flow rates can be adjusted according to current occupancy. The variation of air flows can be controlled either by manual operation, a scheduled pattern or automatically in response to real time conditions. VAV ventilation with such automatic control is called demand controlled ventilation (DCV).

3.2.1 Parameters and indicators

Two factors significantly impact indoor air quality: the amount and quality of the air supplied from outside, and the emissions of pollutants inside the building (Li et al., 2011).

The flow of air supplied to a room can be varied based on either thermal comfort or air quality considerations (REHVA, 2012). The main thermal comfort indicator for control of air flow is indoor temperature, while the main indicator for air quality is carbon dioxide (CO_2) concentration. CO_2 is chosen because it is easy to measure, varies quickly with occupancy and corresponds to other emissions from humans (Keen & Lawrence, 2019). A VAV system can be controlled by open-looped or closed-loop control systems.

The air flow to a single room is controlled either by variable supply air diffusers or by air flow control dampers placed in ducts (REHVA, 2012). It is important to choose supply air diffusers or dampers carefully so that they are able to provide the range of air flow rates necessary for successful implementation of the VAV system. The choice of diffuser also needs to be coordinated with the sizing of the air handling unit. Every air handling unit has a minimum air flow rate needed to assure stable operation. The size of the air handling unit thus imposes a limit on the lowest air flow rate that each individual supply air diffuser needs to maintain in order to distribute all the supply air in the system at any given moment.

If the air handling unit has been sized to handle large heat loads or pollution sources that are localized to a specific part of a building or a specific period of time, this would mean that air diffusers throughout the building have also been sized correspondingly. A consequence of this could be that the smallest air flow rates that can be achieved in a room with VAV ventilation are higher than desired. Consider, for example, that a minimum VAV airflow of $0.35\ \mathrm{l/s \cdot m^2}$ is desired in rooms that are momentarily unoccupied to fulfill minimum regulatory demands. If the air handling units and diffusers have not been carefully sized, the diffusers may not be capable of providing such low air flow rates. This would lead to excessive air flows and consequently excessive cooling of unoccupied rooms.

If there are significant asymmetries in heat loads or pollutant sources between different parts of a building, it might not be sufficient to only have one air handling unit for the whole building.

Having several units of varying sizes that serve their own area allows for closer adaptation to local conditions. It might also be more efficient to have several smaller units that serve the same area and that work together to handle periods of time where loads are larger.

3.2.2 Influence on energy efficiency

The potential energy savings from the use of DCV are largest in buildings with high occupant density and large variations in load intensity (REHVA, 2012). Studies on occupancy in academic office buildings showed that at most, only about 75% of offices were occupied simultaneously, with average values of 50% or even as low as 35% to 20%. Other types of offices buildings showed similar peak occupancy rates of 65% to 84%. These numbers only indicate binary occupancy, not how many people are present in a room.

It is becoming increasingly common to rebuild CAV systems to DCV systems in building renovation (REHVA, 2012).

3.2.3 Influence on indoor environment

Demand controlled ventilation allows for finer control of pollutant concentration in a room but excessive air flow rates can cause larger heat losses than desired. Higher ventilation flows may cause uncomfortable air speeds, although VAV supply air diffusers can change the outlet configuration to maintain air speeds at varying air flow rates (REHVA, 2012). For optimal functionality, control sensors need to be placed in locations with representative conditions. It is also beneficial to the outcome if the entire process, from design to installation and operation of the control system, is monitored and coordinated by one party. This can help avoid misconfiguration of the system which could in turn lead to undesired discomfort.

3.2.4 Strategies for demand controlled ventilation

Li et al. (2011) outline a strategy for controlling DCV according to CO_2 concentration. By predicting where the concentration is going, airflow rates can be set according to an estimated steady state concentration long before it is reached. This is accomplished by assuming that occupancy is constant over a short period of time, about five minutes. Concentration is measured at the start and end of the period and the change is noted. The rate of change can then be divided by the assumed generation rate per person to obtain an estimate of the number of people present in the room. This can then serve as the basis for the magnitude of the supplied airflow. In this way sudden changes in pollutant load can be handled before large spikes in pollutant concentration occur.

4 Miljöbyggnad certification

Since the early 1990's, large efforts have been made to quantify and compare the environmental impacts of buildings by the means of Green Building certification schemes (Yudelson, 2016). The first such scheme was BREEAM, created by a British government agency. Ever since, dozens of schemes have followed all over the world. Miljöbyggnad is a Swedish environmental certification scheme for buildings, operated by Sweden Green Building Council since 2003 (Mahdavi et al., 2020). The scheme measures a building's performance in 16 parameters, awarding each a grade of bronze, silver or gold (Sweden Green Building Council, 2020). The entire building is then awarded a score on the same scale, based on a weighted assessment of the individual grades.

The 16 parameters are divided in three categories: energy, indoor environment and materials. Indicators 1 (Heating power demand), 4 (Share of renewable energy), 5 (Sound), 6 (Radon), 8 (Moisture safety), 12 (Legionella) and 13-16 (Materials) are outside the scope of this thesis and will not be considered. The relevant indicators are Solar heat load (2), Energy consumption (3), Ventilation (7), Thermal comfort (9 & 10) and daylight (11). Solar heat load is defined as the solar heat that goes through a window and heats a room, divided by the floor area. The annual energy consumption for the building is compared with the demands set out in Swedish building regulations BBR. The areas considered are the ones where temperature is kept above 10°C, referred to as A_{temp}. The values required to reach each grade for each indicator are presented in table 2.

Table 2: Criteria for Miljöbyggnad 3.1 grading

Indicator	BRONZE	SILVER	GOLD
2. Solar heat load [W/m^2 floor area]	≤ 40	≤ 32	≤ 22
3. Energy consumption [kWh/m^{2}A$_{temp} \cdot$ year]	$\leq$ SBR[1)] = ≤ 80[2)]	$\leq$ 80% SBR = ≤ 64	$\leq$ 70% SBR = ≤ 56
7. Ventilation	7 l/s + 0.35 l/s·m^2 floor area	BRONZE + CO_2 only temporarily $\geq$ 1000 ppm	SILVER + survey
9. PPD Winter [%]	$\leq$ 15%	$\leq$ 10%	SILVER + survey
10. PPD Summer [%]	$\leq$ 15%	$\leq$ 10%	SILVER + survey
11. Daylight factor [%]	$\geq$ 0.8 %	$\geq$ 1.0 %	$\geq$ 1.3 %

1) Swedish Building Regulations = Boverkets byggregler (BBR)

2) Addition of up to 45.5 can be made if airflow rates are sufficiently large

5 Case study description

A case study is carried out to investigate the concepts mentioned previously under real conditions. A newly renovated building is considered. The existing models and documentation produced by the engineering firm during the renovation process have been made available to the author and serve as the basis for investigations.

5.1 Building description and specifications

The case study building is located in southwestern Sweden. It is a five-story university building with a heated area of approximately 16000 m^2 with a mix of offices, classrooms, study and computer rooms and common spaces. The building is shown in figures 4 and 5 along with the surrounding area. A full renovation of the building was undertaken and finished in 2017. Renovation measures implemented included demand controlled ventilation and dynamic shading. The building has been certified according to Miljöbyggnad and received a silver grade.

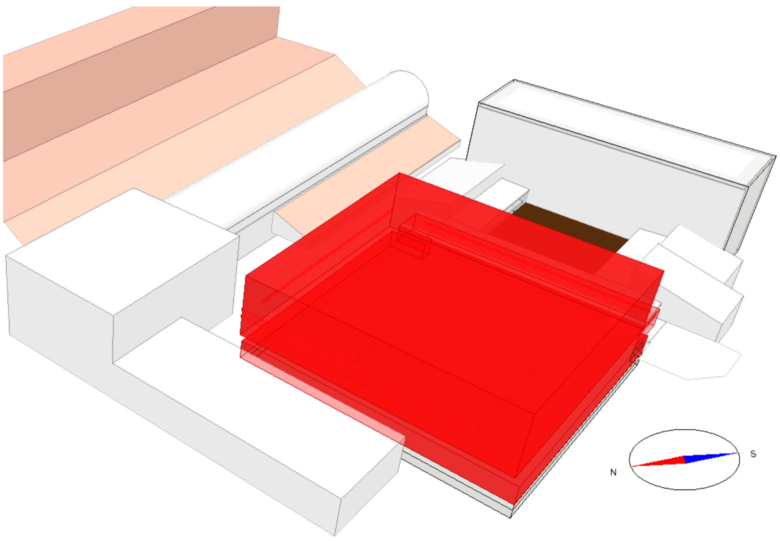


Figure 4: Site with case study building in red, view to the southeast.

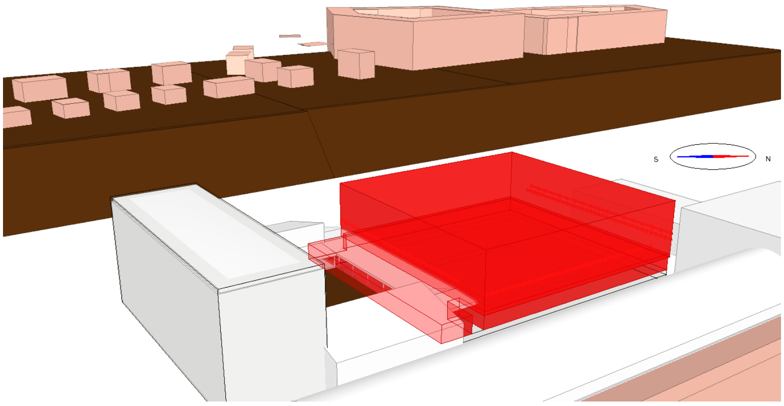


Figure 5: Site with case study building in red, view to the northwest.

The third and fourth floor of the building have offices along the facade, as shown in figure 6. Two types of offices are available, one for two employees with a floor area of approximately 8.6 m^2 and one with an area of 61 m^2 for eight employees.

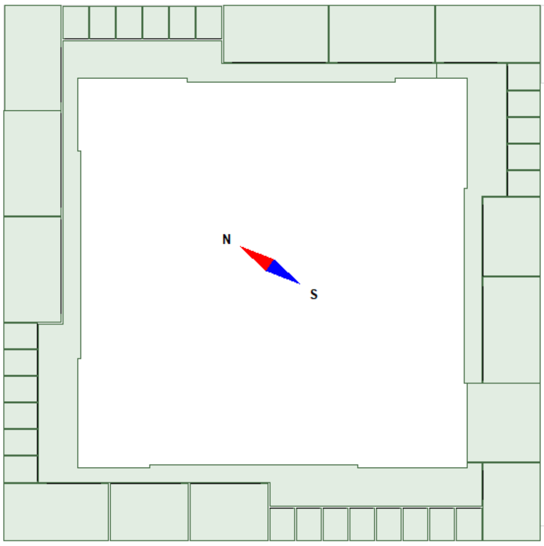


Figure 6: Floor plan with locations of office rooms for floors 3 and 4.

5.1.1 Internal heat loads

The building is occupied between 7:00 and 17:00 on workdays, with breaks at 9:00-9:30, 11:30-12:30 and 14:30-15: During June, July and August occupied hours are 8:00-16:00 and the occupancy is assumed to be 0.25 of regular levels. During occupied hours, small offices are assumed to have 2 employees present at all times as well as 17.4 W/m^2 of heat gains from equipment and

11.6 W/m^2 from lights. Large offices have 8 employees, 9.83 W/m^2 from equipment and 9.83 W/m^2 from lights.

The heating setpoint for occupied rooms is 22°C during working hours and 20°C otherwise. The cooling setpoint is 24°C during occupied hours and 25°C otherwise.

5.1.2 Ventilation system

The ventilation system in the building is in operation between 7:00 and 19:00 on workdays and between 10:00 and 18:00 on weekends. During summer (June to August) the ventilation runs at 25% on weekdays and is turned off on weekends.

The building is equipped with a demand controlled ventilation system. Air flow in all working spaces is controlled by indoor temperature, while rooms with more than 6 occupants are also equipped with CO_2 control. The exact airflow rates in the rooms are not defined in the provided documentation. Initially, it is assumed that the minimum airflow when using VAV is 0.7 $l/s \cdot m^2$ while the maximum is 5 $l/s \cdot m^2$ for the small office rooms and 7 $l/s \cdot m^2$ for the large ones. Later, these values will be varied for investigative purposes. Due to limitations in IDA ICE, it is not possible to set different VAV air flow rates for occupied and unoccupied times during the working day. Any value set for minimum VAV airflow will apply to both occupied and unoccupied hours which might lead to either insufficient air flow rates during occupied hours or excessive air flow rates during breaks.

The temperature of the supply air is varied depending on the current outdoor temperature, as shown in figure 7.

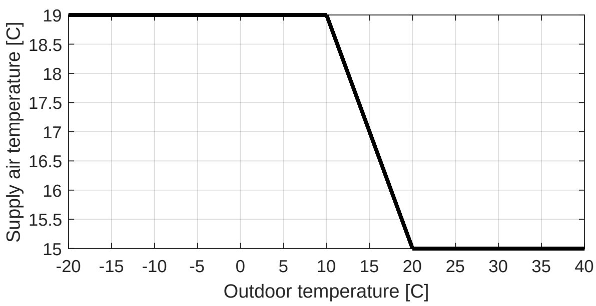


Figure 7: Variation of supply air temperature with outdoor temperature

5.1.3 Windows and shading devices

The building has a total window area of 2430 m^2. The properties of the windows are U = 1.04, g = 0.39 and T_v = 0.6.

The windows are equipped with automatically controlled marquisolette shading devices, as shown in figure 8 along with the dimensions of the device. In the existing building the shades are set to be rolled down fully at a facade irradation of 250 W/m^2. Shades are not rolled down if the outside temperature is below 2°C or if the wind speed is above 12 m/s.

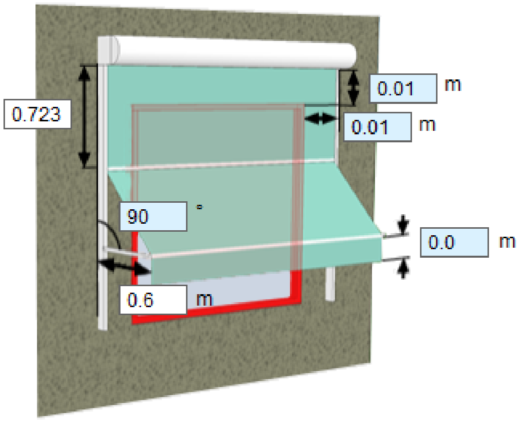


Figure 8: Dimensions of marquisolette shading device

5.2 Occupant survey

An occupant survey was carried out in the building during August and September of 2019 by researchers from Chalmers University of Technology (Jin & Wallbaum, 2020). When asked how they would improve the indoor environment, almost 60% of respondents expressed a desire for higher temperatures, 40% wanted more fresh air and about 37% wanted more daylight.

It is worth noting the contradictory nature of the complaints reported. The desire for more daylight seems to indicate that shades are drawn quite often but the complaints about temperatures being too low indicate that more (or colder) air than necessary might be supplied to the building. From a thermal comfort point of view, it would not be necessary to block the sunlight if occupants feel cold, since the heat from the sun could provide free heating.

5.3 Investigations

The indoor environmental quality and energy use in the building is investigated using building simulation software. Possible reasons for the occupant discomfort reported in surveys are also investigated and modifications to the existing building are simulated too determine how comfort can be improved and how the implemented measures will impact energy use.

5.3.1 Software

The main software used for the case study simulations is the building simulation software **IDA ICE 4.8**, produced by Swedish developer Equa Solutions. Since IDA ICE 4.8 can only simulate illuminance at one point in time, **IDA ICE 5.0 Beta** is used to perform a full-year average illumination study.

For evaluation of glare and luminance distributions, the software suite **Radiance** is used. It consists of a range of tools for simulating light levels in 3D models using ray tracing and Monte Carlo methods (Berkley Lab, n.d.). In this project the software **AcceleradRT** is used as an interface to a selection of Radiance tools. If an illumination simulation is run in IDA ICE at a certain point of time, the 3D model with associated data can be exported from IDA ICE and imported into AcceleradRT where luminance distributions in the model can be visualized.

5.3.2 Conditions and assumptions

For full-year simulations the climate file used is for the year 2018, due to the unusually warm summer that year.

For full-year simulations it is assumed that occupants will adapt their clothing to suit their thermal needs. This is implemented in IDA ICE by setting the clothing level of occupants at 0.75 clo with an allowed variation of $\pm$ 0.25 clo. Occupants are assumed to keep an activity level of 1.0 met.

In order to decide which office rooms should be considered for the simulations, a study of illuminance levels on the facade of the building is carried out. Since shading is usually not needed on facades facing north, this direction is not considered. For other facades, the average daytime illuminance for a whole year is calculated in IDA ICE 5.0 for the facade both with and without surrounding objects and the results are shown in figures 9 and 10.

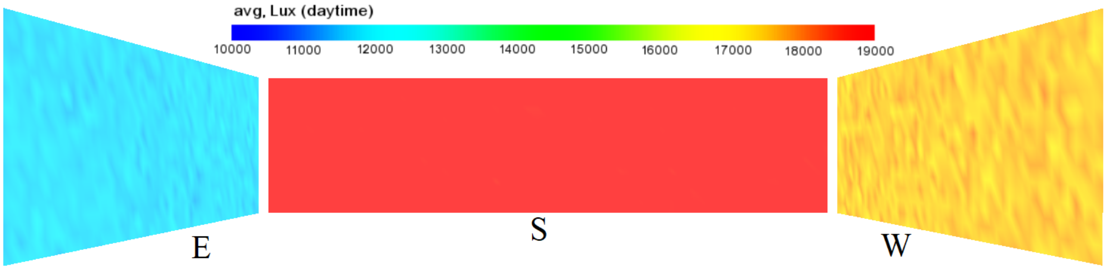


Figure 9: Annual average of daytime illuminance values for facades with surrounding objects removed

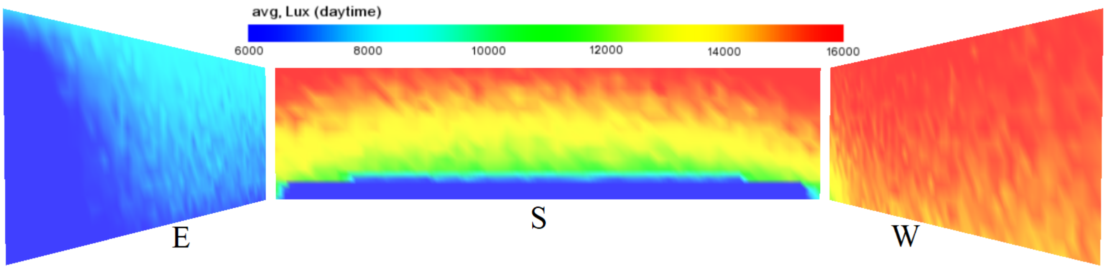


Figure 10: Annual average of daytime illuminance values for facades with surrounding objects present

As figures 9 and 10 show, the eastern facade is heavily shaded in one corner due to a nearby building while the southern facade has an even gradient of shading along the whole facade. For the southern and western facades, rooms are assumed to have the same light conditions if they are placed on the same level while rooms placed on the eastern facade could experience different conditions if they are placed in different regions of illumination. Based on these considerations, one small and one large room in each direction are chosen from figure 6 and placed at the level of the fourth floor. These rooms are shown in figure 11 and are denoted W(est), E(ast) or S(outh) according to cardinal directions and 2 or 8 depending on the number of occupants. The annual average of daytime illuminance is approximately 8000 lux for E2 and E8, 15000 lux for S2 and S8 and 16000 lux for W2 and W8. For the darkest corner of the eastern facade, the level is approximately 5000 lux.

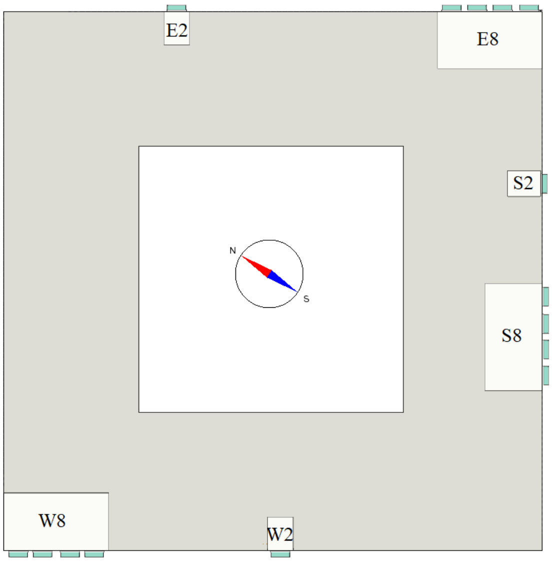


Figure 11: Floor plan with office rooms chosen for further investigations. Rooms are named after the cardinal direction and the number of occupants.

6 Case study investigations

Investigations are carried out to determine the possible causes of the reported occupant discomfort as well as the performance of the building with regard to occupant comfort and energy use.

6.1 Origins of occupant discomfort

As described in section 5.2, a survey conducted after the renovation revealed a certain amount of discomfort among the building's occupants. A majority of respondents complained about cold temperatures while a significant portion also complained about a lack of daylight. The building is equipped with several techniques to reduce heat loads or to provide cooling, such as large and cool air flows and heavy solar shading.

In order to understand the underlying reasons for the perceived discomfort, a simulation is run during a period of time where these techniques are employed heavily. Since the survey was carried out in late August and early September, a possible scenario that could cause significant thermal discomfort is a warm, sunny day where people wear relatively thin clothing (In the region of 0.5 to 0.6 clo, typical summer clothing). The high temperatures outside would lead to relatively low air supply temperatures while high temperatures inside would lead to high ventilation air flow rates, in turn potentially causing high air speeds inside the building, perhaps in the region of 0.2 m/s. The large amounts of solar radiation would activate the solar shading, pushing the heat balance further towards the cool side while simultaneously reducing the visual comfort.

A day like this is found in the beginning of September, with a temperature ranging from 14°C at night and a peak of around 17°C during the early afternoon. Solar radiation peaks at 800 W/m^2 and is mostly unobstructed throughout the day. A simulation is run in a small office facing west (W2). The results from the simulation indicate that the automatic shading devices are pulled down continuously between 12.00 and 18.00, which corroborates the reports of insufficient daylight provision. The values obtained for PMV and PPD for the whole day are shown in figure 12.

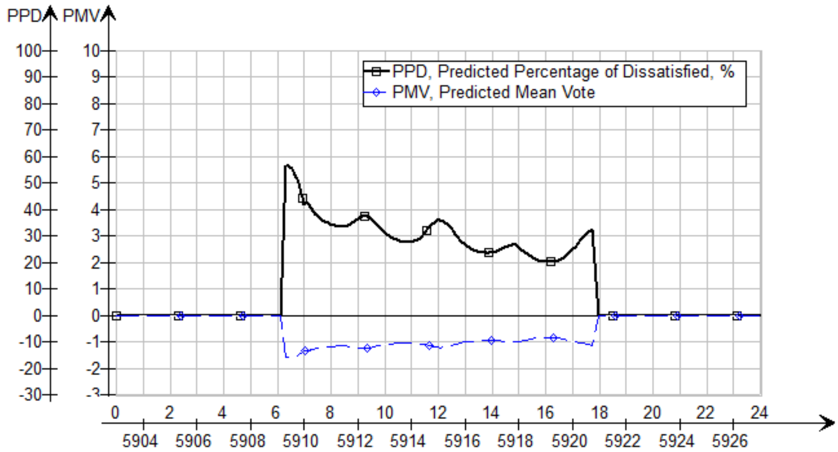


Figure 12: PMV and PPD for office room W2. clo = 0.5, air velocity = 0.2 m/s

Figure 12 shows high values for PPD throughout the day. The negative PMV values indicate that the discomfort is due to a perception of being too cold. As internal heat gains and solar heat increase throughout the day, the discomfort decreases. To determine the largest contributor to the sensation of being cold, the heat balance for the room is shown in figure 13.

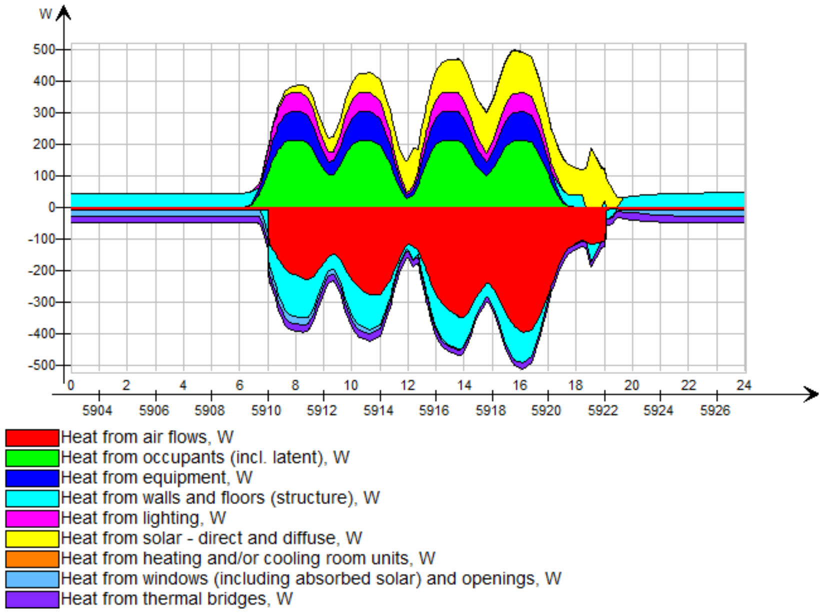


Figure 13: Heat balance for office room W2

Figure 13 shows that the largest contributor to cooling the room is the air flows (shown in red). Heat losses from walls and floors (cyan) have a significantly smaller impact. The graphs for air flow rate and supply air temperature are shown in figures 14 and 15.

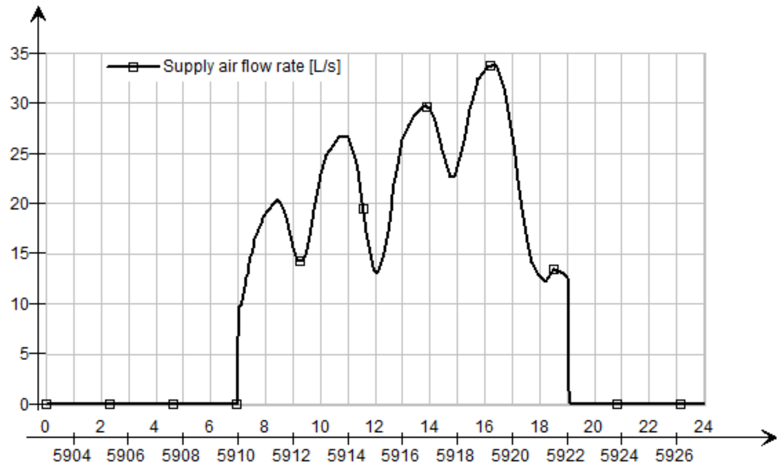


Figure 14: Rate of air supplied to room W2 during one day

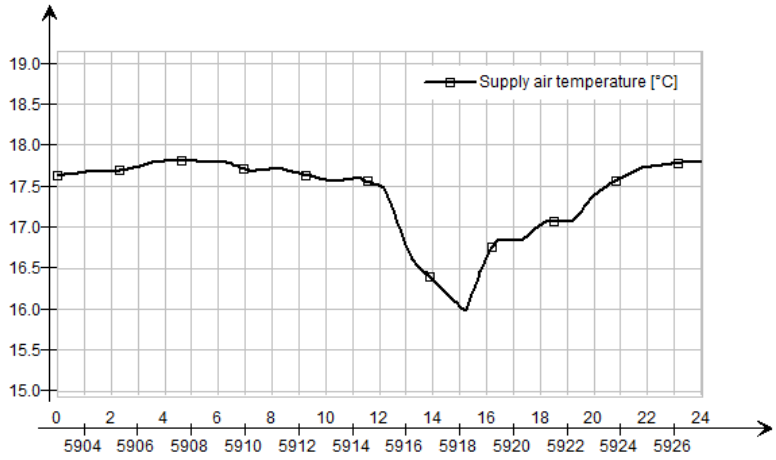
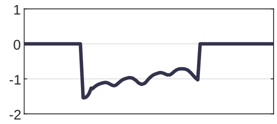
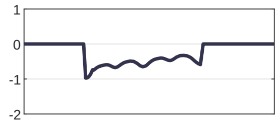
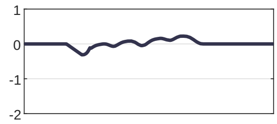
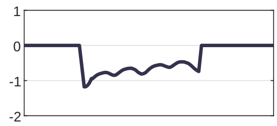
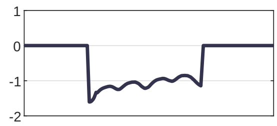


Figure 15: Temperature of air supplied to room W2 during one day

Figures 14 and 15 indicate that large amounts of relatively cold air are being supplied to the room throughout the day even though the overall occupant perception is of being too cold. The accuracy of this observation relies on the veracity of one or several of the underlying assumptions that the occupants are not wearing enough clothes, that the supply air flow rate is too high, that the resulting air speed is too high and that the air supply temperature is too low. In order to determine how these factors impact the energy use and indoor environmental quality, the model for the existing building is run and the parameters of interest are varied. The indicators chosen for investigation for the day in question are the total amount of air supplied to the room, the peak CO_2 concentration and the graph for PMV. In order to obtain the amount of air supplied to only one room, it needs to be equipped with it's own air handling unit in the IDA ICE model. The amount of air supplied to a room gives an idea of how much energy is used for the ventilation system but is not a completely accurate measure since fan power does not vary linearly with air flow rate. Table 3 shows the results for variations of clothing values, air speed and supply air temperature.

Table 3: Parameters and indicators for a small office room (W2) during one day in September. Bolded parameters differ from reference case 1

	Parameters				Results		
Case	Clo	Air volume control	Air speed [m/s]	Supply air temperature	Air supplied [m^3/day]	Peak CO_2 [ppm]	PMV 24h
1	0.5	VAV Temp. control 0.7 - 5 $l/s \cdot m^2$	0.2	Graph [1]	972	877 [2]	
2	**0.7**	VAV Temp. control 0.7 - 5 $l/s \cdot m^2$	0.2	Graph	972	877 [2]	
3	**1.0**	VAV Temp. control 0.7 - 5 $l/s \cdot m^2$	0.2	Graph	972	877 [2]	
4	0.5	VAV Temp. control 0.7 - 5 $l/s \cdot m^2$	**0.1**	Graph	972	877 [2]	
5	0.5	VAV Temp. control 0.7 - 5 $l/s \cdot m^2$	0.2	**Constant 19°C**	1188	798 [2]	

[1] Supply air temperature varied according to outdoor temperature as shown in figure 15
[2] Reached once, at 8:00

Cases 2 and 3 of table 3 show that the magnitude of PMV is reduced significantly if occupants increase their clothing to typical winter indoor clothing (clo = 1.0). Case 4 shows that lowering the air speed will also lower the magnitude of the PMV but for this case it is not enough to achieve acceptable PMV values. Case 5 shows what happens if the supply air temperature is kept constant rather than varied according to outside temperature. Contrary to what might be expected, the values for PMV over the course of the day are actually slightly lower than in case 1, indicating that average air temperatures are lower. The explanation for this can likely be found by comparing the total amount of air supplied for the whole day in the two cases. In the case with constant supply air temperature 22% more air is supplied than in the case with varying temperature. Since the supply air is warmer in case 5, higher air flow rates are needed to provide a similar amount of cooling. Due to limitations of the modeling software, it is hard to ascertain how accurate the values obtained are. In reality, it is likely that occupants sitting close to an air diffuser will experience significant thermal discomfort if the supply air temperature is as low as

16°C like in this case. However, this type of localized effect can not be modeled accurately in the software due to the necessity of averaging measurements in both space and time.

Case 5 also shows the impact of supply air provision on air quality. The increased amount of air supplied to the room in case 5 causes a 9% decrease in the peak CO_2 concentration reached. One possible reason for occupant discomfort is that the smallest VAV air flow rates that the supply air diffusers are capable of delivering could be undesirably high. This could be due to large heat loads in one part of the building leading to a need for an air handling unit with large maximum flow rates. This would also increase the minimum air flow rates needed for stable operation and thus the amount of air that needs to be divided and allocated in the air distribution system. As a consequence, the minimum VAV air flow rates that need to be supplied in each room could be higher than desired.

To investigate this, a number of different air flow rates are tried out to see how they impact the thermal comfort. The hygiene air flow of 0.35 l/s·m^2 is considered as well as two higher air flow rates which will account for a progressively larger portion of the pollution emitted by occupants. The highest rate of 1.4 l/s·m^2 was intended to be the air flow required to achieve the recommendation of 0.35 l/s·m^2 + 7 l/s per person. However, that value is actually larger than 1.4 for a small office but due to a misreading of room measurements 1.4 was used to run the simulations. For the purposes of this study it is sufficient to see the trend of higher air flow rates. The resulting profile of PMV variation for a full working day is shown in figure 16, confirming that PMV values decrease when the minimum VAV air flow rate is increased.

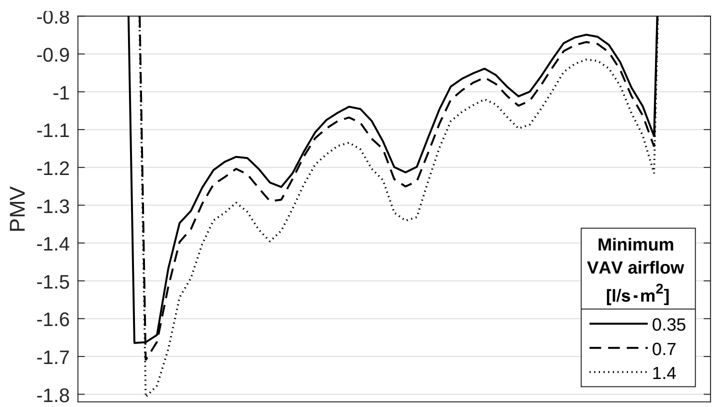
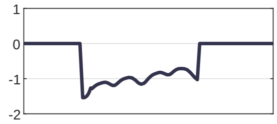
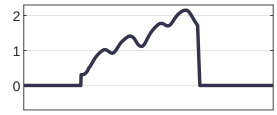
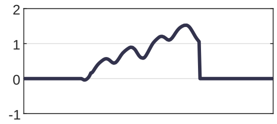
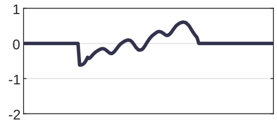


Figure 16: Variation of PMV over the course of a working day for different minimum VAV airflow rates

A number of different CAV air flow rates are tried out to determine how CO_2 concentration and PMV are impacted. The results are shown in table 4.

Table 4: Parameters and indicators for a small office room (W2) during one day in September. Bolded parameters differ from reference case 1

	Parameters				Results		
Case	Clo	Air volume control	Air speed [m/s]	Supply air temperature	Air supplied [m^3/day]	Peak CO_2 [ppm]	PMV 24h
1	0.5	VAV Temp. control 0.7 - 5 l/s · m^2	0.2	Graph [1]	972	877 [2]	
2	0.5	**CAV** **0.35 l/s · m^2**	**0.1**	Graph	130	2600 [3]	
3	0.5	**CAV** **0.7 l/s · m^2**	**0.1**	Graph	260	1654 [3]	
4	0.5	**CAV** **1.4 l/s · m^2**	**0.1**	Graph	519	1070 [3]	

[1] Supply air temperature varied according to outdoor temperature as shown in figure 15
[2] Reached once, at 8:00
[3] Reached several times throughout day

6.2 Ventilation

The interplay between heat loads, pollution sources and the choice of ventilation control strategy is studied in more detail. Both of the south-facing office rooms (S2 and S8) are considered. Both rooms are simulated with full occupancy while the large room is also simulated with low occupancy, with 2 out of 8 employees being present. One sunny and one overcast day are located in March. The outdoor air temperature on both days is around 0°C. Indoor air speed is set to 0.1 m/s and clothing level to 0.8 clo. Windows are equipped with black marquisolettes. Air supply temperature is constant at 19°C. CAV air flow is 1.4 $l/s \cdot m^2$ and the VAV air flow range is 0.7 - 5 $l/s \cdot m^2$. The indicators recorded are the annual energy used to run the ventilation fans, the amount of air supplied during each of the studied days and the graphs of PMV and CO_2 concentration over the course of the same days. Combinations of overcast or sunny skies, different air control strategies and different occupancy levels are simulated and the results for annual fan energy and daily air supply are shown in table 5. The percentage of difference to CAV is calculated for temperature and CO_2 control and these values are shown in figure 17.

Table 5: Fan energy used during one year and air supplied during one specific day.
N.B. sky conditions do not apply to annual fan energy

Parameters				Results	
Sky	Occupancy [Current/Full]	Occupant Density [Persons/m^2]	Air volume control	Annual fan energy [kWh] (Compared to CAV)	Air supplied [m^3/day] (Compared to CAV)
☁ / ☼	2/2	0.23	CAV	50.43 (±0)	519 (±0)
☁	2/2	0.23	VAV Temp. control	41.67 (-17.4%)	259 (-50%)
☼	2/2	0.23	VAV Temp. control	41.67 (-17.4%)	1238 (+138%)
☁	2/2	0.23	VAV Temp. + CO_2 control	47.84 (-5.1%)	350 (-32.6%)
☼	2/2	0.23	VAV Temp. + CO_2 control	47.84 (-5.1%)	1316 (+135%)
☁ / ☼	8/8	0.13	CAV	366.4 (±0)	3758 (±0)
☁	8/8	0.13	VAV Temp. control	289.7 (-21%)	1987 (-47.1%)
☼	8/8	0.13	VAV Temp. control	289.7 (-21%)	7128 (+89.6%)
☁	8/8	0.13	VAV Temp. + CO_2 control	274 (-25.2%)	2160 (-42.5%)
☼	8/8	0.13	VAV Temp. + CO_2 control	274 (-25.2%)	7830 (+108.4%)
☁ / ☼	2/8	0.033	CAV	366.4 (±0)	3758 (±0)
☁	2/8	0.033	VAV Temp. control	235.2 (-35.8%)	1900 (-49.4%)
☼	2/8	0.033	VAV Temp.control	235.2 (-35.8%)	5600 (+49%)
☁	2/8	0.033	VAV Temp. + CO_2 control	220 (-39.9%)	1987 (-47.1%)
☼	2/8	0.033	VAV Temp. + CO_2 control	220 (-39.9%)	6426 (+71%)

☁ Overcast ☼ Sunny

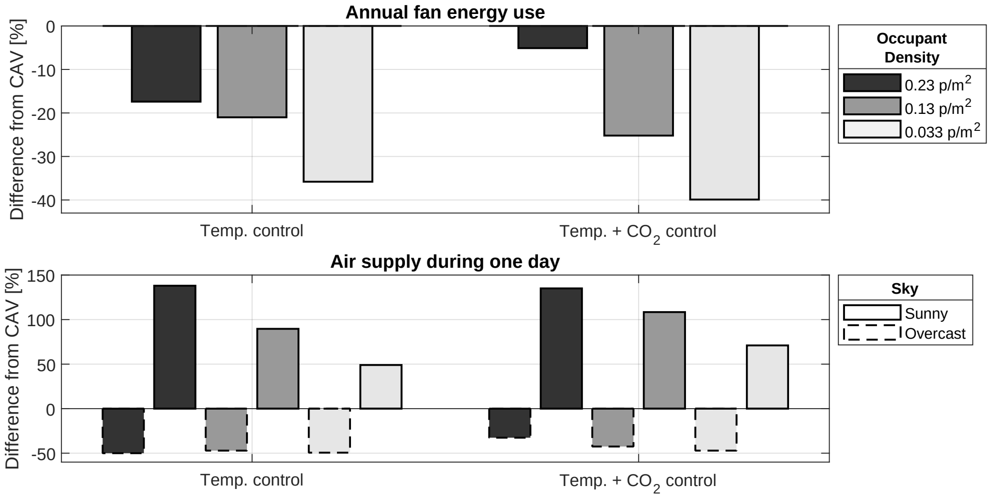


Figure 17: Annual fan energy use and air supply during one day for rooms with varying occupant density (persons/m^2) and varying solar conditions. Values relative to CAV

Table 5 and figure 17 show that large savings can be made annually on fan energy if VAV is implemented instead of CAV, even though significantly more air is supplied during sunny days. Fan energy savings are largest in rooms with low occupant density. In rooms with high occupancy and CO_2 control the annual fan energy savings are only 5.1%.

The profiles of PMV and CO_2 concentration for one day are shown in figure 18.

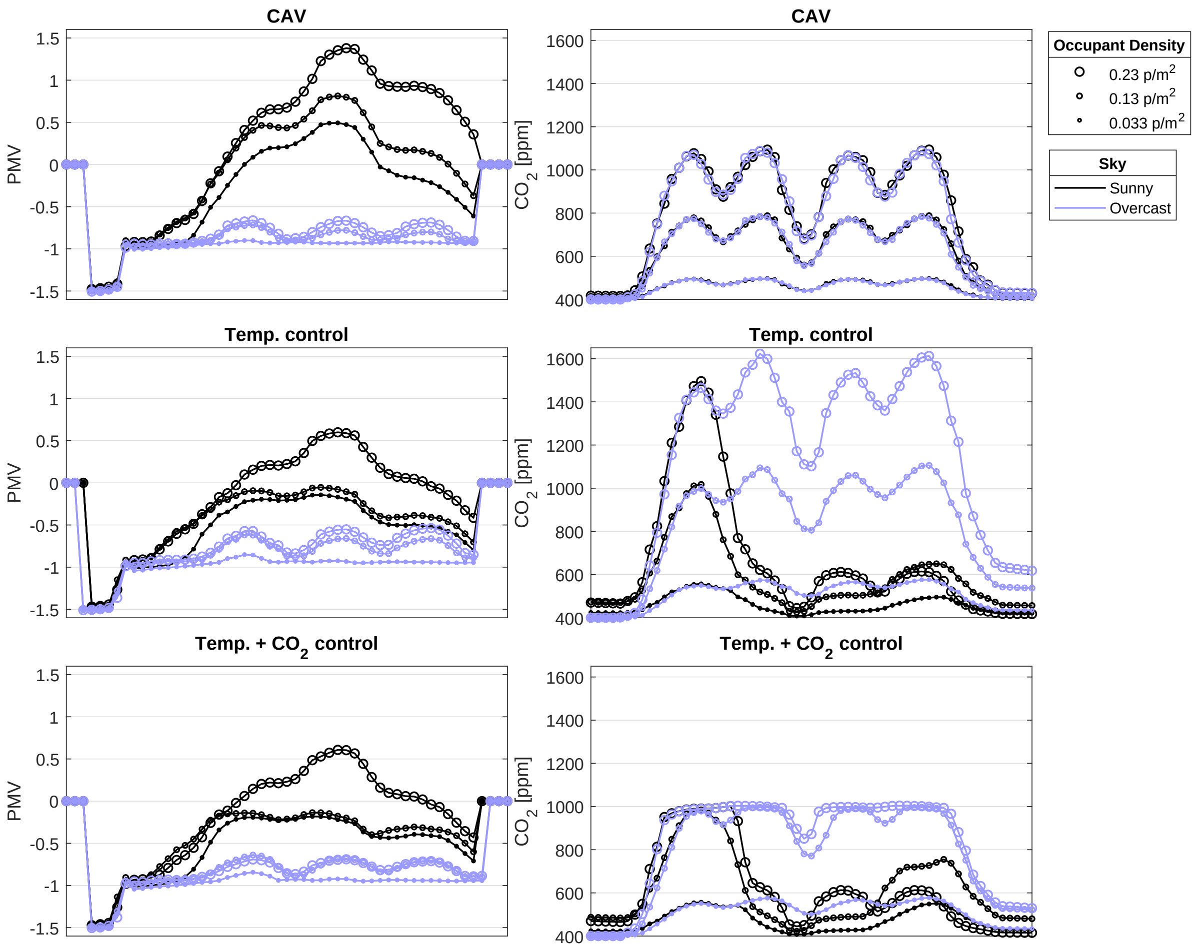


Figure 18: Profiles of PMV and CO_2 concentration over one day for different air flow control strategies

Figure 18 shows that he sun has a large impact on the PMV levels in the room. For the CAV case, PMV values are unacceptably low during overcast and unacceptably high during sunny days. CO_2 levels are too high only in the most densely occupied rooms. If VAV with temperature control is implemented instead of CAV, PMV values are moderated but air flows on overcast days are not sufficient to maintain acceptable CO_2 concentrations. On sunny days the concentration eventually reaches acceptable levels but only once the building has been warmed up and the temperature control has actually started increasing air flow rates. Both temperature control and CO_2 control are necessary to keep both PMV and CO_2 concentration withing acceptable bounds.

6.3 Shading

The impact of dynamic shading on thermal and visual comfort in the case study is studied. Two types of shading devices along with shading fabrics of two different colours are considered, for a total of four distinct combinations. The devices, shown in figure 19, are the marquisolette already implemented on the existing building and a simpler screen device with no awning.

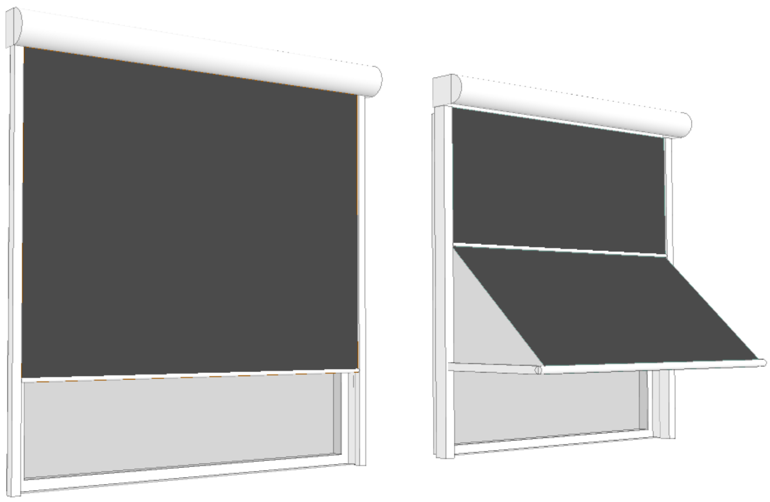


Figure 19: Shading devices. Screen on left and marquisolette on right

Table 6 shows the properties of black and white shading fabrics.

Table 6: Properties of shading fabrics of different colours

Colour	Longwave transmittance	Longwave reflectance	Shortwave transmittance	Shortwave reflectance	Diffusion factor
Black	6.3%	4.6%	6.3%	4.55%	5.4%
White	25.6%	63.6%	23.6%	71.6%	75.2%

6.3.1 Thermal comfort

To determine the impact of dynamic shading devices on thermal comfort, a number of simulations are carried out.

Shading setpoint

The small office rooms E2, S2 and W2 are considered. The windows are equipped with shading screens with black fabric. The ventilation system is VAV with temperature control, constant supply air temperature at 19°C and a range of air flow rates of 1.4 - 5 $l/s \cdot m^2$. Air speed in the rooms is set at 0.1 m/s. Full year simulations are run for each room and the setpoint for when shades are rolled down are varied. The number of hours in a year that PMV sits in the ranges -0.5 < PMV < 0 and 0 < PMV > 0.5 are recorded as well as the hours where ± 0.5 is exceeded. The results are shown in figure 20.

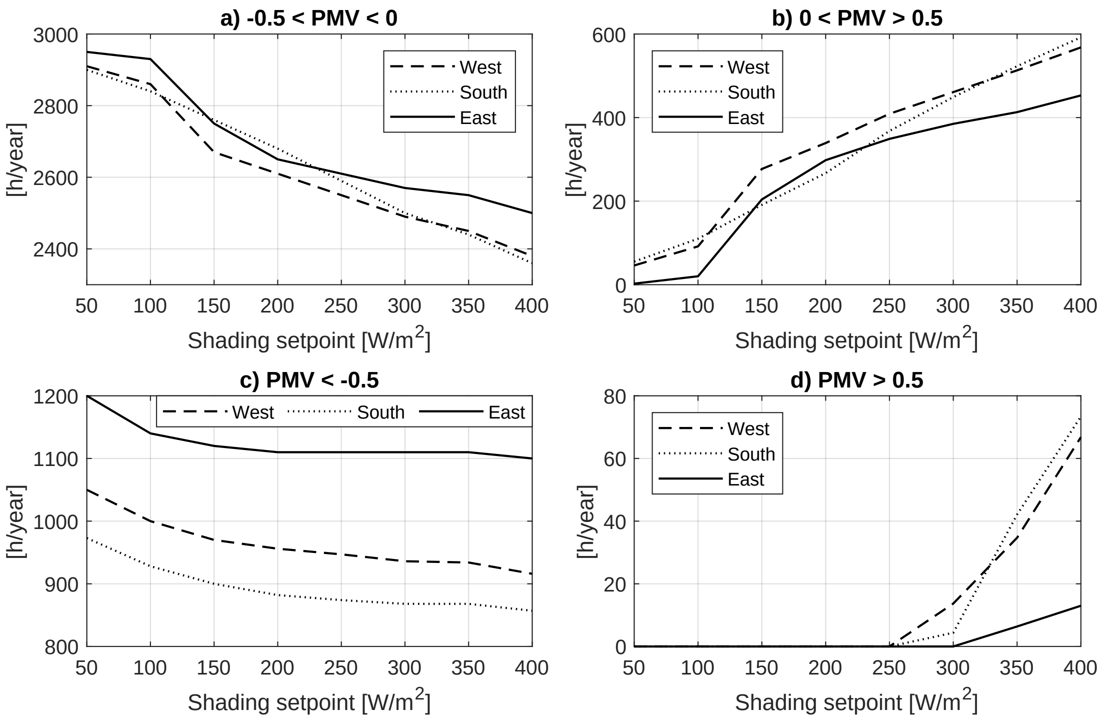


Figure 20: Hours per year where values of PMV lie in specific ranges, relative to shading setpoint

Figure 20 shows that the number of hours where PMV is in the range of -0.5 to 0.5 varies more or less linearly with varying shading setpoint (figures a and b). As expected, when the setpoint is higher the shades are down less often and more heat is let in, shifting more hours towards the warmer side of the PMV scale. This behaviour is seen in each direction and the values are also similar between the directions. However, a larger disparity is observed between the directions when considering the graphs for the number of hours where ± 0.5 is exceeded (figures c and d). Here, the east-facing room has decoupled more from the other directions, exhibiting a skew towards the cooler side. This indicates that for a given setpoint, a room facing east will have more hours per year where PMV is below -0.5.

Device type and fabric colour

Next, the impact of shading device type and fabric colour on thermal comfort is considered. The rooms E2, S2 and W2 are considered again with the same ventilation parameters as in the previous simulation. However, this time the shading setpoint is set at 250 W/m^2 and all four combinations of shading device and fabric colour are considered. The number of hours where PMV is above 0 is recorded and the results are shown in figure 21.

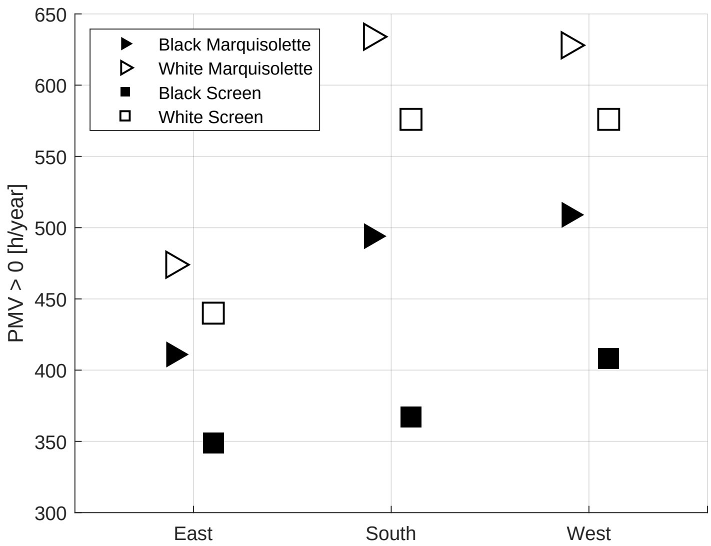


Figure 21: Hours per year with positive PMV values

Figure 21 shows that, as expected, lighter fabrics will let more heat in to the room and thereby shift more hours per year to higher PMV values. It is also clear that, for a given fabric colour, a marquisolette will let more heat in than a screen. However, it can be observed that the differences between different shading devices and different fabric colours are smaller for rooms facing east. For rooms facing south and west, the difference between a black screen and a white marquisolette is approximately 200 to 250 hours per year. For a room facing east, the difference is only about 125 hours per year.

The cooling energy used in each case is also calculated and presented in figure 22.

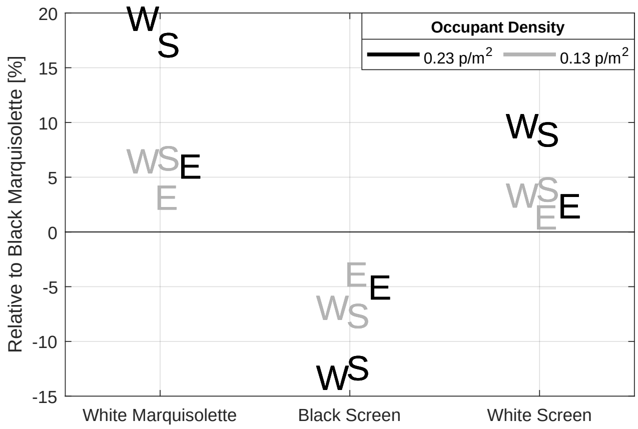


Figure 22: Annual cooling energy for rooms with different shading devices and directions (West, South, East), values relative to cooling energy for room equipped with black marquisolette device

6.3.2 Visual comfort

Simulations are performed to study the impact of shading devices on visual comfort.

Shading setpoint

The rooms E2, S2 and W2 are simulated for a full year and the shading setpoint is varied. The number of hours per year where the shades are rolled down is recorded and shown in figure 23.

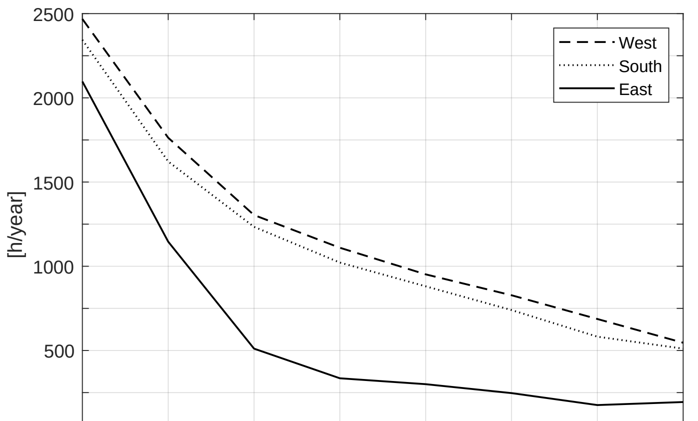


Figure 23: Closed hours for shading for varying setpoints

Figure 23 shows that the annual number of closed hours drops steeply for shading setpoints of up to 150 W/m^2 and then evens out somewhat meaning that the largest improvements can be found by increasing the setpoint up to around 200 W/m^2. After this, raising the setpoint in an east-facing room does not make significant changes to the number of closed hours per year. For rooms facing west and south, improvements can still be found at higher setpoints.

Next, a spring day with full, unobstructed solar radiation for the whole day is found and the hours when the shades are rolled down and rolled up are recorded. The results are shown in figure 24.

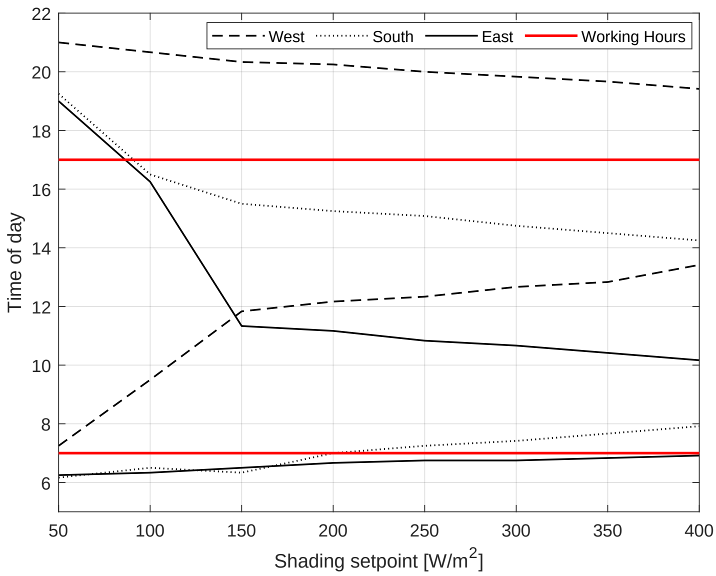


Figure 24: Closed hours for shading for varying setpoints. Upper and lower lines indicate the time when shades are rolled up and down, respectively

Figure 24 shows that after a large initial drop in the closed hours during the sunny day, the slope of further change with increased shading setpoint is quite low. For a west-facing window, a setpoint of 150 W/m^2 keeps the shades rolled down between 11:50 and 20:20 (total 8h30m), while for a setpoint of 400 W/m^2 the hours are 13:05 to 19:25 (6h20m). In both cases, shades are kept down for the entire afternoon office working hours and well into the evening. For the south-facing window the corresponding numbers are 6:40 to 15:30 (8h50m) and 7:55 to 14:15 (6h20m), keeping the shades down from the start of the working day to well into the afternoon. Finally, the numbers for an east-facing room are 6:30 to 11:20 (4h50m) and 6:55 to 10:10 (3h15m).

Diffuse light

To investigate how the amount of diffuse light entering trough a window is affected by different shading devices, rooms are placed in the facade regions with the lowest and highest annual average facade illuminance. The lowest levels, at around 5000 lux, are found in the lower northern corner of the eastern facade while the highest levels of around 16000 lux are found along the top of the western facade. The daylight factor is calculated in IDA ICE for these locations for small and large office rooms with the four different combinations of shading devices and fabric colours. The results are shown in figure 25. Since shades are not meant to be rolled down when skies are overcast, the daylight factor in itself is not a relevant measure. If shades cause insufficient light levels in a room, electrical lights will be used. It can however be relevant in cases where shades are rolled down excessively often or when they are broken and stuck in the down position. Additionally, comparing the daylight factor of different devices and fabrics gives a sense of their relative light transmissions levels.

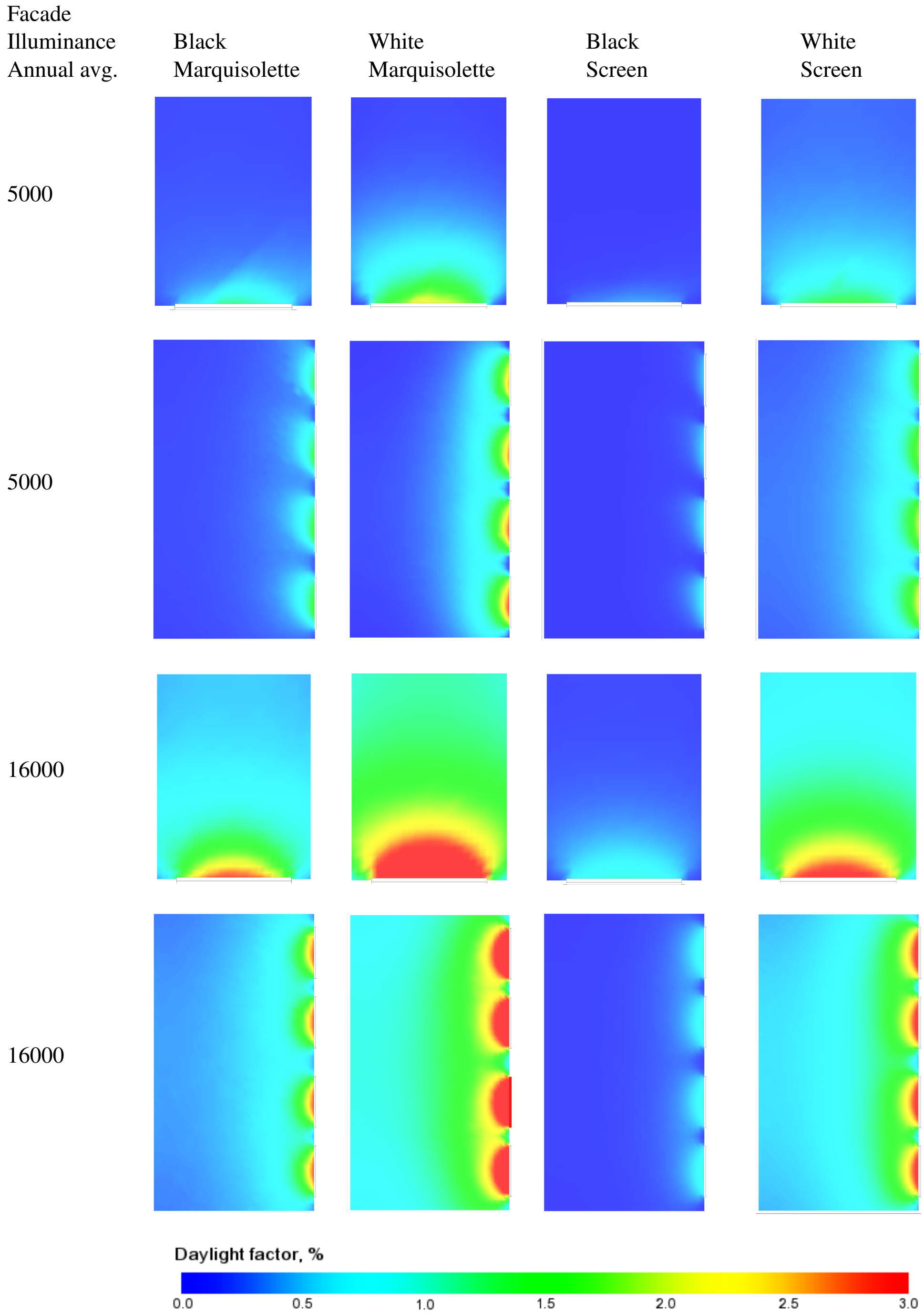


Figure 25: Daylight factor distribution for small and large offices

As expected, figure 25 shows that white fabrics allow more light ingress than black ones, while a marquisolette lets in more light than a screen. It can however also be seen that a white screen will make the whole room brighter than with a black marquisolette. Due to built-in awning feature, a marquisolette will also let significantly more light in to the area directly adjacent to the window than a screen will. Again it is worth observing that a white screen will perform better in this regard than a black marquisolette. The white screen will also provide a more even light distribution in the room when light is incident from the side as in the case with the low facade illuminance.

It is also apparent that the depth of the room impacts the daylight factor. The large rooms are deeper than the small rooms and so will have lower daylight levels at the back wall.

Direct light

Since the marquisolette is not parallel to the window over it's whole length, it will allow rays of direct sunlight to pass through the window in some specific pattern. This creates a light distribution inside the room which is constantly varying in both space and intensity. To visualize and map these variations, a small office room in each direction is taken from the IDA ICE model and an illuminance simulation is run for a specific point in time. The model is then exported to the software AcceleradRT where an image of the luminance distribution in the room is captured. The times chosen are midsummer, June 21st, where the sun it at it's highest, and one of the equinoxes, 21st of March or 21st of September, where the sun is at an "average" height. Since the shading season corresponds approximately to the period of time between the equinoxes, the equinox may be seen as approximately the lowest solar position that is likely to occur when shades are in use. It is confirmed, but not shown here, that the light distributions are almost identical on the spring and autumn equinoxes and therefore only one of them is considered.

Images are captured both with black marquisolette shades and with no shading. This makes it possible to determine how effective the shades are at preventing direct solar radiation at different points of time. By comparing the size and location of patch of direct sunlight in the room when the shading device is in place to how large the patch is without shading, a deeper understanding of the device's performance can be gained. Direct observation of the unshaded solar path can also provide insight on the characteristics of the incident sunlight at any given moment. Images for rooms in every direction are shown in figures 26, 27 and 28.

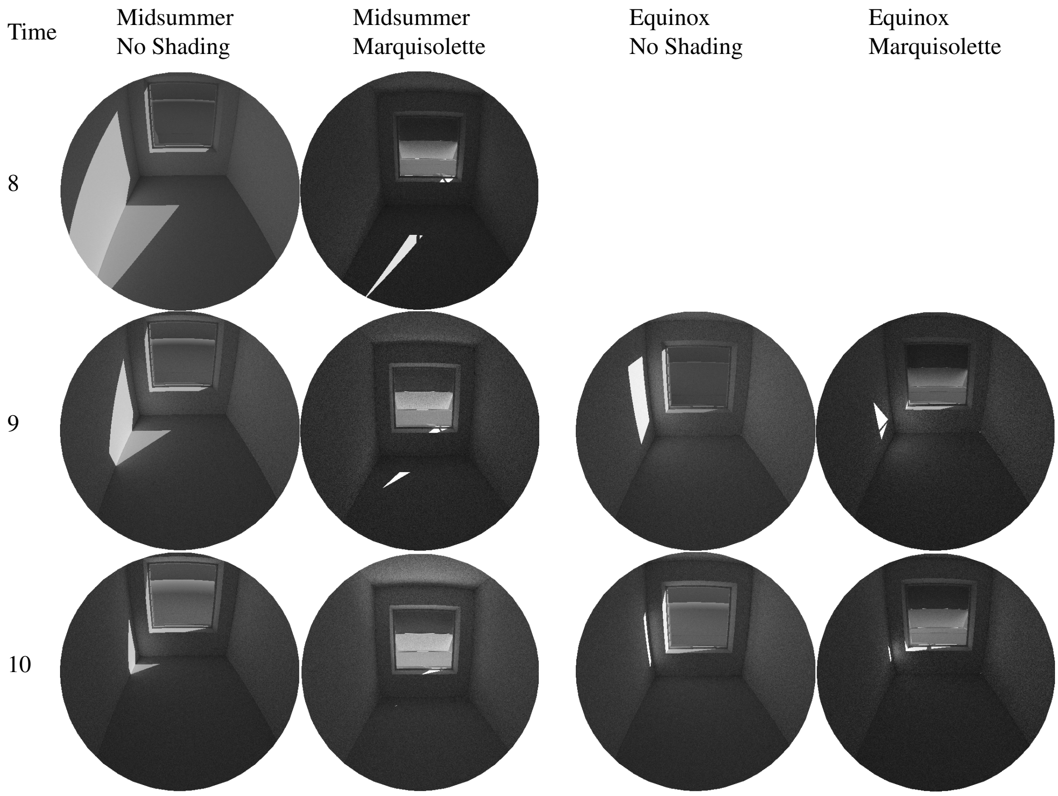


Figure 26: Variation of direct sunlight during one day in room facing east

Figure 26 shows that in the room facing east the sun only enters the room for a few hours in the morning. In midsummer the sun sits quite low at 8.00 and enters deep into the room but as the sun rises and moves towards the south the light hits the window more and more from the side and the patch of direct illumination is quickly reduced in size. On the equinox the light hits largely from the side and does not enter very far into the room to begin with.

It is clear from the images that the marquisolette is very effective in reducing the ingress of direct sunlight into the room. The patch of direct sunlight is reduced to a small fraction of it's unshaded size.

Figure 27: Variation of direct sunlight during one day in room facing south

Figure 27 shows that direct sunlight enters the south-facing room from the morning until the early afternoon. It can be observed that the marquisolette is extremely effective at preventing entry of direct sunlight when it is oriented towards the south and the sun is high in the sky. At the equinox, when the sun is lower, more light is able to enter below the marquisolette.

Figure 28: Variation of direct sunlight during one day in room facing west

Figure 28 shows that direct sunlight enters the west-facing room from the early afternoon until the end of the working day. On midsummer, the sun does not start to enter from the side the marquisolette until the very end of the working day. On the equinox the low sun in the late afternoon can enter below the marquisolette and potentially cause glare issues.

Luminance and glare

To investigate the magnitude of glare through shading fabrics of different colours, moments in time where the sun is directly visible through a window are identified. This can occur in mornings to the east and south, in the evenings to the west and during mid-day to the south. The higher the sun is in the sky, the closer one has to be to the window to have a direct view of it. Consequently, the prevalence of glare is higher in moments when the sun is low and reaches far into the room since the probability of an occupant having a view of the sun is higher. For the moments in question, a view out of a window is simulated in AcceleradRT with different screens implemented over the window. Due to limitations in the interaction between IDA ICE and AcceleradRT, it is not possible to set values for the diffusion factor for objects exported to AcceleradRT, including the shadings considered here. The default value for the diffusion factor in the IDA ICE daylight module is 0 but it is not known if that value is used by AcceleradRT or if some other value is substituted. Consequently it is likely that the true behaviour of the white screen is not captured and that the illuminance reduction values recorded are lower than they are in reality. Vertical illuminance at eye level is recorded, as well as the daylight glare probability. These results, along with the camera view showing the solar position, are presented in table 7.

Table 7: Reduction of glare for white and black fabric screens with direct view of the sun

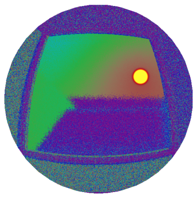
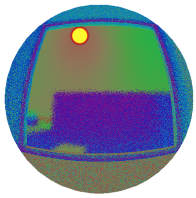
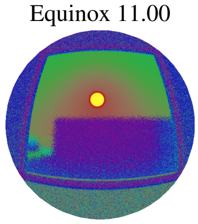
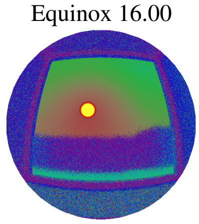
Direction Time	East Midsummer 08.00	South Midsummer 11.00	South Equinox 11.00	West Equinox 16.00
Solar position				
No screen				
Vertical eye illuminance	37976 lux	34800 lux	45557 lux	44180 lux
DGP	100%	100%	100%	100%
White screen				
Vertical eye illuminance	16400 lux (-56.8%)	21290 lux (-38.8%)	21609 lux (-52.6%)	20588 lux (-53.4%)
DGP	100%	100%	100%	100%
Black screen				
Vertical eye illuminance	3965 lux (-89.6%)	5153 lux (-85.2%)	5245 lux (-88.5%)	5014 lux (-88.7%)
DGP	72%	73%	80%	81%

Table 7 shows that the white screen fabric reduces vertical eye illuminance 38% and 57%, which is not enough of reduce the daylight glare factor to less than 100%. The black screen fares better, with reductions of vertical eye illuminance of between 85% and 90% and resulting DGP levels of 70% to 80%. As explained previously, IDA ICE does not allow setting diffusion factors for objects exported to AcceleradRT. It is therefore possible that the values obtained for vertical eye illuminance for the white screen are lower than they would be in reality.

To determine the effect that various shading devices and fabrics have on the brightness of surfaces inside a room, luminance studies are carried out in AcceleradRT. All four shade combinations are simulated at two times on midsummer. At 12.00 the sun is positioned directly in front of the marquisolette in such a way that all direct light is effectively blocked, meaning that no patch of direct sunlight is visible in the room. This means that at this specific point in time, only diffuse sunlight enters the room. At this moment, a comparison is made between marquisolette and screen devices to determine how much brighter the room will be with a marquisolette in the case where no direct light enters the room.

Simulations are also run for the same room with the same shading combinations at 10.00 on the same day, at which time a certain amount of direct light is able to enter the room underneath the marquisolette. This enables the comparison of cases to determine if this added direct light has an impact on the observed luminance of surfaces.

In all cases the daylight glare probability (DGP) is recorded for each full view and presented under each picture. The results are presented in figure 29.

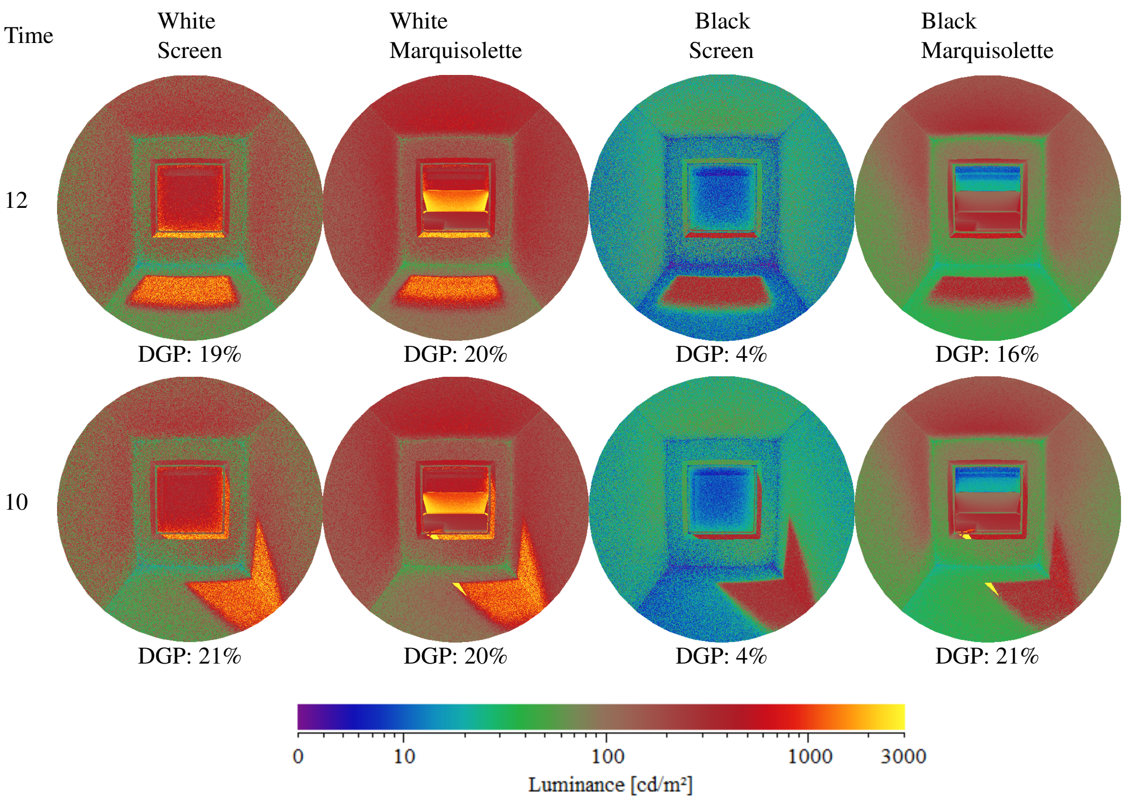


Figure 29: Luminance distribution in small southfacing office room on Midsummer

Figure 29 shows that the surfaces in a room where the window is shaded with a marquisolette will be brighter than if it were shaded with a screen. The difference is larger for devices with black fabric than for ones with white fabric. It can also be seen that there is no significant difference in luminance distribution due to direct sunlight entering on the side of the marquisolette, compared to if the marquisolette effectively blocks all direct light.

The investigations of solar paths and direct sunlight (figures 26, 27 and 28) showed that there are times when the sun hits a window at a very small angle, allowing only a relatively small amount of direct sunlight into the room. Heat transmission through the window is also lower when the angle of incidence is small. In this situation it is likely that the irradiation of the facade is still sufficient too keep the shades lowered even though a relatively small amount of heat is actually transmitted into the room. This would lead to a loss of daylight that might not be justified by the comparatively small savings on cooling. To visualise the loss of daylight in this situation, two points in time where it occurs are identified and luminance distribution images are captured in AcceleradRT. It is found that the particular conditions occur in the east-facing room on midsummer at 10.00 and in the south-facing room on the equinox at 14.00. Results are shown in figure 30 both with and without shading.

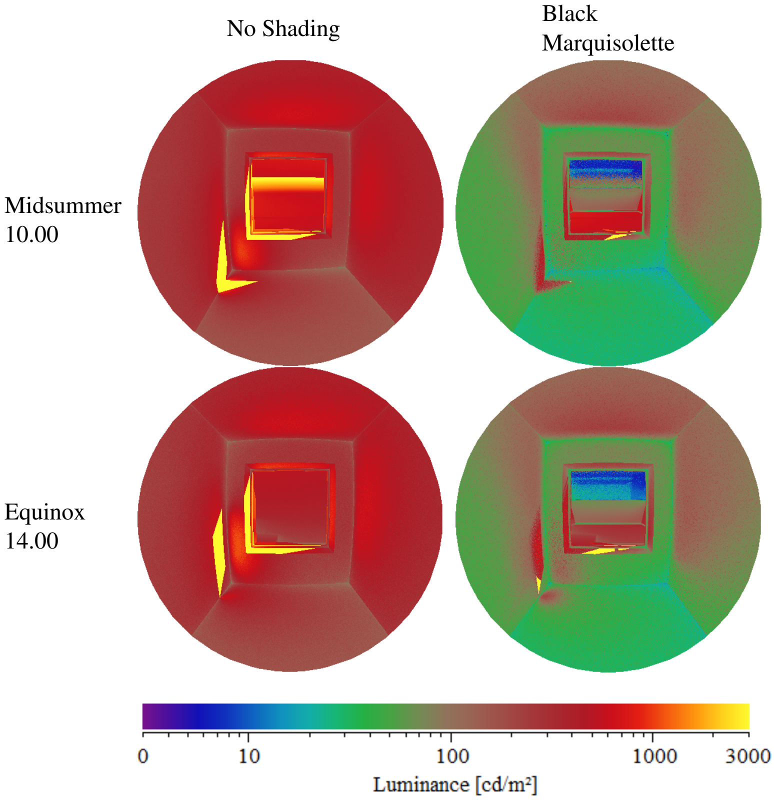


Figure 30: Luminance distributions in small east-facing (top row) and south-facing (bottom row) office rooms

Figure 30 shows the relatively small size of the patch of direct sunlight which enters the room when the window is not shaded. Comparing this image with the shaded case shows a significant decrease in luminance levels in the room. It should still be noted that the bright patch of direct sunlight on the floor or wall in the unshaded case could be a source of glare, depending on how the room is furnished and the positions of occupants.

7 Discussion

The results obtained in the study are analysed and discussed.

7.1 Thermal comfort

Several possible causes were investigated for the occupant discomfort reported in the occupant survey. The building has several features and properties that can cause undesirable conditions under certain circumstances. The magnitude and temperature of the supply air flow were found to play a large role in the thermal comfort of occupants, as well as their clothing level. The velocity of the supply air was also found to be impact the results in the model but it is hard to say if this problem exists in the real case. The hypothesis that increased air flow leads to higher air velocities in the room is not necessarily correct since the supply air diffusers may be designed to avoid this issue. Accurate modeling of this phenomenon is not possible irrespective of the applicability of the underlying assumptions.

In general, it is risky to make claims about the thermal comfort of a room based on assumptions about clothing levels. In the investigation it was assumed that occupants were wearing relatively little clothing and that this was to some extent the cause of their discomfort. It was shown that the discomfort could be eliminated almost entirely if occupants wore clothing with a thermal resistance of 1.0 clo. In reality people can, to some extent, adapt their clothing to existing conditions. In the full-year simulations this was taken into consideration by allowing clothing levels to vary within certain bounds automatically. In the investigations of the survey results, however, it was assumed the value of clo was kept constant. This could be said to correspond to a situation where an occupant has left home dressed for warm weather and therefore has not brought along additional clothing. Under certain circumstances the building could then provide more cooling than is comfortable for the lightly dressed occupant.

Air flow rates were also shown to play a large role both in the heat balance and for CO_2 concentration. Although the exact air low rates used in the real building are not known, a minimum air flow of 0.35 $l/s \cdot m^2$ needs to be maintained at all times. This provides a baseline from which further investigations can start. As explained, it is not possible to set varying air flow rates for different times when using the default VAV control strategies in IDA ICE. It is possible to make a custom VAV control macro but this was not attempted due to lack of time and knowledge.

7.2 Ventilation

It was found that VAV ventilation with temperature or CO_2 control could provide between 20% and 25% reduction in annual use of fan energy for large office rooms with constant full occupancy. For the smaller office room savings were smaller, 17.4% for temperature control and only 5.1% for combined temperature and CO_2 control. The small office is more likely to be fully occupied but neither room type is fully occupied all the time. For the large office, savings of 20% to 25% were found with VAV control when occupancy was only 2 out of 8 employees. It might be tempting to think of this as an "average" occupancy over the whole year but in reality the occupant density will be constantly fluctuating and the impact of the associated heat loads on the heat balance will depend on the conditions at any given moment. Accurate modeling of variations in occupancy is complicated and would likely need to involve statistical treatment of randomized occupancy. Irrespective of this, there appears to be a pattern where savings are smaller the more densely occupied a room is.

In addition to occupant density, sunlight was found to have a significant impact on the performance of the ventilation system. Even with marquisolette shades in place, PMV values rise sharply over the course of a sunny day. For a CAV system the values reached depend on the air flow and occupancy rates. For the small rooms with full occupancy (2 employees) PMV values of up to 1.5 are recorded at the peak, indicating quite severe thermal discomfort. For less densely occupied rooms the PMV values are kept at more acceptable levels. However, it is apparent that the air flow rates needed to mitigate the thermal discomfort due to overheating are too high on days where the skies are overcast. On these days, not even the most densely occupied rooms have PMV values reaching -0.5. Consequently, if CAV is used it will be very difficult to maintain thermal comfort without the use of added cooling.

Temperature controlled CAV was shown to be capable of moderating PMV throughout the day but the decreased air flow rates compared to CAV lead to higher concentrations of CO_2, exceeding 1000 ppm in both rooms at full occupancy. The small office rooms have especially high concentrations, peaking at around 1600 ppm. Since higher indoor temperatures are needed in order for the system to supply sufficient air flows, on overcast days and in the early morning the system is not capable of simultaneously maintaining acceptable thermal comfort and acceptable air quality.

In order to maintain an acceptable concentration of CO_2 in the fully occupied rooms, temperature controlled VAV is not sufficient. It is necessary to also have CO_2 control. In the existing building CO_2 control is implemented in rooms with a capacity of more than six occupants. However, the results obtained here seem to indicate that the largest need for CO_2 control is actually in the small office rooms with only two occupants since that is where the highest CO_2 concentrations are reached. This shows the benefit of considering occupant density rather than just the number of people present.

It was that the annual fan energy is lower when VAV is used rather than CAV. In most cases it was also clear that the combination of temperature and CO_2 control yielded slightly lower fan energy use than if only temmperature control is used. However, this does not hold true in the rooms with the highest occupant density, which are the small office rooms. Here it was instead observed that more fan energy is used annually if CO_2 control is implemented. The reason for this outcome is not entirely clear and it is possible that some error was made in the process of obtaining the results. A possible explanation of the discrepancy could be that there exists a point where increasing occupant density leads to such high concentrations of CO_2 that the pattern of correlation between the control strategies is flipped because the amount of time that the fans need to be in use increases significantly.

7.3 Shading

As expected, the investigations showed that shades block sunlight of all wavelengths, meaning that if shading is implemented in order to decrease heat gains from the sun, it will also decrease the amount of visible light which enters the room. One way of interpreting this is that indoor environmental quality and visual comfort of occupants can be increased by reducing the amount of shading at the cost of increased heat gains. The added heat gains are likely to lead to increased costs for cooling but the extent of this increase depends highly on the specific building. Many occupants reported in the survey that they were both too cold and that they thought there wasn't enough daylight. The investigations of the case study building showed that the building often exhibited large negative PMV values even on days with strong sunshine. In this particular building it is thus clear that the windows are shaded when it is not needed, unnecessarily reducing both the thermal and visual comfort of occupants. However, this observation is only valid for this particular building and for a given set of assumptions and circumstances. This shows the importance of keeping all factors in mind when designing the building so that factors that work against each other are balanced.

The results for thermal comfort for east-facing windows stood out in the investigations of shading devices. The reason for this is not entirely clear but it is possible that it is related to the comparatively smaller amounts of sunlight that reach the eastern facade during the course of the day compared to the other facades. Since the building has been shown to warm up over the course of the day, the fact that rooms to the east can not receive any sunlight after noon could explain why the cumulative time spent at PMV values below -0.5 is higher for these rooms. Similarly, rooms to the south and west would have more hours above 0.5. It was also found that the annual cooling energy used in the rooms is in general lower for east-facing rooms than for other directions. This effect is especially pronounced in rooms with comparatively high occupant density.

Although the reasons for the variation of PMV and cooling energy with direction are difficult to ascertain, it illustrates the importance of closely investigating how the building behaves both in space and in time. In the case of this specific building it means that there might be room to allow more extensive measures to improve occupant comfort in east-facing rooms since they have been shown to behave differently from rooms in the other directions. Examples of these measures could be to implement shades with brighter colours on the eastern facade or to have marquisolettes which cover less of the window or that have awnings which are less obtrusive. It could also be a good idea to plan the layout of the building so that rooms with high occupant densities are placed in rooms facing east since they will not have the same high solar heat gains in the afternoon.

Simulations showed that for the shading setpoint implemented in the existing case study building, shades are rolled down for large portions of the working day, negatively impacting visual comfort both by blocking daylight and by reducing the view to the outside. If shades were to be rolled up occasionally even though facade irradiation exceeded the setpoint, occupants would have temporary reprieve from the darkness and the obstructed view to the outside. This increase in visual comfort can be weighed against the increased cooling demand. Considering that most electricity in Sweden is produced from renewable sources the main reason to limit the amount of energy spent on cooling is the added cost to the owner of the building. From this perspective it can be considered that this increased cost is actually the cost of increased occupant comfort. However, depending on the type of cooling and ventilation systems used, the added heat gains through the unshaded windows can actually contribute to overheating which will increase thermal comfort even if visual comfort is improved.

When considering the visual comfort at times when the shades are rolled down, it is also necessary to keep in mind the impression that the colour and brightness of the shade fabric has on the indoor visual comfort since it will essentially be a part of the indoor environment, equivalent to something like a wallpaper. To some extent this is subjective and perhaps mostly a matter of interior design or decoration. Although no scientific findings on the subject were identified in the literature study, it is reasonable to assume that a black shade fabric will create a darker and perhaps gloomier indoor atmosphere than a brighter, or even white, fabric will. It is known how these properties of the fabric affect glare and diffuse light transmission but the psychological effects of the colour in itself and the resulting visual impression is harder to gauge.

Through detailed study of the solar path around the building at various parts of the year, it was found that there are certain moments in time when the shades are likely to be rolled down because the irradiation of the facade is sufficiently high but the angle of incidence of the light on the window is so small that a significant portion of the light will not be transmitted through the window. If the signal for rolling down the shade only takes facade irradiation into account, there will be times when the shading device is rolled down even though the heat gain through the window is comparatively small. This needlessly lengthens the already extensive time that the shades spend rolled down. It may be considered to place sensors on the inside of the window instead of on the facade to measure the actual transmitted radiation but this would require customized control for each room and exact placement of sensors in a good spot. Since the solar path varies so much during the year it would be difficult to find a sensible placement.

It was confirmed that a dark shading fabric is more efficient at minimizing glare, while also making the room darker. It was not clear to what extent the simulations were capable of capturing the exact behaviour of brighter shades in terms of the luminance of the screen itself. Due to limitations of the softwares used, it was not possible to set the diffusion fraction of the transmitted light for the shades. Because the fabrics have significantly different values for visible light transmission, it was expected that the room shaded with white fabric would exhibit much higher levels of vertical eye illuminance than the room with the black one. A large portion of this effect can be attributed to the higher transmission of direct light but exactly how much depends on how the value for diffusion fraction was set in the Radiance calculations. If it was set to a default value of zero then it would indicate that the values obtained are entirely due to direct transmission and that there would in reality be an additional amount of diffuse transmission, further increasing the vertical eye illuminance behind the screen. If the value of the diffusion fraction was higher than zero, it would indicate that a certain portion of the vertical eye illuminance was due to diffusion of light within the shading fabric.

No reasonable strategy for automatic glare control was found or attempted. Due to the dynamic and complex nature of glare it is difficult to imagine a way of automatically blocking the light that doesn't involve blocking windows completely. If only glare control is desired, for example in winter when heat gains from the sun are beneficial, a reasonably useful automatic glare control system would have to detect the presence of occupants as well their position and the direction of their gaze. Some type of automatic shading device would then have to be deployed to shade only the occupant's view of the sun. Such a technology is clearly not realistic. A more realistic glare control system might be implemented by shading parts of a window during certain times when the sun is known to present glare issues. Awareness of the sun's daily and annual path as well as the expected positions of occupants at different times can help in identifying situations where simple measures can be implemented to improve glare issues.

The most sensible solution to glare problems is likely to provide shading devices that occupants can use on their own to suit their current needs. This could mean venetian blinds or curtains or some other device which is accessible to the occupant and which can be manipulated to achieve varied coverage of the window. It may also be beneficial if the layout and furnishing of a room allows occupants to change their position or direction in order to continuously adapt to changing conditions. Glare mitigation measures that rely and depend on occupant behaviour are extremely difficult to model and quantify but are likely to provide better performance than any attempt at making automatized solutions.

7.4 Complexity and fragility

A recurring phenomenon in many of the situations studied is that the building is poorly equipped to handle conditions that vary, either in space or in time. This could be for example when sources of heat or pollution (such as humans) are added or removed suddenly or when there is a large discrepancy between the sizes of heat loads in different parts of a building. Occupant discomfort can occur if appropriate measures are not taken to address changing conditions. In order to optimize the indoor environmental quality in each possible set of circumstances, time and effort needs to be expended to investigate how the building behaves, what the issues are and how they can be mitigated. Attempting to rectify an issue in one particular place at one particular time can cause new issues in some other place or time.

The more the building and it's features are customized to achieve the desired improvements, the more complex it will be both to design and to maintain. For example, simulations showed that if the VAV system in a densely occupied office room was only controlled by the temperature, the CO_2 concentration in the room exceeded acceptable levels during times when skies were overcast since the temperature in the room only reaches levels high enough to increase the air flow rate when the sun is out. This illustrates the complexity of dealing with several indicators with highly variable loads. It also shows how successful management of this increasing complexity in a system relies heavily on the existence of appropriate sensing equipment.

It has been shown that a VAV system controlled both by temperature and CO_2 is capable of maintaining desirable conditions both for thermal comfort and air quality. However, both of these techniques require sensors, i.e. thermometers and CO_2 meters, to function. These sensors introduce both added costs and added complexity, with added fragility as a result. For completely accurate control, each room needs to be equipped with it's own set of sensors. Each sensor needs to be chosen, installed, integrated into a control system and maintained. Financial considerations are likely to play a large role in all of these aspects. The health and comfort of occupants may be neglected if the responsible party decides that it is too expensive to equip each room with sensors. The more sensors are used, the more likely it is that some of them will break or malfunction, necessitating adjustments or repairs by skilled workers. Replacing a broken sensor might be difficult or impossible if a certain product is no longer available on the market or if the system has been outdated and replaced by newer technology. The rapid advancement of digital technology makes it difficult to predict the longevity of a control system.

Another risk of excessive complexity is that there may be discrepancies between the intended configuration and performance of a control system and the real outcome. If workers tasked with installing, operating or maintaining a control system have insufficient information or training, the system may not be configured or operated according to the intended design. A lack of information can be caused by a lack of communication between different actors in the building process. A possible outcome of this could be for example that the setpoint for shading devices in a building is left at a default setting which is unnecessarily low, causing shades to roll down when they are not needed and thus significantly decreasing the visual comfort of any occupants.

Another example of complexity is the added fragility inherent in the design of movable shading devices relative to their fixed counterparts. A fixed overhang or awning is unlikely to break very easily while a movable shading device like a marquisolette is sensitive both to mechanical or electrical malfunctions and to damage from harsh weather like frost or strong winds. This can be mitigated by programming the shades so that they are not rolled out if conditions are inclement but this depends on correct implementation of the intended design. In any case it should be assumed that movable shades will require more frequent maintenance and repair than fixed shades.

In order to facilitate and encourage increased consideration of occupant health and comfort when implementing energy saving measures, it would be beneficial to identify what measures and strategies are the most efficient at improving occupant comfort and to then develop more standardized and streamlined methods for implementing those measures and strategies. The investigations undertaken in this project were exploratory and time consuming. To exemplify, visualizing the daily and annual path of the sun and the resulting intrusion of direct light was useful for understanding the building and how to improve it but it relies on the right knowledge of "hidden" capabilities of a certain software and how to integrate it with another software which is itself experimental. Obtaining the results exhibited here required running a large number of simulations and a significant amount of organization. If occupant comfort is not a priority it might be hard to justify spending large amounts of time on these types of investigations. If a software existed that could automatically simulate the solar path and visualize the results, these observations could serve as the basis for decisions on the type and colour of shading devices or the configuration of VAV systems.

8 Conclusions

The conclusions from the project are presented as follows.

General conclusions

- The behaviour of a building needs to be investigated under as many circumstances as possible to ensure that incidences of occupant discomfort are not missed.
- Some amount of improvement in occupant comfort can be made by careful customization of the building and it's features.
- Accurate modeling is very complex. Significant simplification is necessary but not so much that occupant discomfort is hidden and missed.
- Increased customization of a building leads to more complexity. The more complex a system is, the more expensive and fragile it is to design, run and maintain, decreasing the probability of successful implementation.
- Development of standardized and streamlined methods for identifying and addressing sources of discomfort would facilitate increased consideration of occupant health and comfort.

Ventilation

- Due to large variations in solar heat loads it is difficult to provide stable thermal comfort using CAV.
- Temperature controlled VAV can moderate thermal discomfort but there is a risk that air quality is neglected in densely occupied rooms due to low air flow rates on overcast days.
- The combination of temperature control and CO_2 control for VAV can achieve both thermal comfort and acceptable air quality in densely occupied rooms.
- Occupant density can be a useful metric for determining if it is necessary to implement CO_2 controlled VAV.
- Up to 40% savings in annual fan energy use can be obtained through the use of VAV over CAV. Savings are larger the less densely occupied the room is.
- If there are large differences between heat loads in different parts of a building, it may be useful to have several air handling units serving separate areas. This provides more control over the range of airflow rates available.

Shading

- Detailed study of the solar path and the pattern of ingress of direct light in a room can be useful in deciding what measures to implement.

- During sunny days, shades are likely to be rolled down during large portions of the working day, reducing daylight and view to the outside. Temporary breaks in shading can be employed to provide a boost of visual comfort at the expense of added cooling energy.
- When the sun hits a window at a small angle from the facade it is likely that the transmitted heat is so small that the efficacy of the shading is not high enough to justify its use. If possible, shading could be rolled up earlier even if irradiation setpoint is exceeded.
- Shades with lighter colours allow more light into the room but also more heat. The colour of the shading fabric can be modified to achieve a desired balance of heat gains and daylight provision.
- Dark shade fabrics are better at reducing glare. If shades are too light-coloured they can become a source of glare.
- Glare is difficult to control automatically. Providing occupants with manually operated devices such as venetian blinds or curtains is a better solution.
- The direction of a window is important in determining how shading impacts the thermal and visual comfort of a room. The floor plans in the building as well as the layout and furnishing of rooms can be planned to make use of existing variations in heat loads and direct sunlight.
- Rooms facing east are less likely to overheat than rooms facing south or west. Lighter and more open shades could be allowed in these rooms.

9 Future research

As stated in the conclusions, there is a need for further research into how and why occupant discomfort arises and how it can be mitigated. The more complex and costly it is to identify these sources the less likely it is that they will be dealt with. If research was carried out to identify common sources of occupant discomfort, methods could then be developed to make it as easy and inexpensive as possible to minimize the discomfort.

It would also be useful to conduct further investigations on the economical and organizational aspects of the issue, to identify any obstacles that prevent the successful implementation of measures that promote improved comfort and health. For example, it has been discussed in the thesis how a lack of training or documentation can lead to outcomes that differ from the intended design. It could be studied how to improve coordination between different actors and disciplines. From the economical perspective it would be useful to perform holistic studies of the costs and benefits of the measures. Focusing on occupant comfort and health is likely to incur costs, at least initially. Engineering time needs to be spent on finding and correcting issues, investments have to be made on equipment and continuous maintenance is required during operation. It can, however, be assumed that economical savings can be achieved through these efforts, if they lead to increased performance and decreased absenteeism among employees. If these savings are balanced against the added costs, it may turn out that a focus on comfort and health is actually a net benefit.

10 References

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