Fei Ding

Daylight integration and visual comfort in sports halls in Norway

Master’s thesis in daylighting in sports halls

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Abstract

Sustainability has been the trend of architecture industry in recent years. It is now more acceptable that daylight, when available, should be the predominant form of lighting in most types of building. However, there has been a concern of introducing daylight into sports halls. For it may cause visual discomfort and overheating.

This master thesis investigates visual comfort of two types of roof daylight system in large scale sports hall. The daylight systems of the two alternatives were inspired by Pajol sports hall in Paris and sports hall of secondary school in Klaus, a saw tooth roof and a skylight roof. A dot pattern laser cut panel was combined with the skylight roof to scatter the sunlight which is the main source of glare. The two alternatives were further developed by studying the impact of different parameters of a 3D model through computer simulations of annual daylight distribution. Daylight autonomy was simulated with the climate file of Trondheim, Norway.

The designs that meet the requirement of 4% average daylight factor on the plane which is 1m above the floor are used to make the physical models. The series of images taken from the interior space of the physical models can be merged to HDR Images. These images can be used to analyze the luminance distribution and calculate luminance contrast ratio for glare estimation in Radiance and Grasshopper.

In order to estimate the energy saving potential of the two daylight systems, three SIMIEN models were constructed to compare the lighting energy consumption and total energy consumption of the two alternatives and a black box sports hall.

The results of the luminance analysis show that the dot pattern laser cut panel on skylight roof resulted in extreme high luminance value, the luminance contrast ratio between the target object and its close surroundings is 1: 9.2 which means the visual comfort is low in the room. While the luminance contrast ratio in north orientated saw tooth roof sports hall is 1: 3.7 which means that the visual comfort is moderate in the room.

The data collected from SIMIEN simulations show that the two alternatives can save more than 40% of lighting energy consumption comparing to a black box sports hall. However, when considering the heat loss, the saw tooth roof only saved 2.6% of total energy consumption, and the skylight roof can save 12.7% of that.

To introduce daylight in sports halls is not as easy as other types of buildings; there should be more research to be continued.

Acknowledgements

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I would also like to express my deepest gratitude to my husband and family, for their support and understand during my thesis work.

Last, but not least, I am very grateful for the contribution of Professor Barbara Szybinska Matusiak at NTNU who provided important instructions and many constructive suggestions, and reviewed this thesis.

SIAT

SIAT is the center for sports facilities and technology, which is located in the faculty of engineering science and technology at NTNU. There are nine employees in the center. They work closely with the Department of Culture and The Norwegian Olympic and Paralympic Committee and Confederation of Sports. The focus is to achieve high quality, cost efficient, energy efficient building performance of sports facilities through scientific knowledge and technological solutions. There are over 3 billion NOK of sport facilities built every year in Norway. However the demand for knowledge within the field of sport facilities is increasing. They proposed the topic of this master thesis to gain additional information about daylighting which may aid them in further sports facility projects.

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Abbreviations

DA Daylight autonomy

DF Daylight factor

DGP Daylight glare possibility

GFAR Glass to floor area ratio

HDR Images High dynamic range images

LDR Images Low dynamic range images

LCP Laser cut panel

UGR CIE Unified Glare Ratings

1. Introduction

1.1. Background

Daylight inlet in sports halls is controversial. In Norway it has been common to build sports halls completely without windows in the hall area (Kulturdepartementet, 2016). Even with windows they are quite small, figure 1.1. Since there are no specific daylight requirements in Norwegian building code for sports halls, window becomes an element excluded from the sports hall design. Windows are normally considered as the potential glare source which may cause visual discomfort for users. Additionally, when direct sunlight hits a TV screen, it may cause undesirable reflections of sunlight. Windows create a number of design, construction and operating issues that tend to increase capital costs (SportEngland, 2012).

However, with increased concern for users and environment, daylight, which is essential for human beings health, is often introduced into different types of building to reduce lighting consumption and ensure architecture quality. If the daylight system is appropriately designed, it can minimize visual discomfort, improve the users' experience and reduce the energy consumption which makes it worthy of investigation (D.Ander, 2016).

a) b)

Figure 1.1 Sports halls from the 70s in Norway.

a) Interior of Makrellbekken Njårdhallen in Oslo. Photo from (Leif, 1960). b) Interior of combine hall at Slependen in Bærum. Photo from (Leif, 1974).

1.1.1. Benefits of daylight

As stated in LEED certification:

The intent of daylighting is to connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space.

LEED v4: Daylight, 2013

The *International Energy Agency* states that lighting consumption accounts for near 20% of global electricity consumption which is more than the yearly total electricity production of nuclear power stations in the world (McSmith, 2006). In building industry, artificial lighting consumption represents about 11% of energy use in residential buildings and 18 percent in commercial buildings (*Building energy data book*, 2011). It can generate billion tons of carbon every year. The consumption of lighting will increase by twice in the future because of the world's development, and the carbon dioxide emission will be even higher.

The sustainability has been promoted to save energy and to reduce environmental impact in building industry for many years. However, energy usage of artificial lighting can't be reduced unless the artificial lighting can be dimmed down or switched off according to the interior daylight level (Leslie, 2003). A properly designed daylighting system not only can reduce the lighting consumption; but also can further reduce the cooling loads of internal equipment. The reduction of the artificial lighting energy usage can additionally save 10% to 20% of energy usage of the cooling loads (D.Ander, 2016). By implementing daylight strategies the artificial lighting energy consumption can be reduced that directly lowers the carbon emission and green gas effect, as well as the material usage of bulbs and lighting system and the maintenance. For many institutional and commercial buildings, the total energy costs can be reduced by one-third through optimal integration of daylighting strategies (D.Ander, 2016).

In addition, another powerful impact of implementing daylight strategies is on the building users. It is known that daylight is essential for adjustment of human circadian system which keeps human body sync with the 24-hour day. Among all the factors the melatonin, which chemically causes drowsiness and lowers body temperature, plays a key role in controlling the biological clock. There are no specific research's results about the impact of daylight on the performance of athletes yet. However, the research of Edwards and Torcellini (2002) shows that daylight can improve performance and productivity of office workers. The yearly lighting cost of one worker is equivalent to his or her one hour salary. The British Council for Offices (BCO), conducted a study which shows that good daylight design and adequately daylit space result in 3–20% increase of office workers' productivity (Morrell, 2005). Thus the financial importance of a well daylit environment can't be ignored. Studies also state that natural light is helpful to increase attention and alertness for monotonous work. Through the view towards outside people gain additional information, such as weather, time, and orientation. Views can even make people satisfactory and pleasant by providing images of nature. Therefore, it is quite possible that natural light also has positive effects for players' psychological and physical health in sports facilities.

1.2. Limitations

Visual conditions in sports halls are different from the typical stationary working space. Players move around inside the playing area instead of staying in a fixed position at the work area, which makes the analysis difficult. Moreover, the material choices for making physical models in the workshop are limited, and the time allocated for the master thesis is limited too. The physical models are not quite detailed. The chosen materials have higher surface reflections than the recommendations stated in *idrettshaller planleging og bygging*. And the windows in physical models only have one layer of clear acrylic which will increase the interior daylight level than expected.

1.3. Aim

The aim of the thesis is to investigate the visual comfort inside sports hall in Norway when changing building orientation and applying two types of roof lights, saw tooth and point skylights. Modelling tools like Rhino and Grasshopper are used to perform climate-based studies of appropriate size and position of the roof openings. Physical models are made in order to get calibrated HDR Images which can be used for luminance ratio calculation. And SIMIEN simulations are also performed to compare the energy saving potential of the two alternatives and sports hall without windows.

2. Literature review

2.1. Sports hall in Norway

2.1.1. Size of sports hall

The Sports hall provides space for training and different activities for children and youth. There are three basic sizes of sports halls, small, middle and large, as shown in table 2.1. A sports hall for training and competitions for wide-angle sports shall have a free internal floor area of at least 25 × 45 m, with a ceiling height of at least 7 m across the entire activity area. However, more athletes want higher ceilings and require a minimum of 9 m ceilings at national and international competitions. The large size sports hall with a 9 m ceiling height is also described as a normal size in *idrettshaller planleging og bygging*. That is why it is used as the size for the base model.

Type	Length (m)	Width (m)	Height (m)
Small	23	20	Min 7m ceiling height
Middel	30	23	
Large	45	25	Min 9m ceiling height

Table 2.1 Sports halls types in Norway. Source from (Kulturdepartementet, 2016)

2.1.1. History of sports hall in Norway

From 1900 sport arose in Norway as a type of leisure activities. As the development of the activity, new facilities became necessary to house users. The financial support mainly came from gaming funds which is the profits from betting and lotteries since 1948. From 1965 to 1985, the sports share of the gaming funds increased from 12 million NOK to 324 million NOK. And a massive amount of sports facilities were built (Goksøyr, 2008).

From 1970 to 1984 there were 260 sports halls built in Norway. From 1985 to 1999 the number increases slightly to 285. The data collected from the *Sports Facility Register*, which is a public register updated frequently by the municipalities in Norway (at minimum once a year), shows that 482 sports halls have been built in Norway from 1996 to 2015. The annual built number of sports hall is shown in figure 2.1.

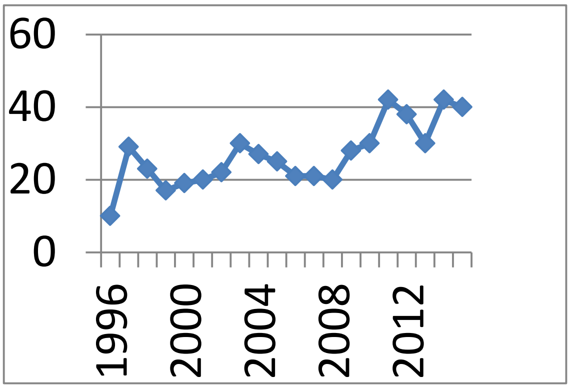


Figure 2.1 Number of built sports hall from 1996 to 2015 in Norway.

However the daylight performance in sports halls didn't cause as much attention as the increased construction numbers. Sports halls from the 1980s normally have no openings or small clerestory windows. In addition, many of 41 sports halls built in 2014 keep this form. Eleven of them are completely without windows. Five of them only have small windows on the facades. The last twenty-five lack certain information. It has been customary to build sports halls without windows in Norway.

There are several reasons behind this phenomenon. The first reason is the lack of the requirement. There is no regulation of sports hall design in Norway that specifies the daylight requirements, actually the mixture of daylight and artificial lighting should be avoided for some specific activities, like basketball and badminton (Kulturdepartementet, 2016). The second reason is the cost effectivity. Sports halls with large proportion of windows have higher cost in the construction phase and increase the heating and cooling energy consumption even lighting energy consumption is reduced (SportEngland, 2012). The third reason is the difficulty to achieve visual comfort in daylit sports hall.

Visual comfort has different dimensions: daylight availability, eye readapting ability, and view to exterior, contrast in the field of view, color and glare. The biggest challenge of visual comfort is to avoid glare problem which can cause visual disability for the audience and the players in sports halls.

2.1.3. Current daylight standards of in sports halls

Currently there are no specific requirements of daylight in sports halls according to the author’s search. In *Idrettshaller planlegging og bygging* it only says that the requirement for illuminance for international matches is 500 lux measured 1m above the floor, and with a uniform of 0.7, but it doesn’t give requirements of daylight.

The Norwegian building code TEK10 (2011) requires that rooms for permanent residence shall have satisfactory access to daylight. Requirements for daylight can be verified either by calculation confirming that average daylight factor in the room is a minimum of 2%, or by the room's glass area represents at least 10% of the floor area.

With room for permanent residence means living room, kitchen, bedrooms and workrooms in the unit. In construction works for public and work buildings, additionally, all work areas and public space are room for permanent residence.

TEK 10, 2011

It is not clear if a sports hall is a permanently occupied space. However, in TEK17 the “permanently occupied space” is defined as a space where people will stay continuously for more than 1 hour, or stay for more than 2 hours in a day. The players and the coaches train inside sports halls for more than 6 hours in workdays. And students have classes inside which can last for more than one hour. Rooms for permanent occupation should have windows providing adequate access to daylight. Thus there is a trend to introduce sufficient daylight in sports halls..

In the British rating system BREEAM-NOR (2016) which is an environmental certification system, one of criteria for pre-schools, schools and further education colleges requires that at least 80% of floor area in occupied spaces has average DF of more than 2.2%. And occupied space is defined as a room or space within the assessed building that is likely to be occupied for 30 minutes or more by a building user.

It is now more acceptable that daylight, when available, should be the predominant form of lighting in most types of building.

2.1.4. Examples of sports halls with well integrated daylight strategies

Actually there are some sports halls successfully integrated with daylight systems among recent built sports buildings. Most of these examples use roof light, for example, the saw tooth roof of sports hall in Paris and the skylight of sports hall in Austria.

Sports hall in Paris

The Pajol Sports is a new sports center designed by Brisac Gonzalez. The building has three levels so that it has the same height as the surrounding buildings as shown in photo below.

Figure 2.2 Pajol sports hall in Paris. From (Archdaily, 2014)

The lower two floors house the public space, material art and fitness center, figure 2.3. The 47 by 24 meter sports hall is placed on the top floor, so it can make use of the daylight which comes from the roof openings, figure 2.4. The vertical glazing panels of saw tooth roof are orientated towards north which is an advantage to avoid glare.

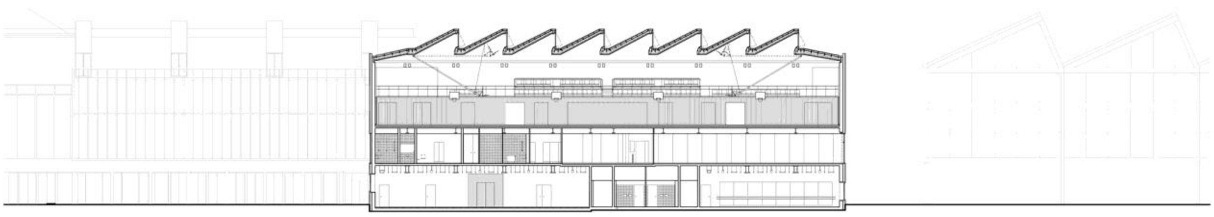


Figure 2.3 Longitudinal section. From (Archdaily, 2014)

There are eight windows on the east wall to provide view. When sunlight is too strong, they can be closed manually. The floor of sports hall is made of rubber, and the walls are made of two different colors of wood, the lower half part of wooden wall are painted with a darker color to avoid high contrast of objects, while the upper half part of wall and the ceiling are painted with a lighter color to help reflect the light down, figure 2.4.

Figure 2.4 Courtesy view from east. From (Archdaily, 2014)

Sports hall in Austria

Another excellent example of daylight integrated sports hall is the sports facility in the new secondary school of Klaus in Austria which is designed by Dietrich Untertrifaller Architects. The building has an energy consumption less than 15 kWh/m^2 and fulfils passive house standard. The three stories multi-purpose area is located in the eastern side which accommodates the day care, clubs and events rooms. The two-story high sports hall is situated next to the western side, as shown in figure 2.5.

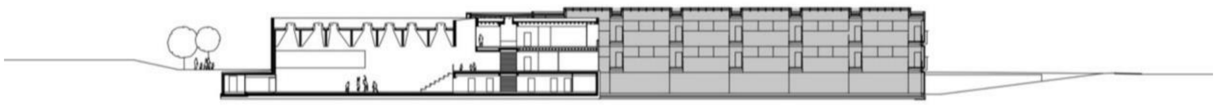


Figure 2.5 Section of the whole building. From (Archdaily, 2016)

The sports hall takes advantage of even daylight via a series of skylights. The light will be reflected by the inclined ceiling before it reaches the interior which helps avoid overheating and too bright scene, figure 2.6.

Figure 2.6 Courtesy section. From (Archdaily, 2016)

Figure 2.7 Courtesy view from west. From (Archdaily, 2016)

2.2. Daylight system overview

This chapter will describe how to introduce daylight into large sports hall. There are many important daylight redirection systems for windows openings. Only the relative systems will be described here.

2.2.1. Daylight openings

There are mainly two categories of daylighting openings: side light and top light openings. The key difference of them is that side light opening introduces daylight from the perimeter walls of building while top light opening introduces daylight through the top of the building.

Side lighting

Side lighting provides daylight through apertures in the perimeter walls of a building which includes curtain walls and other kinds of windows, figure 2.8. The daylight distribution is very uneven in a single side lighted room. The light level is high close to the window but lower deeper into the space (Green Building Tech HK, 2007).

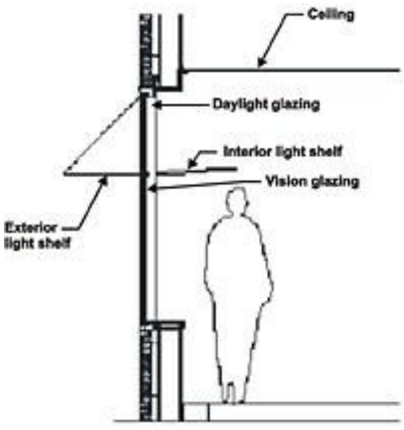


Figure 2.8 A typical side lighting concept . From (Green Building Tech HK, 2007)

As a general rule, the depth of daylight penetration equals 1.5 times the window head height (Reinhart & LoVerso, 2010). The windows are placed as close to the ceiling as possible to let daylight penetrate deeper in the space.

In general shading devices should be installed to control glare problem. The usable perimeter of walls and the exterior obstruction condition also highly influence the result of side lighting. Well-oriented apertures can maximize the daylight harvesting potential as well as minimizing glare and solar heat gain.

Since the sports hall is a quite large space, the area of the side windows have to be quite large to provide enough daylight. And the daylight distribution could be uneven. So side windows are recommended to provide views rather than be the main source of daylight.

Top lighting

Top lighting is a daylight strategy to provide uniform distribution of daylight to the entire top floor plan through roof openings. It is often applied in large single story buildings and the top floor of multi-story buildings (Leslie, 2003). The advantage is that it has no building orientation limitation and can provide even daylight distribution in the space. However it has to be well integrated with architecture and can be more expensive than side windows.

There are three general types of top lighting: roof monitor, saw tooth roofs, and skylights, as illustrated in the figure below.

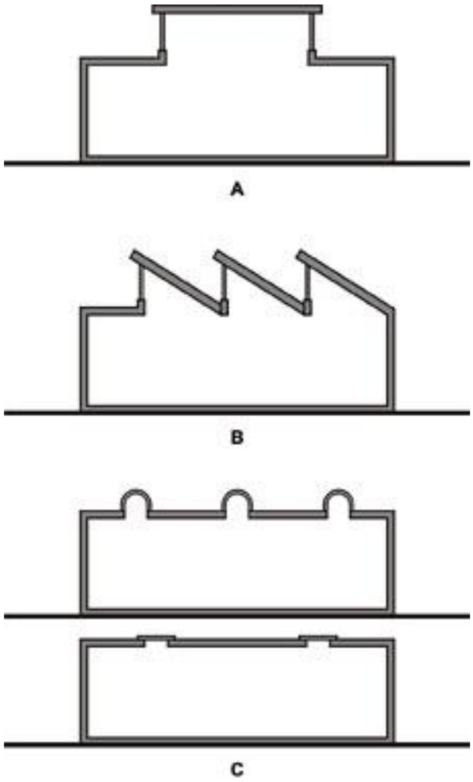


Figure 2.9 Different types of roof daylighting strategies. From (Green Building Tech HK, 2007) A) Roof monitors; B) saw tooth roof; C) skylights

Roof monitor

A roof monitor consists of a flat roof section raised above the adjacent roof, with vertical glazing on at all sides of the raised bay. This composition provides daylight in all directions, but also may result in higher solar heat gain (Green Building Tech HK, 2007).

Saw tooth

Saw tooth roof consists of a series of either vertical or sloped glasses which are separated by sloped roof elements. Saw tooth roof is used to uniformly distribute light in a large floor area. The orientation of the glazing can be selected to maximize daylight level while reducing direct solar radiation and heat gain.

Skylights

There are several forms of skylights including dome, pitched and flat panels that are placed in the plane of the building's roof. Horizontal skylights can cause overheating problem because they receive direct solar radiation at noon. It can be solved by integration of louver systems to control solar heat gain as well as glare in skylight (Green Building Tech HK, 2007).

2.2.2. Advanced roof daylight systems overview

Daylight in building consists of three types of source, direct sunlight, diffuse skylight and reflected light. Diffuse skylight has lower intensity, cooler color and general luminous which means that it is an excellent light source. Direct sunlight has a high intense source of light which causes the risk of glare and overheating in summer, hence it is often considered to be controlled in building in some climates (Kischkoweit-Lopin, 2002). According to this, roof daylight systems can be divided into two categories:

- Daylight system with shading devices which can reject or redirect the sunlight while admitting diffuse skylight.
- Daylight system without shading devices but can scatter sunlight and guide light by itself.

The figures collected from Kischkoweit-Lopin (2002) give a clear overview of advanced roof daylight systems available for the building profession in different climates.

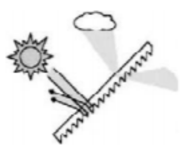
System		Climate	Attachment	Criteria for the choice of elements
Prismatic panels		All climates	Vertical windows, skylights	– Glare protection (D) – View outside (D) – Saving potential (artificial lighting) – Need for tracking (D) – Available
Directional selective shading system with concentrating HOE		All climates	Vertical windows, skylights, glazed roofs	– Glare protection (D) – View outside – Saving potential (artificial lighting) – Need for tracking – Available

Table 2.2 Shading systems block direct sunlight but admit diffuse skylight in cold climates. From (Kischkoweit-Lopin, 2002).

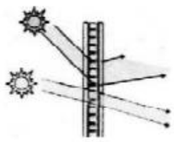
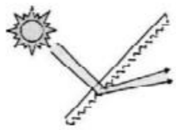
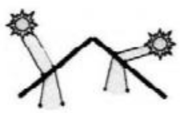
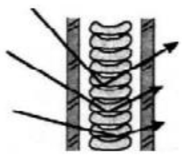
System	Climate	Attachment	Criteria for the choice of elements
Laser Cut Panel (LCP) 	All climates	Vertical windows, skylights	– View outside (D) – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available
Prismatic panels 	All climates	Vertical windows, skylights	– View outside (D) – Lightguiding into the depth of the room – Saving potential (artificial lighting) – Available
Holographic Optical Elements in the skylight 	All climates	Skylights	– View outside – Homogeneous illumination – (artificial lighting) (artificial lighting) – Available
Light guiding glass 	All climates	Vertical windows, skylights	– Glare protection – View outside – Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available

Table 2.3 Direct light guiding systems. From (Kischkoweit-Lopin, 2002).

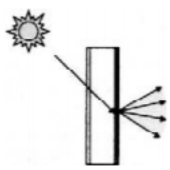
System	Climate	Attachment	Criteria for the choice of elements
Scattering systems (light diffusing glass, capillary glass, frosted glass) 	All climates	Vertical windows, skylights	– Lightguiding into the depth of the room – Homogeneous illumination – Saving potential (artificial lighting) – Available

Table 2.4 Scattering systems. From (Kischkoweit-Lopin, 2002).

The disadvantages of the shading system which blocks sunlight are that it needs to track the solar position and it is expensive. Since the sun is seldom appears in winter in Trondheim, the sun tracking system is kind of waste during that period. Some daylight redirection systems can also assure even daylight distribution in the interior and view outside while admitting sunlight. Prismatic panels only redirect the light in one direction. While laser cut panel (LCP) can scatter the light in different directions, and it is easy to produce and apply in construction. (Arnesen, Kolås, & Matusiak, 2011) In addition, Barbara's team has developed a new type of LCP. In this thesis, this type of LCP will be used in the skylight alternative.

2.2.3. Physical and optical principles

When light strikes a surface, it can either be reflected, transmitted or absorbed depending on material properties, figure 2.10. Reflection factors (r), absorption factors (a) and transmission factors (t) are given in the range of 0 to 1 (0 -100%). And the sum of the three factors is always 1. The absorption factor of a material defines how much light is absorbed by the material. The absorbed radiation energy is transferred to another type of energy, normally heat. The reflection factor indicates how much light is reflected. Transmission factor indicates how much light passes through the material.

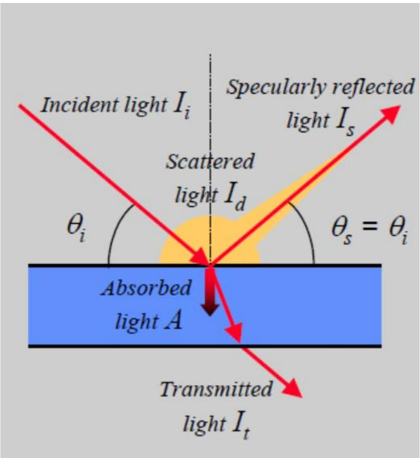


Figure 2.10 Light interaction on material surface. From (Arnesen et al., 2011)

Both transmitted and reflected light can be regular, scattered or completely diffuse depending on surface characteristic. Specular (or regular) reflection is the mirror like reflection of light, the angle of specular reflectance (θ_s) equals the angle of incidence (θ_i). Diffuse reflection is the reflection of light on a surface where the incident flux is reflected at many different directions without specular reflection (Arnesen et al., 2011). Uniform diffuse reflection is a special type of diffuse reflection in which the radiance or luminance is the same in all direction, figure 2.11. Normally smooth polished surface produces specular reflection, while matte surfaces, such as cardboard and cloth, produce diffuse reflection. Most opaque materials produce a combination of regular and diffuse reflection which is called mixed reflection.

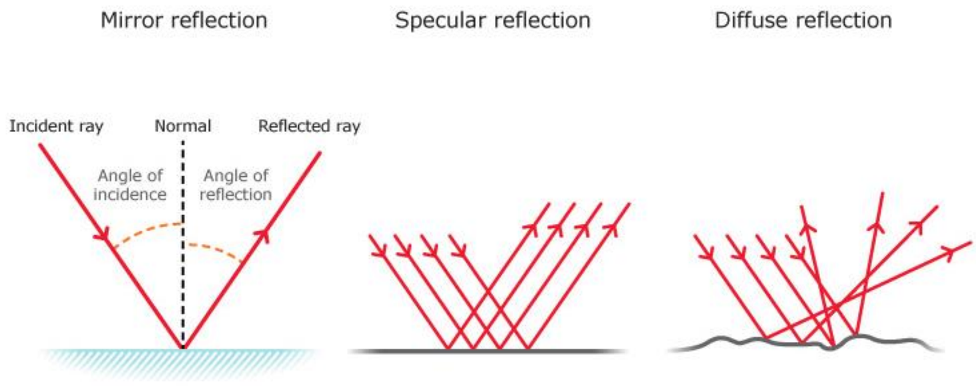


Figure 2.11 Different types of reflection. From (University of Waikato, 2012)

Total Internal reflection

The transmission factor of clear glass is around 90%, while the reflection and absorption factor are around 7% and 3% respectively. When light enters a clear glass panel, the direction of it within the glass will be altered by refraction. When it exits the glass panel, normally it remains the same direction. However, there are some redirecting systems which can scatter sunlight and enhance the daylight distribution by refraction, reflection or diffraction. The related principle is called total internal reflection, figure 2.12. It is a phenomenon which occurs when light strikes the material boundary at an angle larger than a particular critical angle. The critical angle is the incidence angle for which angle of refraction is 90°. If the incidence angle is greater than the critical angle, the light will not pass through the boundary but be totally internally reflected in the material. This only happens when the light comes from the higher refractive index material to the lower one; for example, light in the glass reaches air. In the process of total internal reflection 100% of light is reflected which is very effective.

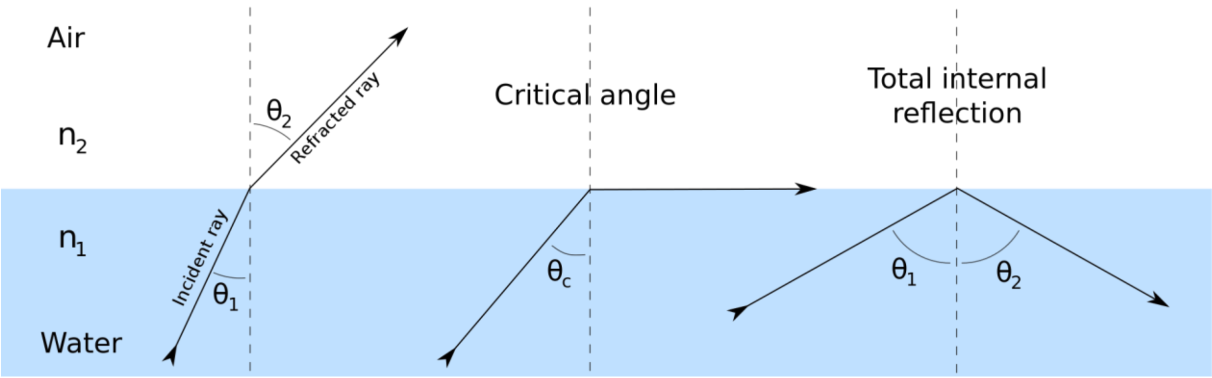


Figure 2.12 Total internal reflection. From (Wikipedia, 2012)

2.2.4. Laser cut panels

The name LCP refers to a method that has been used in the production of a powerful light deflection system. The mechanism used in the LCP is total internal reflection. And due to the mechanism of total internal reflection very little light is absorbed in the LCP. The original LCP system was developed by Edmonds (1993) and is also known as Edmonds panel. The principle of operation is illustrated in figure 2.13.

The dot pattern LCP is developed based on the same optical principle by Barbara's group. It can be mounted as the primary glazing or as a second internal glazing in the skylight windows. This type of LCP is produced by making circular laser cuts to generate voids in a clear acrylic panel. The surface of each laser cut becomes a small internal mirror which scatters light passing through the panel. Light that passes through the panel is deflected at each surface by a sequential process of refraction, reflection and refraction. So the sunlight is internally reflected inside the material many times before it comes out, and the sunlight will be redirected in different directions.

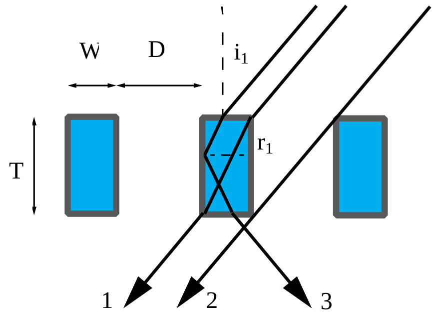


Figure 2.13 Operation principle. Light incident on a LCP may pass through, ray 1, or be deflected, ray 3. If the hole distance is too large, light beam goes out without passing the LCP, ray 2.

The holes in the acrylic panel are designed in a way to make the direct sun light reflected inside the material as much as possible. The solar zenith angle in Trondheim is 50 ° in 21st June, so incidence angle i_1 is 40 °.

The thickness T of the acrylic panel is 4mm. The refractive index n of acrylic is 1.49. According to Snell's law formula, the refraction angle r_1 is 25.6°. The critical angle for acrylic-air boundary is 41.8 °.

The distance D should be so small that the light beam can't pass through the gap directly:

D= T × tan 40 ° =4 × 0.84= 3.36 mm

And the width W should be small enough to deflect the entire light beam:

W= T × tan 25.6 ° =4 × 0.48= 1.92 mm

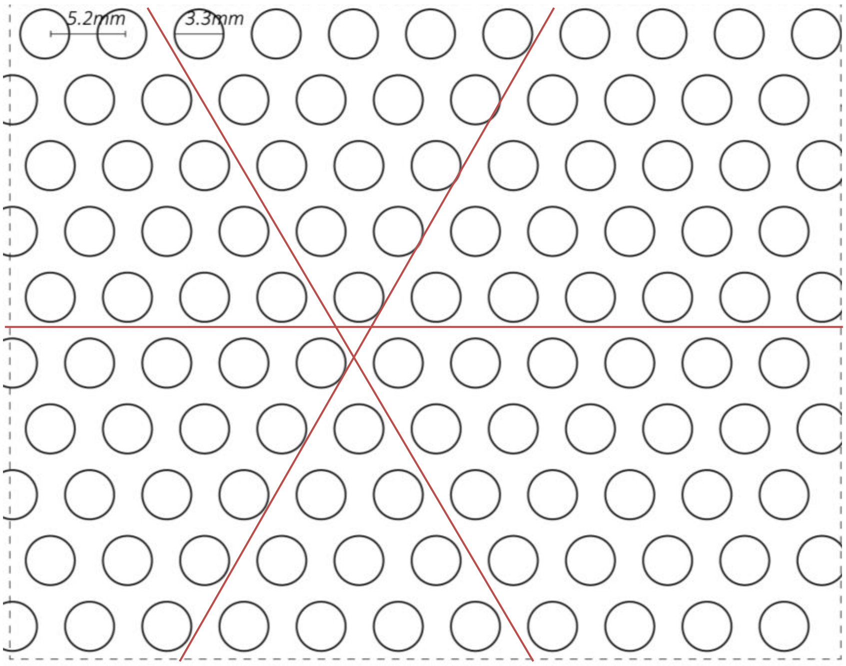


Figure 2.14 Dot pattern LCP. Potentially letting some sunlight passes through.

Eventually no openings are larger than the thickness of the material which was 4 mm, as shown in figure 2.14. Besides, the holes should block the sun light from every direction. The light rays coming from the direction as displayed as the red lines in figure 2.14 can still pass through the acrylic panel. Therefore smaller holes must be added in the area where the distance between the center of two adjacent circles is larger than D. In the end the perforation becomes larger, figure 2.15..

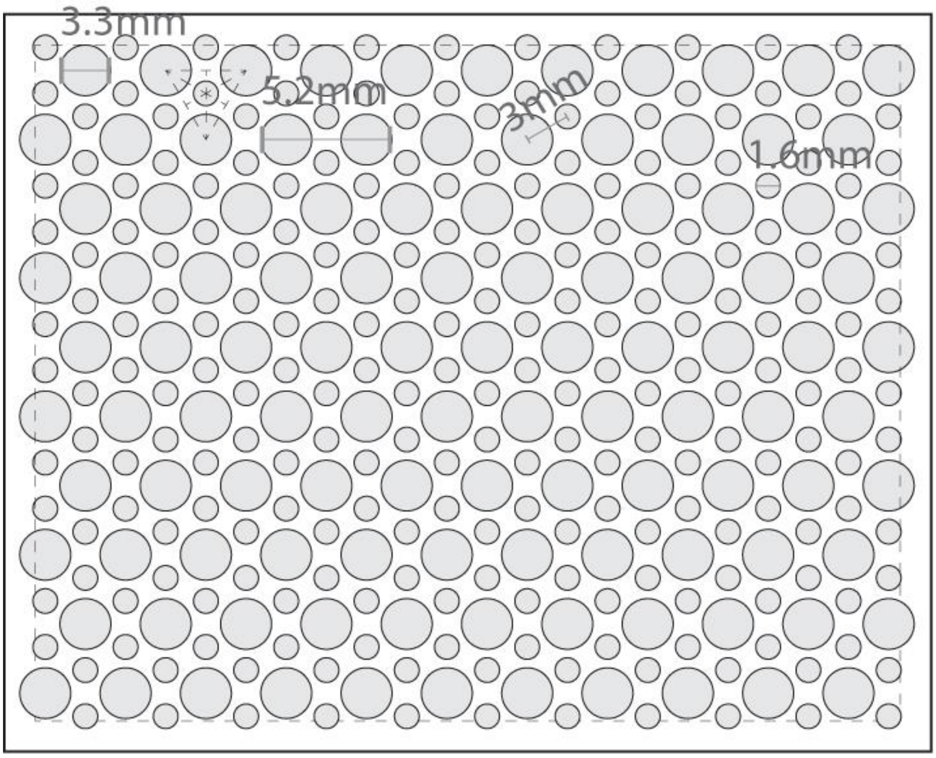


Figure 2.15 Dot pattern LCP. No lines with acrylic for the sun to go through.

Research has shown that LCP has very little effect on the daylight factor and view blocking. The light transmittance of the dot pattern acrylic panel is above 90%. Theses superior optical properties make LCP suitable for all climates including overcast sky condition. It is also worth mention that reflectance of ceiling is also an important factor for the daylight distribution.

The disadvantage of LCP is the risk of glare problem. Part of direct sunlight which transmits through the panel without being scattered might cause glare. And when the direct sunlight strikes on the hole edges, the reflected light which has high luminance can cause glare as well (Edmonds 2002). To solve this problem, Edmonds suggested combining LCP with interior blinds.

2.3. Glare

This chapter describes why glare occurs in building and the available glare indices of daylight.

2.3.1. Glare

According to International Commission on Illumination (CIE) definition, glare is a condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme contrasts. It occurs when there are bright areas within the visual field or if the contrast is reduced due to veiling reflections. The perception of glare is dependent on the luminance distribution in the field of view and is therefore strongly dependent on the spatial position and the line of sight (Osterhaus, 2005).

Both direct and reflected sunlight can cause the difficulty of seeing things. Even though the eyes can adapt themselves to a large range of luminance, the adaptation process takes time. And glare may cause side or after effects in the form of headaches or fatigue at a later time (Van Den Wymelenberg, 2010). Thus it is better to avoid too bright scene for players when they training and playing.

Glare perception increases when the size or luminance of the glare source increases or when the total amount of light reaching the eyes increases. Glare perception decreases, the larger the angular distance of the glare source to the line of sight is. Perceived glare also increases when the contrast ratio between foveal and central or peripheral vision increases (Rea, 2000). Usually the foveal vision is directed towards the visual task.

There two categories of glare which are divided based on people's reaction:

Discomfort Glare

If the glare sources are not too bright, they are merely a nuisance and do not directly interfere with vision. This condition is called discomfort glare. Discomfort glare results in difficulty in seeing a task. The influence scale ranges from imperceptible to intolerable. It also can cause headaches or fatigue on people which are often not direct measurable (Reinhart, 2011).

Disability Glare

If the luminance of the glare source is much higher, disability glare arises. Disability glare impairs the vision of objects without necessarily causing discomfort. Generally, if discomfort glare limits are met, disability glare is usually not a major concern (NS-EN-12464-1, 2012).

2.3.2. Glare assessment indices

The three most common glare indices for calculating discomfort glare from daylight and electric light in buildings are:

- UGR (CIE Unified Glare Ratings);
- DGP (Daylight Glare Probability).
- Luminance contrast ratio

The difference between UGR and DGP is that UGR is used to calculate glare from artificial lighting while DGP is normally used for calculating glare from daylight (Dubois, 2016).

Daylight glare possibility (DGP)

In 2005 Jan Wienold and Jens Christoffersen proposed a new glare equation called daylight glare probability. DGP is an illuminance-based measure which describes the percentage of people disturbed due to the level of vertical eye illuminance (Wienold, 2006). It is a metric that can predict the appearance of glare in a daylit room.

The evaluation of the results from the experiments shows good correlation between the DGP and the user's response. The daylight glare probability metric can be applied to both, high dynamic range (HDR) photographs of daylit scenes and HDR renderings generated using daylight simulation software such as Radiance.

DGP can be applied to any daylit indoor space which is mainly side-lit and where the expected working tasks are comparable to office tasks. While it should not be applied to situations where it can be expected that the vertical illuminance is not a good indicator for the glare perception. With regards to measurement of visual comfort it was found that DGP gave poor agreement with occupant reports of discomfort glare in open-plan spaces with skylights (Isoardi, 2012).

Luminance contrast ratio

Since DGP is not appropriate for open plan spaces with skylights like a sports hall with roof lights. Luminance contrast ratio can be considered to assess glare in sports hall. The luminance contrast ratio between foveal and near peripheral or far peripheral vision can be described by equation below:

$$C = \frac{L_H}{L_L}$$

Where

L_H: Greater luminance [cd/m²]

L_L: Lesser luminance [cd/m²]

Luminance within the visual field should be limited and balanced, in order to avoid glare or excessive luminance ratios. For visual comfort to be achieved luminance ratios should also not exceed certain values. Typical recommendations assume a 1:3 ratio between the visual task and its immediate surroundings, a 1:10 ratio between the visual task and other more near surfaces in the visual field (Osterhaus, 2002). And a ratio of 1:20 for the more distant surfaces in the visual field. A 1:40 ratio between the task and any surface in the field of view is generally seen as the maximum permissible (Osterhaus, 2009). A tolerance for a ratio of 1:50 has even been observed when the luminance from the window occupied a small portion of the visual field (Dubois, 2016). Luminance ratios in the field of view exceeding 1:100 should not be tolerated (Osterhaus, 2002).

	Visual requirement		
Location	**High**	**Moderate**	**Low**
Between work zone and its close surrounding	Between 1: 3	Between 1: 5	Between 1: 10
Between work zone and surrounding zone	Between 1: 5	Between 1: 10	Between 1: 20
Between a window and nearby walls	< 20: 1	< 50: 1	< 100: 1

Table 2.5 Recommended luminance ratios in the visual field. Data source from (Osterhaus, 2002) and (Dubois, 2016)

Table 2.5 presents recommendation of luminance ratios specified for the location and the level of requirement in the visual field. The visual requirements depend on the type of the visual task. High visual requirement is for example watchmaker; moderate is for reading or writing, low is for visibility of rather large objects like a ball.

However, it is not easy to be sure what the work zone in the case of a sport hall is, as people may move around over the whole area. It is appropriate to see the whole area as a work zone and consequently, the whole space as a surrounding zone, but then the windows and skylights appears in the surrounding zone.

Therefore, there are two ways to calculate the luminance contrast ratios in sports hall:

a) Contrast ratio between luminance values of any points in the HDR image, the brightest and the darkest.

b) Contrast ratio between luminance values of the target object, like a ball, and any point in its surrounding zone (which is 30 degrees around the view direction)

3. Method

3.1. Computer simulations

There are many different modeling tools and simulation tools available, such as Rhinoceros, grasshopper for Rhino, DIVA for Rhino, Radiance, Daysim and so on. Rhino is a strong 3D modeling tool, DIVA for Rhino is a highly optimized daylighting and energy modeling plug-in which was developed at the Graduate School of Design at Harvard University. They are well integrated for evaluating environmental performance of complex geometry including the Climate-based daylight metrics and annual glare analysis (Reinhart, 2012).

Standard model and assumptions

In the beginning, a standard model was used as the base for simulations later on, figure 3.1. The studied sports hall is the most common in used that can house five volleyball places and two basketball place. The size is 48 meters long, 27 meters wide and 9 meters ceiling high. Regular side windows are placed on the east facade to provide view for users; each has 0.9 meter sill height. Since roof monitor is a mix of skylights and saw tooth roof, to simplify the experiment and analysis, only saw tooth and skylights will be investigated in the study.

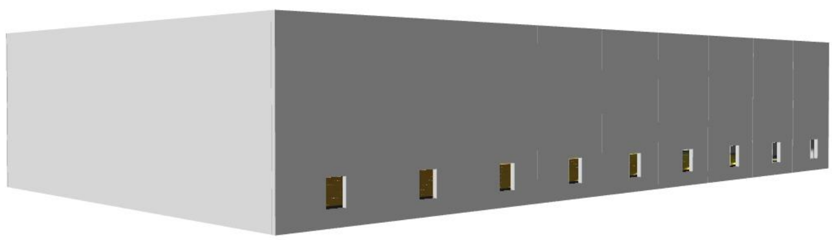


Figure 3.1 standard model for base simulations.

Reflectance of surfaces were set according to the recommendation values in *Idrettshaller planleging og bygging* (2016), i.e. $R_{ceiling} = 0.9$, $R_{walls} = 0.72$, $R_{floor} = 0.4$, as shown in table 3.1. The light transmittance of the side windows were set to 0.25 because they may be heavily obstructed by a sun shading elements. The light transmittance of the saw tooth windows were set to 0.65 in DIVA material assignment, which is a typical value of three layers glass with argon gas filled. The light transmittance of the skylight windows were set to 0.61 which equals to the multiplication of light transmittance of a layer of LCP (0.93) and a three layers glazing window on top of it.

<table>
<tr><th></th><th>Floor</th><th>Walls</th><th>Ceiling</th><th>Side windows</th><th>Roof windows</th></tr>
<tr><td>Alternative 1:
Saw tooth roof</td><td rowspan="2">r = 0.40</td><td rowspan="2">r = 0.72</td><td rowspan="2">r = 0.90</td><td rowspan="2">t = 0.25</td><td>t =0.65</td></tr>
<tr><td>Alternative 2:
Skylights with LCPs</td><td>t =0.93 ×0.65
=0.61</td></tr>
</table>

Table 3.1 Material assignments in DIVA for Rhino. Reflectance (r), transmittance (t)

In order to simplify the work process, some assumptions were made, for example, there were no internal obstructions such as furniture and occupants. And there were no external obstructions as well such as trees and buildings. The climate data of Trondheim was used for daylight simulation.

The work process consists of three steps:

a) Modeling: a model which is based on the standard model was created with specific parameters.
b) Simulation: Dynamic daylight simulation was performed to test the chosen parameters.
c) Collection: the data collection includes the simulation results and tested parameters. The .csv file can be used for lighting energy calculation.

3.1.1. Daylight factor method

Daylight factor (DF) is the ratio which represents the amount of illuminance available indoors relative to the illuminance present outdoors at the same time under overcast sky.

DF is given as a percentage, and can be expressed as the following equation:

$DF = E_I / E_O \times 100$ [%]

Where

E_I is the illuminance at a point in the room

E_O is the illuminance of a horizontal surface outside under the overcast sky

DF is a helpful method to make comparisons of relative daylight penetration of different designs under overcast sky conditions. It is mostly considered statically regardless of the time of day and year which makes this method quite simple. However, the static daylight metric also introduces certain limitations. Since it is taken under CIE standard overcast sky, DF is the same regardless of the orientation and building location (Reinhart, 2006).

In the following modelling and simulation process, DF is used to decide the roof shape because it is a simple and fast method. The target average DF is 4% measured 1m from the floor. The daylight autonomy will be calculated later on to get the lighting consumption inputs to SIMIEN.

3.1.2. Dynamic daylight metrics

Dynamic daylight performance metrics are based on time series of illuminance or luminance within a building. These time series usually extend over the whole calendar year and are based on external, annual solar radiation data for the building site. *"The key advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quality and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events" (Reinhart, 2006).*

Daylight autonomy (DA) was the first of a string of annual daylight metrics, now commonly referred to as "dynamic daylight metrics" (Reinhart, 2001). It is often used as an alternative to the daylight factor-based approaches.

3.1.3. Daylight autonomy

Daylight autonomy (DA) is an innovative method which evaluates the daylight quantity within any given hour, location, and sky condition on an annual basis. It is presented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level (Erlendsson, 2014). Furthermore, daylight autonomy uses work plane illuminance as an indicator of whether there is sufficient daylight in a space so that occupants can work by daylight alone (Erlendsson, 2014). Sports hall ambient lighting criteria can range widely depending on the level of competition and videography needs. In this pattern, 300 lux was selected as one of the daylighting design criterion. The percentage of floor area above this value is presented for each alternative.

3.2. Physical model

Based on the results of Rhino model and DF calculation, the physical models of each alternative were made to take HDR Images in the daylight lab.

According to *idrettshaller planleging og bygging* the reflection factor of interior wall in sports hall could be between 0.2 and 0.5, the ceiling should have a reflection factor of 0.60 or higher. However, the materials used in physical models are slightly different from the recommendation because of limited available materials in the workshop, see table 3.2. And the glazing panel made in the physical model is one layer of 4mm thick acrylic panel which is also different from the 3D model. This will make the analysis result overestimated. :

	Floor	Walls	Ceiling	Roof windows
Alternative 1: Saw tooth roof	MDF, r = 0.40	Light plywood, r = 0.72	*plywood painted with color Y20R, r = 0.90*	*One layer of acrylic panel : t =0.93*
Alternative 2: Skylights with LCPs				*One layer of acrylic panel : t =0.93*

Table 3.2 Properties of material used in the physical models.

3.2.1. Luminance mapping in the daylight lab

After the physical models were completed, low range images could be taken in the artificial sun with fisheye lens. The fisheye lens is advantageous because it allows acquiring luminance over a hemisphere. Then the series of low dynamic range (LDR) images of the same scene can be converted into a single HDR Image by Photosphere which is image processing software (Reinhart, 2010). The HDR images can then be analyzed using the program Evalglare embedded into Radiance.

To study the impact of different parameters on glare of the two alternatives, both of the physical models should be tested at different time and orientation, as shown in table 3.3.

Orientation	Time	Date
East	8am	21 March
South-east	10am	21 June
South	Noon	21 December

Table 3.3 Test parameters of two physical models in daylight lab.

Steps of experiment:

- Place the model east orientated without obstructions in the artificial sun lab
- Adjust the angle of the table to achieve right date and time
- Take pictures from west facade towards east and from north to south
- Move the table to change the time and date, repeat the step above.
- Repeat the above steps with south-east orientation and south orientation

And the physical model should be placed 5m to the artificial sun along the central axis as shown in figure 3.2, because the luminance level of artificial sun is uneven. However, the advantage to make experiments in daylight lab is that different sun positon can be simulated at any time by the artificial sun regardless of the weather. In addition, the experiments are repeatable.

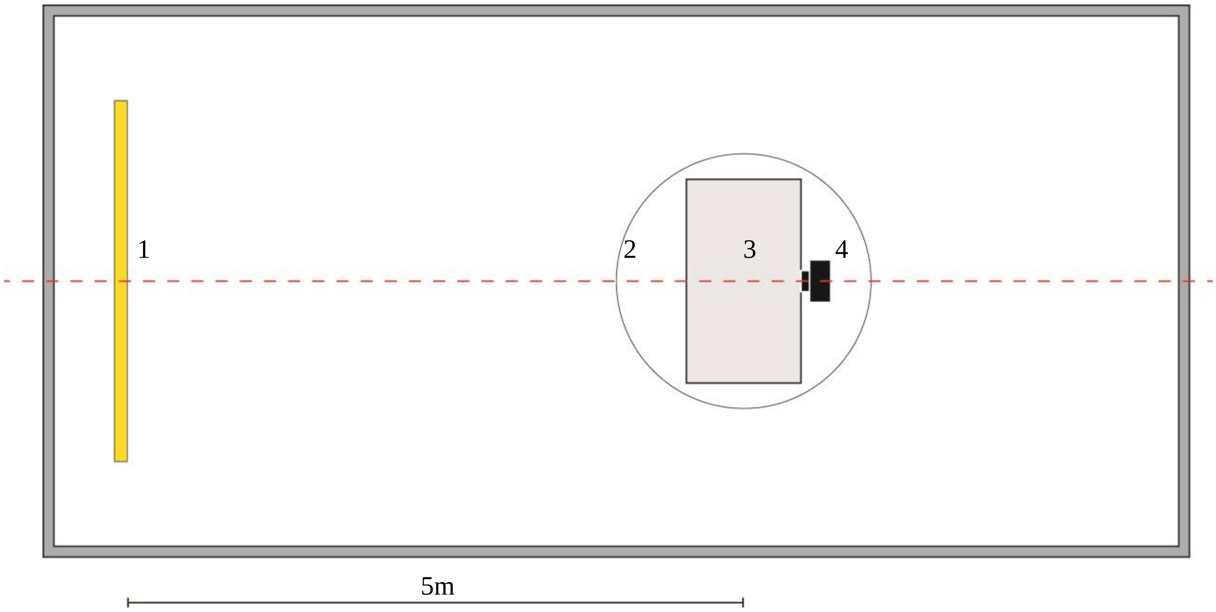


Figure 3.2 Experiment equipment in the daylight lab. 1. Artificial sun; 2. Adjustable table; 3. Test model; 4. Camera

3.2.2. Image processing and programs for glare analysis

HDR Imaging attempts to represent the full dynamic range of a scene, from direct sunlight to deep shadow. It is used as a luminance mapping tool. Multiple exposure photographs of a static scene will be used to capture the wide luminance variation within a scene. The pixel values in the HDR photographs correspond to the physical quantity of luminance in that space with reasonable precision and repeatability. The quantities can then be used for glare analysis. HDR photographs have the capability to serve as a predictive daylighting tool.

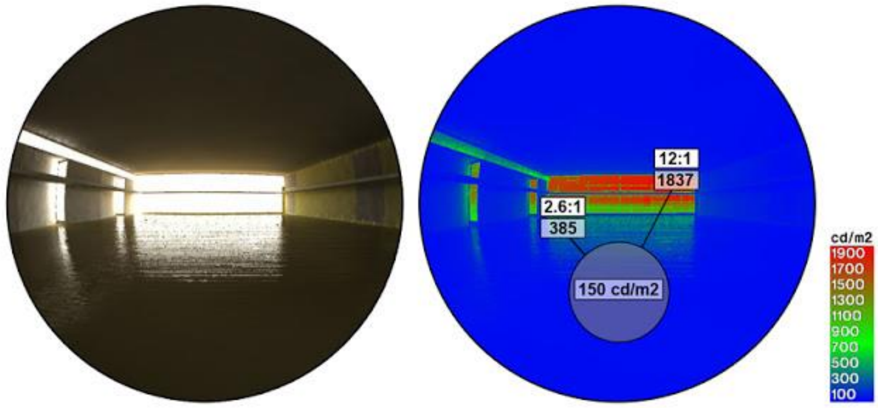


Figure 3.3 HDR Image example. Illustrated by (Overbey, 2012)

The HDR photographs can be made by Photosphere which is a mac program. After choosing a series of low dynamic range images that were taken in the same scene, and the 'Make HDR' command in the Photosphere program (with additional settings), the HDR Image will appear. The next step is to calibrate the generated image with luminance value of a point in the physical model measured by luminance meter. It could be simply done by selecting the area of interest in the HDR image and press the 'Calibration' button in the 'Apply Menu'. And Radiance 32-bit RGBE format provides the .hdr file extension. The .hdr file can be opened in Radiance Image viewer. It is possible to click on any point of the scene to obtain a luminance value, see an example in figure 3.3. After finishing these steps, the luminance or glare analysis of the .hdr image may be started. (Reinhart, 2010)

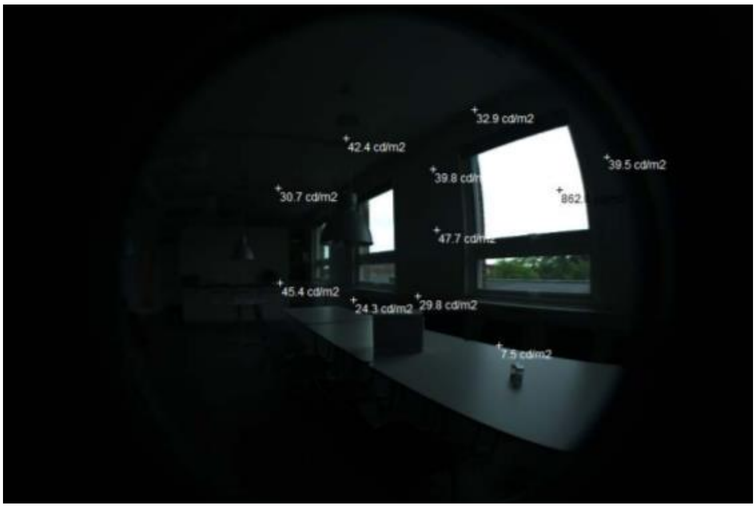


Figure 3.4 Example of a HDR image opened in Radiance. From (Dubois, 2016)

4. Results and discussions

In the following sections, results from the computer simulations and analysis are presented along with a short discussion on each simulation. Each section includes images of the most relevant results, while a complete collection of the results are presented in appendix A, B and C.

4.1. Computer simulation results

Alternative 1: saw tooth roof

The two alternatives have the same ceiling height of 9m. And the additional roof structure was added on top of that. The saw tooth roof alternative is inspired by Pajol sports hall in Paris as described previously. It consists of a series of vertical glazing panels and pitched roofs. The height, size position and orientation of the saw tooth roof and reflectance of interior materials can influence the daylight penetrated into the space. The purpose of the DF simulation is to find the optimum shape of saw tooth roof and the glass to floor area ratio (GFAR) by combining DIVA for Rhino and grasshopper. The simple structures such as the truss systems were modelled in the Rhino model but not the appliances, furniture or occupants.

The assumed roof supporting structure is parallel chord truss; the depth calculation is done as following steps:

Length =27m

Depth = L/10= 27m/10= 2.7m

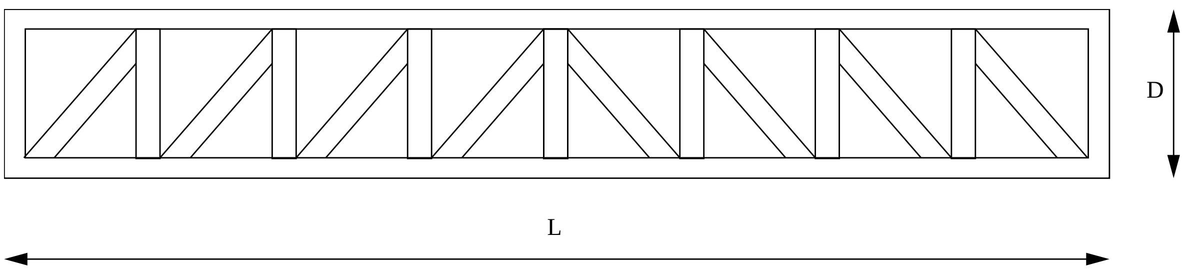


Figure 4.1 Parallel chord trusses.

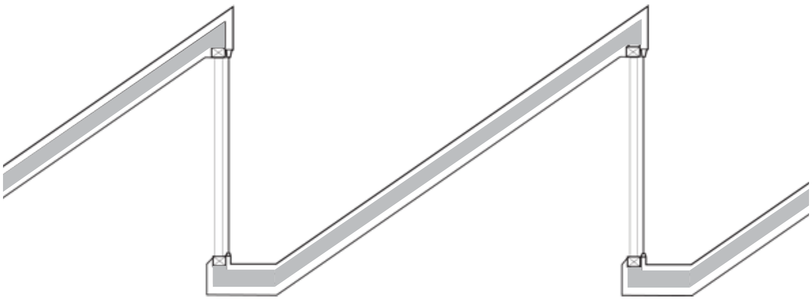


Figure 4.2 Saw tooth roof construction detail.

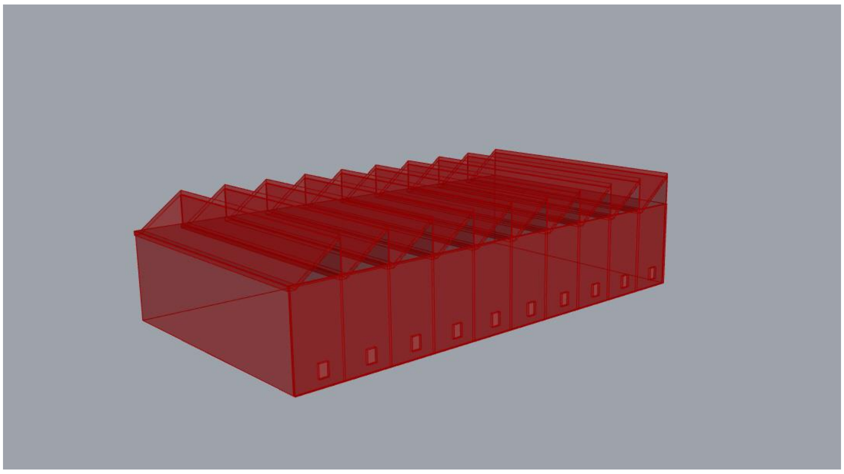
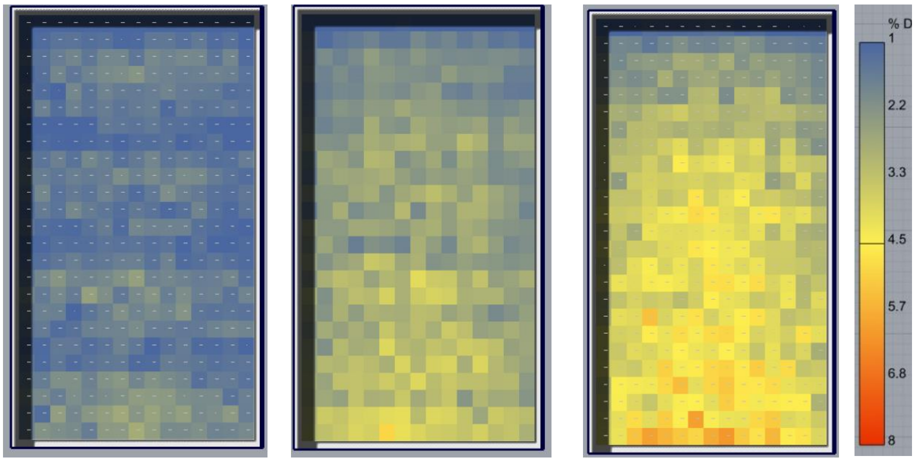


Figure 4.3 Parametric saw tooth sports hall model made by Grasshopper.

The depth of the truss system determines the maximum height of saw tooth roof which is about 2.7m. Based on the maximum height, the impact of the number of saw tooth on interior daylight distribution can be evaluated. The results presented in figure 4.3 shows that the daylight factor increases when the saw tooth number increases. The saw tooth roof results in strong directional light which means that the daylit zone is the largest on the opposite side of glazing orientation. So the DF in the area near north facade doesn't change too much. When the number of north orientated saw tooth is 10, and the GFAR is 45.6%, the average DF of work area achieves 4.4%.



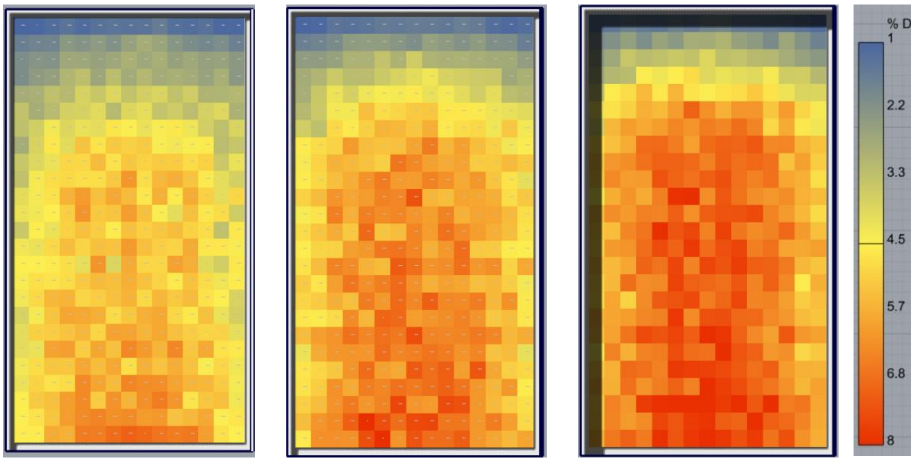


Figure 4.4 DF distribution compared between sports hall of different saw tooth number. From top left to bottom right are 4, 6, 8, 10, 12 and 14 saw tooth respectively.

Glazing	width(m)	length(m)	number	area	transmittance
Side window	1	1.5	10		25%
Saw tooth	2.4	2.4	10× 10		65%
Floor area				27m × 48m	
Glass to floor area ratio (GFAR) 45.6%					

Table 4.1 GFAR calculation of saw tooth roof alternative.

Alternative 2: skylights

The skylight system is inspired by the sports hall in Austria designed by Dietrich Untertrifaller Architects. The skylight system consists of a three layers glazing and a LCP. The three layers glazing with argon gas filled has lower U-value which helps the energy saving. The LCPs help redirect the sunlight. Figure 4.5 shows the construction detail of a skylight opening. During simulation, it was hard to simulate the light transition in dot pattern LCP in DIVA as in the real world. In order to get a reliable result and simplify the process, the light transmission of the skylight system was set to 0.61. The displacement of skylight openings was designed based on the glulam beam structure grid and the column grid. The calculation of beam size is as following:

Span=27m

Beam Depth = span/15 ~ 20 = 1.5m

Beam width= depth/ 3 =0.5m

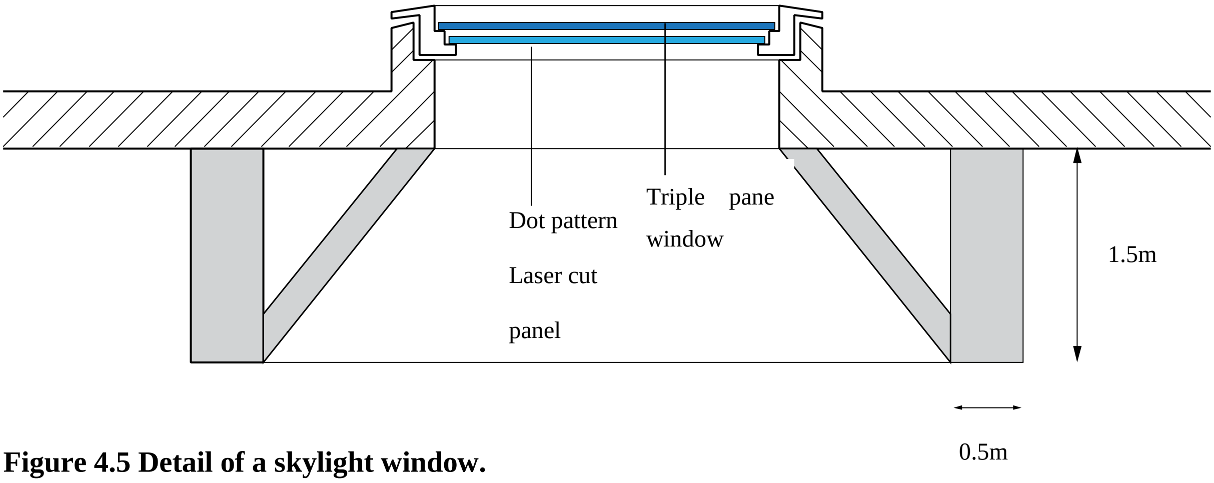


Figure 4.5 Detail of a skylight window.

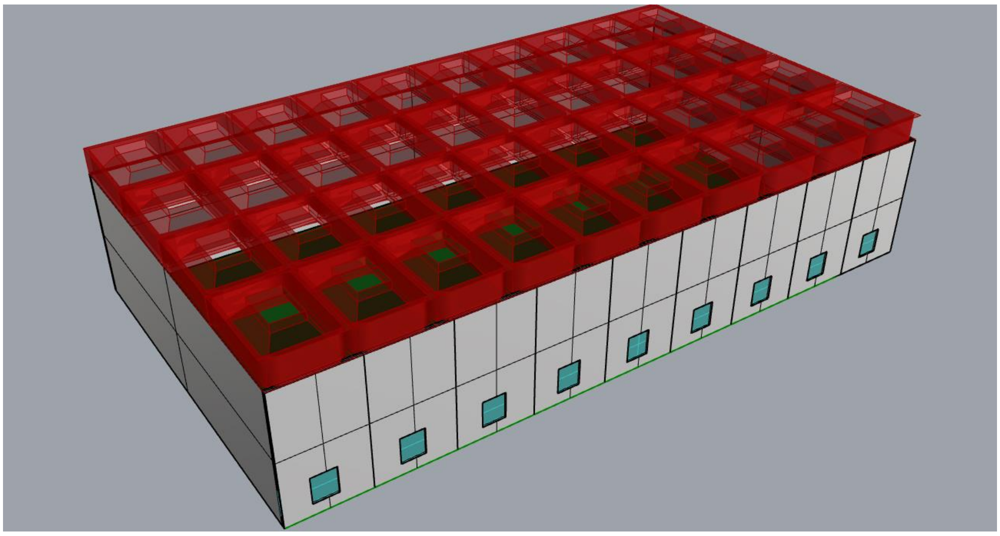


Figure 4.6 Parametric skylights roof model in Rhino and Grasshopper.

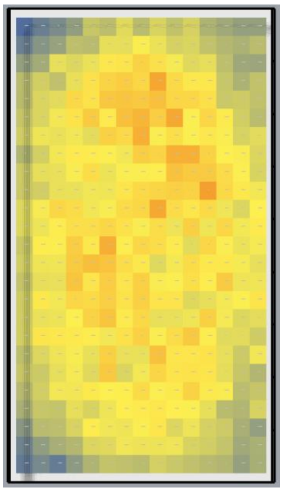


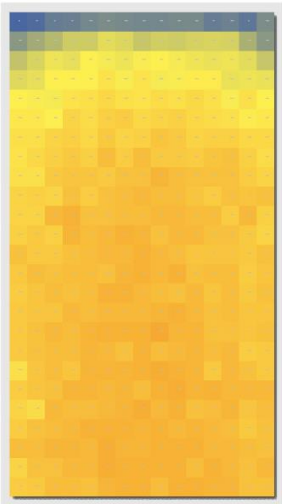
Figure 4.7 DF distribution in sports hall of skylights.

Bigger size of skylight openings results in higher DF on working area. By adjusting the size parameters in Grasshopper, the average DF on the working area can achieves 4.2% when there are 32 pieces of skylight openings and the GFAR is 15.7%, see table4.2.

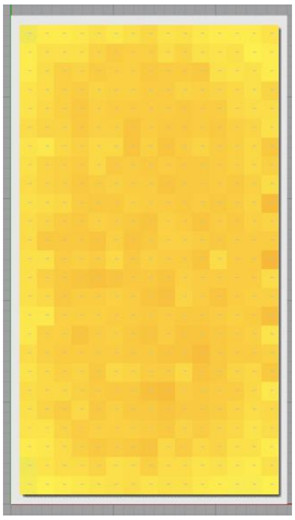
Glazing	width(m)	Length(m)	number	area	transmittance
Side window	1	1.5	10		25%
Skylight	2.2 (no frame)	2.8 (no frame)	34 p		61%
Floor area				27m × 48m	
Glass to floor area ratio (GFAR) 15.7%					

Table 4.2 GFAR calculation of skylights roof alternative

The daylight autonomy distribution of the two alternatives shows that the skylights roof has a more uniform daylight distribution than the saw tooth roof. There is 84% of floor area above 50% DA_{300lux} in saw tooth roof sports hall, while there is 98% of floor area above 50% DA_{300lux} in skylights roof sports hall.



a)



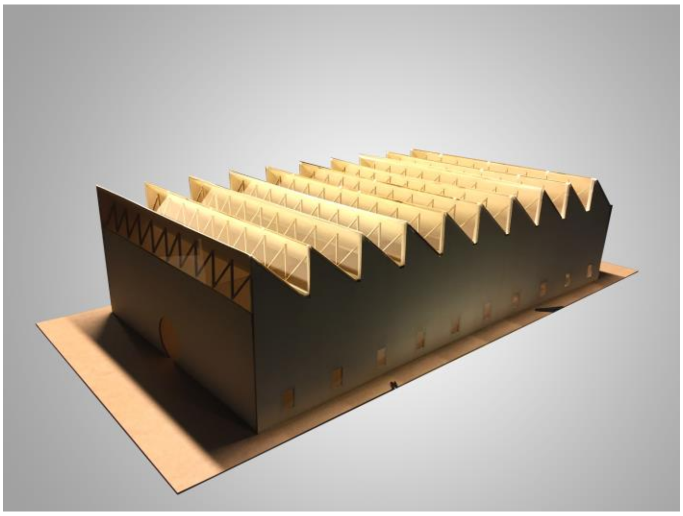
b)

Figure 4.8 Daylight autonomy distribution: a) saw tooth roof; b) skylights roof.

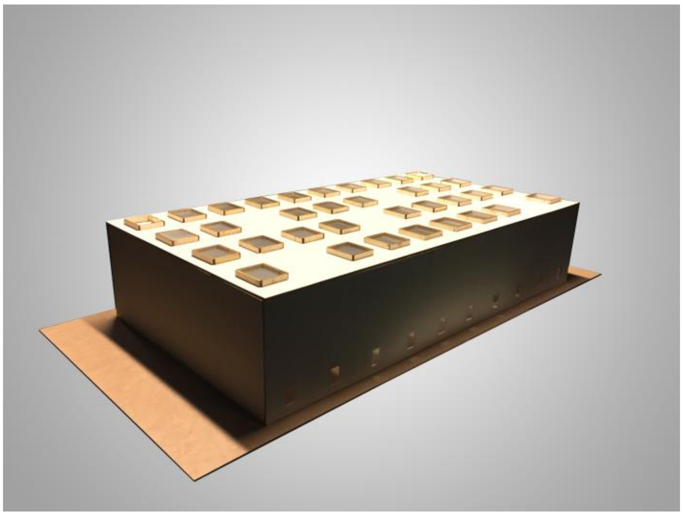
Both of the two alternatives achieved the target average DF on the working area. But the saw tooth roof option has a much higher GFAR than skylights roof option. More glazing area means more heat loss and material consumption. North orientated saw tooth glazing can avoid glare caused by direct sunlight, while the daylight autonomy is slightly lower than skylight option with same orientation.

4.2. HDR Images and luminance contrast ratio

In order to put the camera lens in the model, a 77mm diameter's hole was made in the west and north facades of the physical models, figure 4.9.



a)

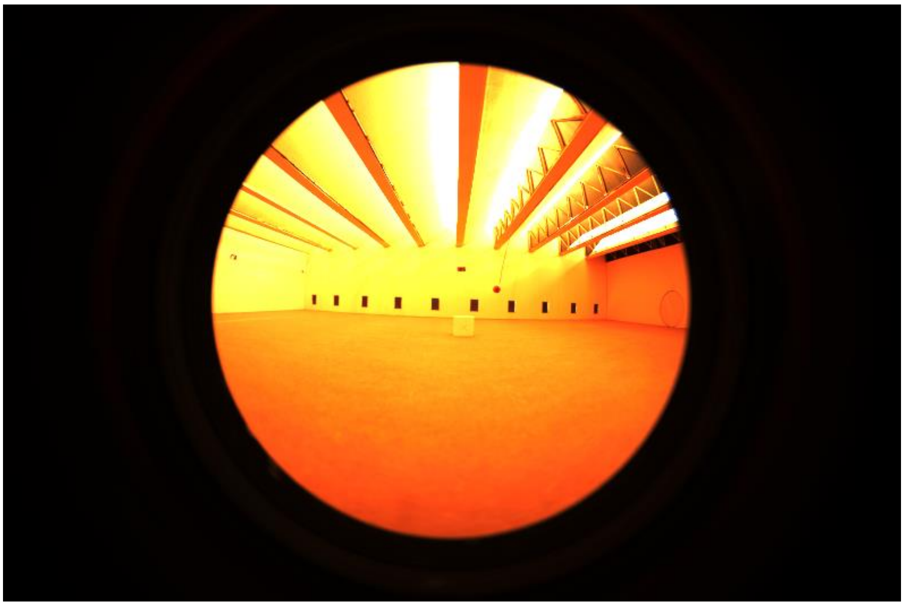


b)

c)

Figure 4.9 Physical models and LCP sample. a) Saw tooth model. b) Skylight model. c) Dot pattern LCP.

The series of LDR Images were merged to a HDR Image, examples are shown in figure 4.10. Then HDR Images were converted to false color images which are easier to compare the area of high luminance.



a)

b)

Figure 4.10 Examples of HDR Image took at 12am 21st June. a) Saw tooth roof. b) Skylights roof

Saw tooth roof: HDR Images analysis

Table 4.3 presents the false color images of east orientated saw tooth roof sports hall taken at different time and date. The false color images give a comparison of interior luminance level of different time and different orientation. As shown in the pictures, the interior luminance level is the highest at 12am in summer solstice which is the solar zenith angle. And the interior luminance level is relatively stable through a day when the saw tooth glazing faces north, except that there are some high luminance values on the roof and floor in the morning of spring equinox and summer solstice. Since the out roof surface of the physical model hasn't been treated at all, it resulted in high reflection and extreme luminance values when sunlight incidents on the light color wooden roof surface. The appearance of high luminance patterns on the floor and walls near side windows is because of the low solar azimuth angle and no outside obstruction. This can be simply solved by shutting down the blinds on the side windows or add trees in the outside.

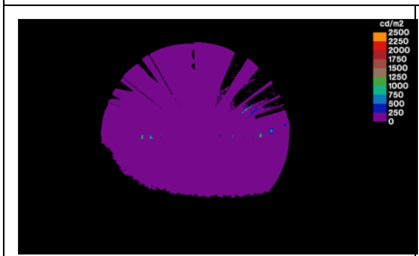
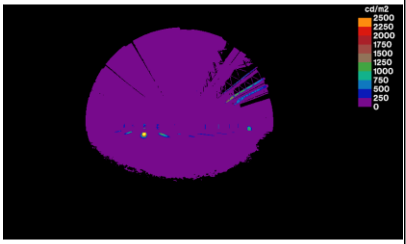
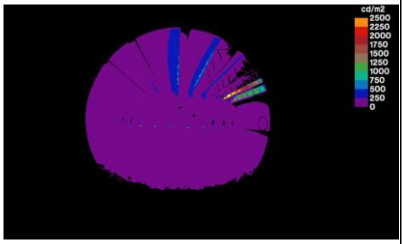
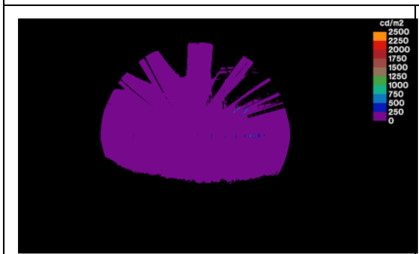
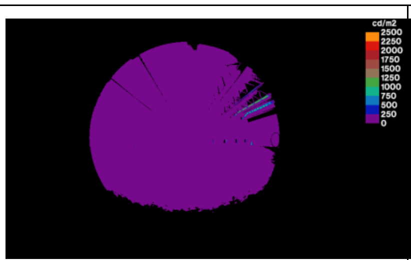
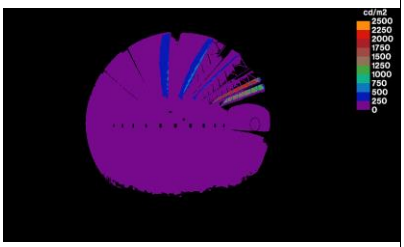
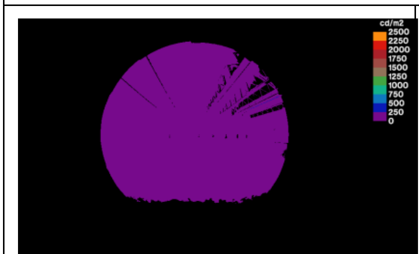
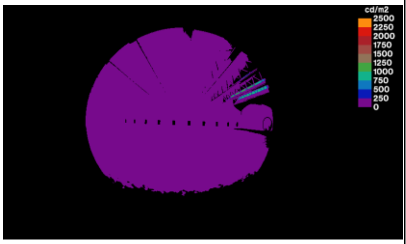
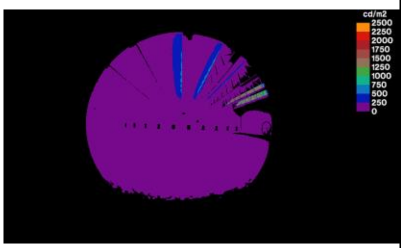
Winter solstice	**Spring equinox**	**Summer solstice**
8am		
		
10am		
		
12am		
		

Table 4.3 Summary of false color images of east orientated saw tooth roof sports hall taken at different time.

When the orientation changes to 45° southeast or south, direct sunlight passes through the saw tooth glazing and enters into the sports hall. That is why the luminance level suddenly increased in the pictures of the two right columns in the table 4.4. This causes large luminance contrast area on floors, walls opposite to the sun direction and ceiling.

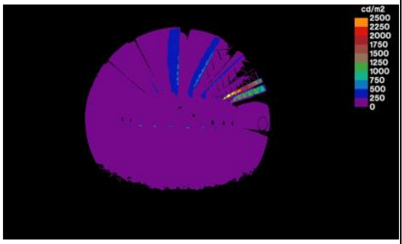
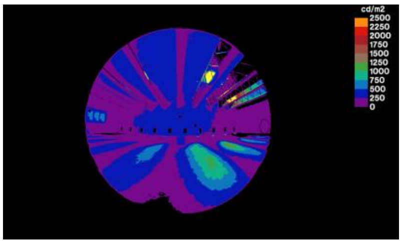
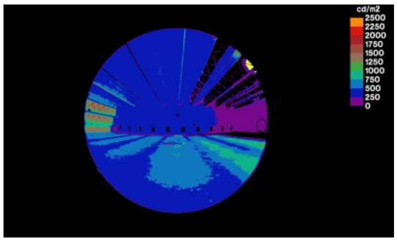
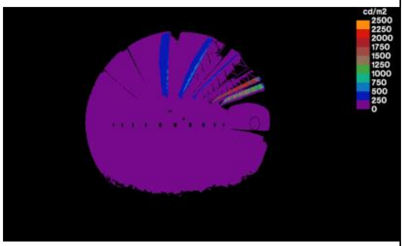
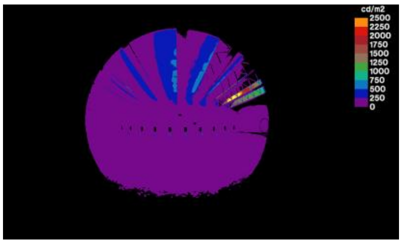
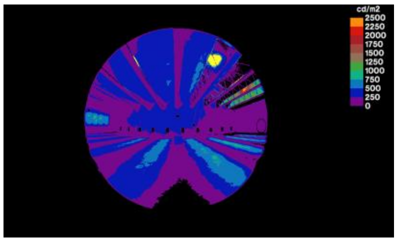
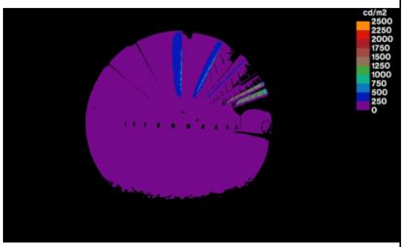
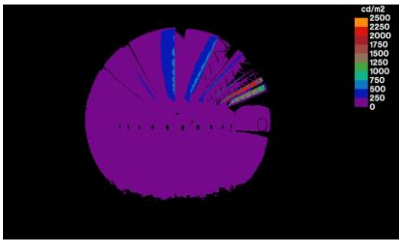
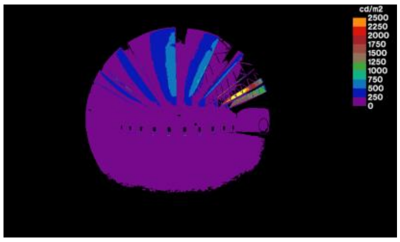
East orientation	**Southeast orientation**	**South orientation**
8am		
		
10am		
		
12am		
		

Table 4.4 Summary of false color images of different orientated sports hall in summer solstice.

Skylights roof: HDR Images analysis

Table 4.5 is the summary of the false color images of east orientated skylight sports hall. It shows that the sunlight could seldom penetrate into the room in winter solstice. While in summer solstice luminance scale ranges the largest between the roof windows and adjacent surfaces, especially when at noon. The reason of high luminance value in the LCP could be the high reflection of light which occurs when sun beams strike on the dots' edges of LCPs.

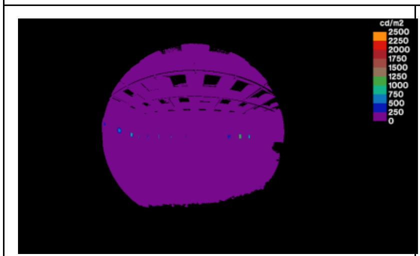
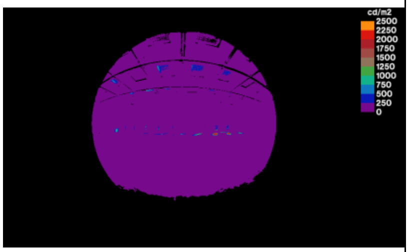
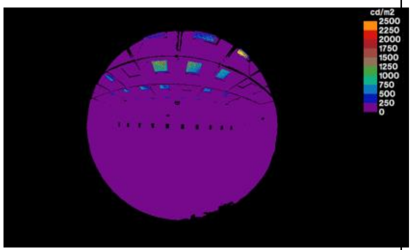
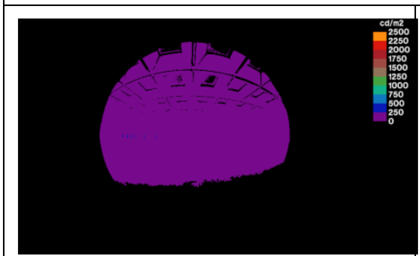
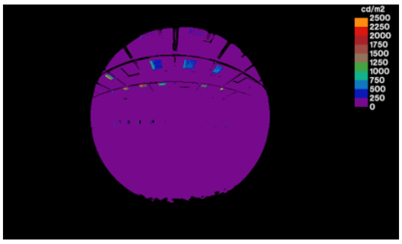
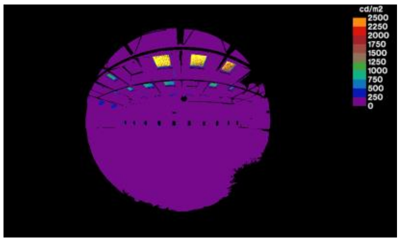
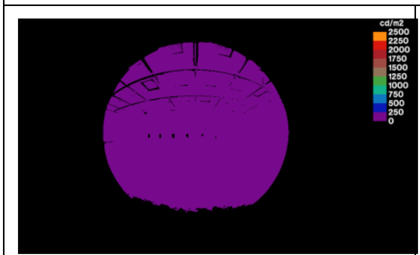
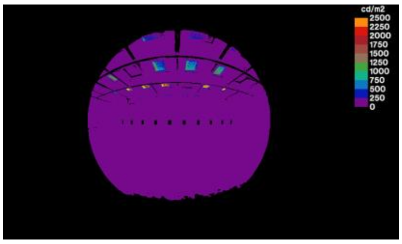
Winter solstice	**Spring equinox**	**Summer solstice**
8am		
		
10am		
		
12am		
		

Table 4.5 Summary of false color images of east orientated skylights sports hall.

Table 4.6 shows the false color images of different orientated sports hall in summer solstice. It illustrates that the extreme luminance values normally occurs on the laser cut acrylic panels, but the position changes as the sun position changes. In general there is no big difference of luminance scale in the interior of sports hall of different orientations, east, southeast and south.

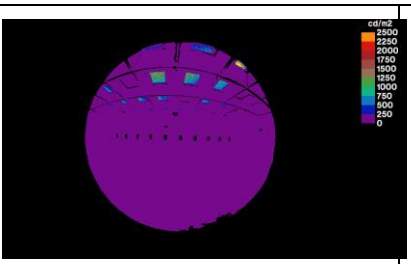
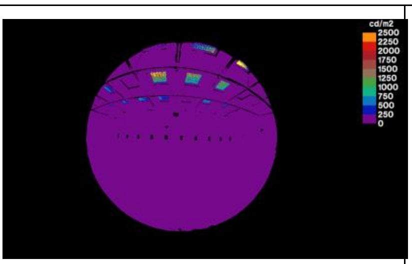
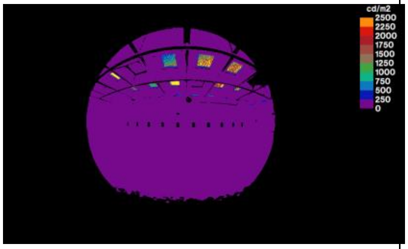
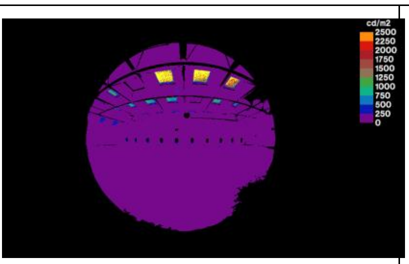
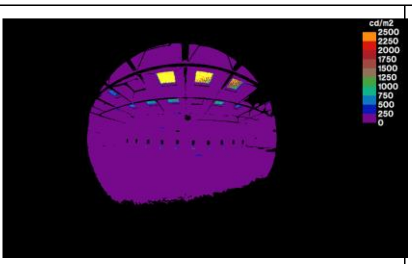
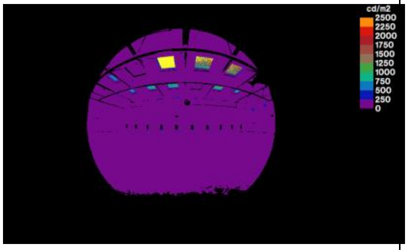
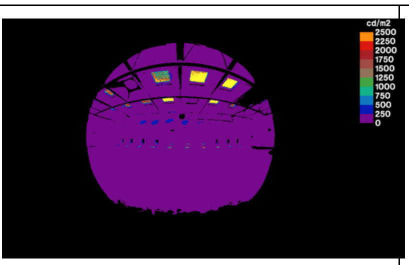
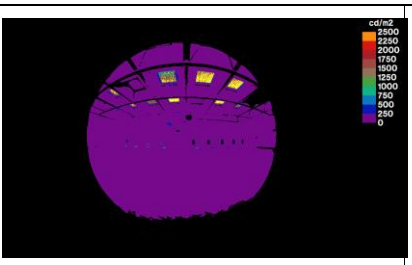
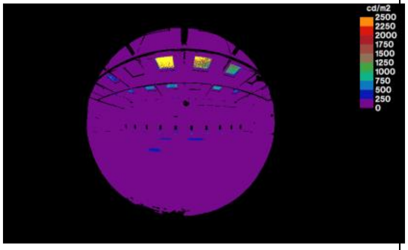
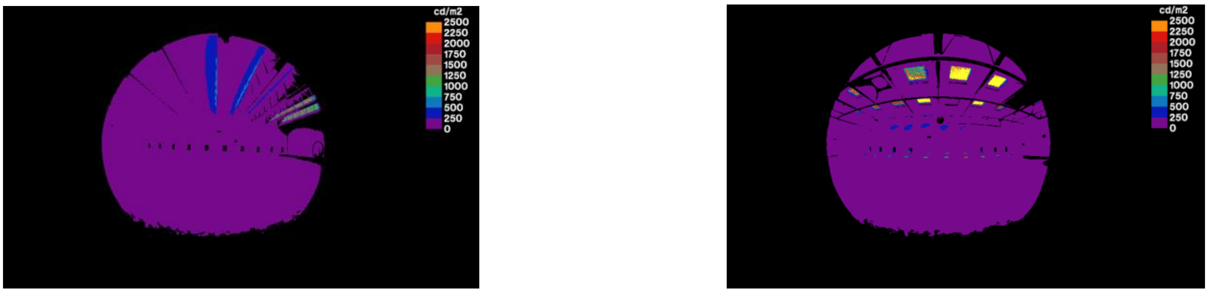
East orientation	**Southeast orientation**	**South orientation**
8am		
		
10am		
		
12am		
		

Table 4.6 Summary of false color images of different orientated sports hall in summer solstice.

Comparison

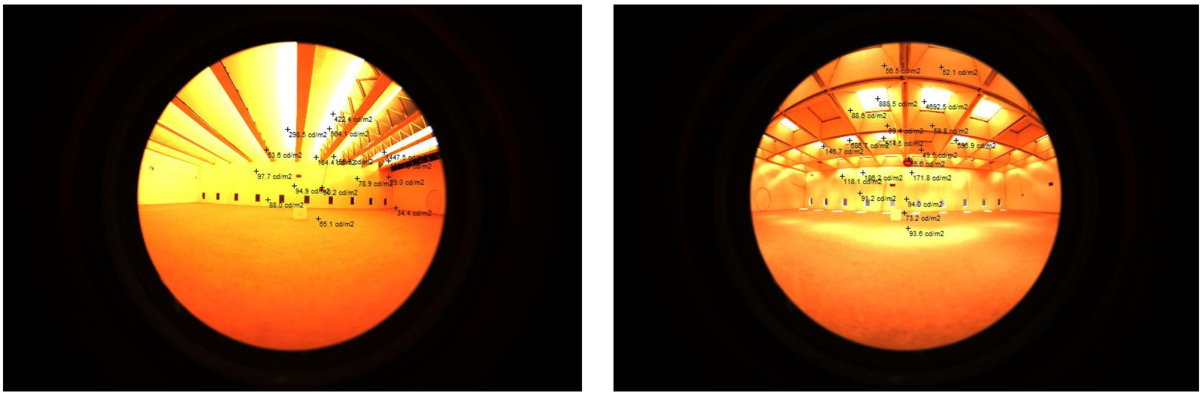


a) b)

Figure 4.11 False color images at 12am 21st June. a) Saw tooth roof. b) skylight roof.

Comparing the false color images of the first and second alternatives at noon with east orientation, it is clear that the skylights roof has higher luminance contrast between the window and the surrounding surfaces. However, the GFAR of saw tooth roof is 46% which is much higher than that of skylights roof. It means that the saw tooth roof could result in higher heat loss which will be evaluated in the next section.

The luminance contrast ratios are calculated by pointing many points including the brightest and the darkest area in the HDR Images, as shown in figure 4.12,



a) b)

Figure 4.12 Points in HDR Images for luminance contrast ratio calculation. a) Saw tooth roof. b) Skylights roof.

Again it is quite difficult to select the points on the LCP, since the values varies too much. The brightest is used to calculate the luminance ratio of windows and the nearby surface.

The values on the table 4.7 displays that all the ratios didn't exceed the maximum ratio in the requirements. This means that both alternatives create well enough visual conditions for ball visibility. And the visual comfort is slightly higher in saw tooth roof comparing to the ratios to the requirements. Even the contrast ratio between window and adjacent surrounds is 78.5:

1in the skylights roof sports hall, the interior space is visually comfortable if we take into consideration the type of activity.

Definition (surfaces in ratio)	Ratio of saw tooth roof	Ratio of skylight roof
Window: adjacent surrounds (ceilings)[1]	49.9:1	78.5: 1
Adjacent surrounds : target (ball)[2]	3.7 :1	9.2: 1
Ratios outside recommended max of 10:1?	No	No
Ratios outside recommended max of 100:1?	No	No

Table 4.7 Luminance ratios of two alternatives.

4.3. Energy performance simulation

SIMIEN is a dynamic building simulation tool developed by the Norwegian company Programbyggerne. It is based on the method described in the Norwegian standard NS 3031: 2014. SIMIEN is frequently used by Norwegian building designers to work with various simulations, such as heating demand calculation, cooling demand calculation, annual building performance simulation, evaluation according to the Norwegian building regulations (TEK), energy labelling calculation, evaluation according to the Norwegian passive house or low energy requirement and profitability calculation.

In this thesis SIMIEN version 6.0 was used to calculate the annual energy saving of the two alternatives comparing with the original design which is a black box. The lighting energy calculation of the two alternatives was done through the DA calculation in DIVA. The detailed process is displayed in the appendix C.

[1] < 100 is OK for Low requirement (large objects like a ball), < 50 is OK even for Moderate (reading).
[2] < 20 is OK for Low requirement, < 10 is OK even for Moderate (reading)

Results of sports hall without windows

The table below shows the predicted annual energy demand of the sports hall without any windows. The total lighting energy consumption is 38.3kWh/year, which is the installed power multiplied by the operation hours. It counts for the largest proportion in the total energy consumption which is the green part in the pie chart.

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	403 kWh	0,3 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	22679 kWh	17,5 kWh/m²
2 Varmtvann (tappevann)	9079 kWh	7,0 kWh/m²
3a Vifter	27200 kWh	21,0 kWh/m²
3b Pumper	843 kWh	0,7 kWh/m²
4 Belysning	49669 kWh	38,3 kWh/m²
5 Teknisk utstyr	35478 kWh	27,4 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1707 kWh	1,3 kWh/m²
Totalt netto energibehov, sum 1-6	147058 kWh	113,5 kWh/m²

Table 4.8 Annual energy demand of sports hall with no windows.

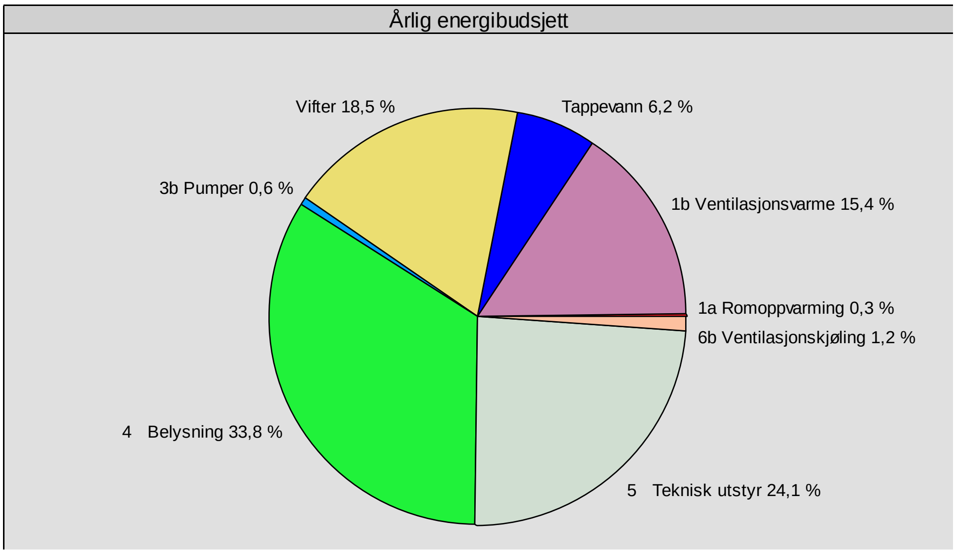


Table 4.9 Pie chart of energy budget in sports hall with no windows.

Results of sports hall with saw tooth roof

After applying the designed saw tooth roof, the total lighting energy demand is reduced to 21.6 kWh/m^2. However due to the large roof glazing area, the heating energy consumption increases to 17.3 kWh/m^2. And the total energy consumption is only reduced by 2.6%.

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	22068 kWh	17,0 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	29746 kWh	23,0 kWh/m²
2 Varmtvann (tappevann)	9079 kWh	7,0 kWh/m²
3a Vifter	23652 kWh	18,3 kWh/m²
3b Pumper	784 kWh	0,6 kWh/m²
4 Belysning	27989 kWh	21,6 kWh/m²
5 Teknisk utstyr	28382 kWh	21,9 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1654 kWh	1,3 kWh/m²
Totalt netto energibehov, sum 1-6	143355 kWh	110,6 kWh/m²

Table 4.10 Annual energy demand of saw tooth roof sports hall.

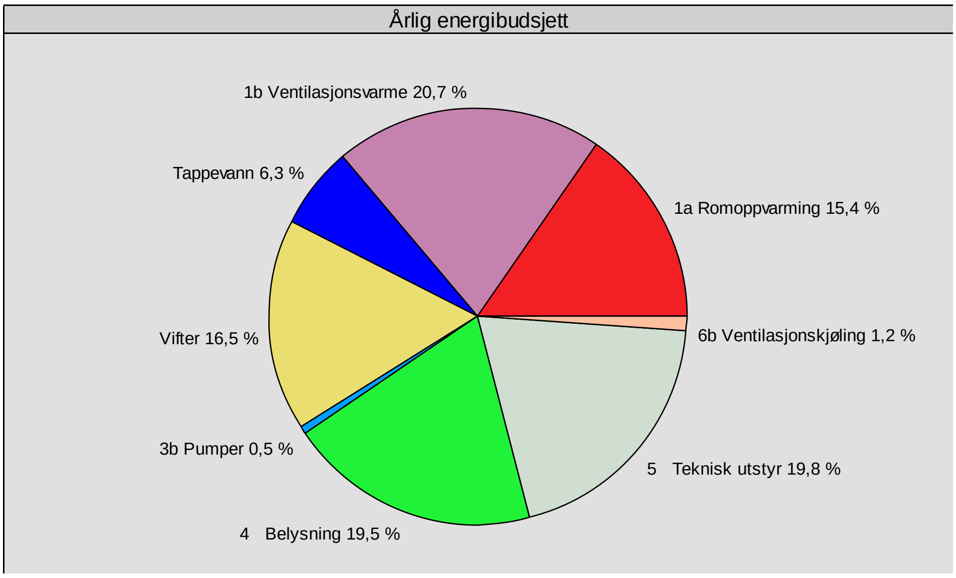


Table 4.11 Pie chart of energy budget in saw tooth roof sports hall.

Results of sports hall with skylights roof

For the skylight roof sports hall, the total lighting energy consumption is reduced by 54.3%, In this alternative, the GFAR is 16% which is only one third area of the first alternative. The heating energy increases slightly. The total energy demand is decreased by 12.7%.

Energibudsjett		
Energipost	Energibehov	Spesifikt energibehov
1a Romoppvarming	3134 kWh	2,4 kWh/m²
1b Ventilasjonsvarme (varmebatterier)	28311 kWh	21,8 kWh/m²
2 Varmtvann (tappevann)	9079 kWh	7,0 kWh/m²
3a Vifter	27200 kWh	21,0 kWh/m²
3b Pumper	819 kWh	0,6 kWh/m²
4 Belysning	22640 kWh	17,5 kWh/m²
5 Teknisk utstyr	35478 kWh	27,4 kWh/m²
6a Romkjøling	0 kWh	0,0 kWh/m²
6b Ventilasjonskjøling (kjølebatterier)	1707 kWh	1,3 kWh/m²
Totalt netto energibehov, sum 1-6	128368 kWh	99,0 kWh/m²

Table 4.12 Annual energy demand of skylights roof sports hall.

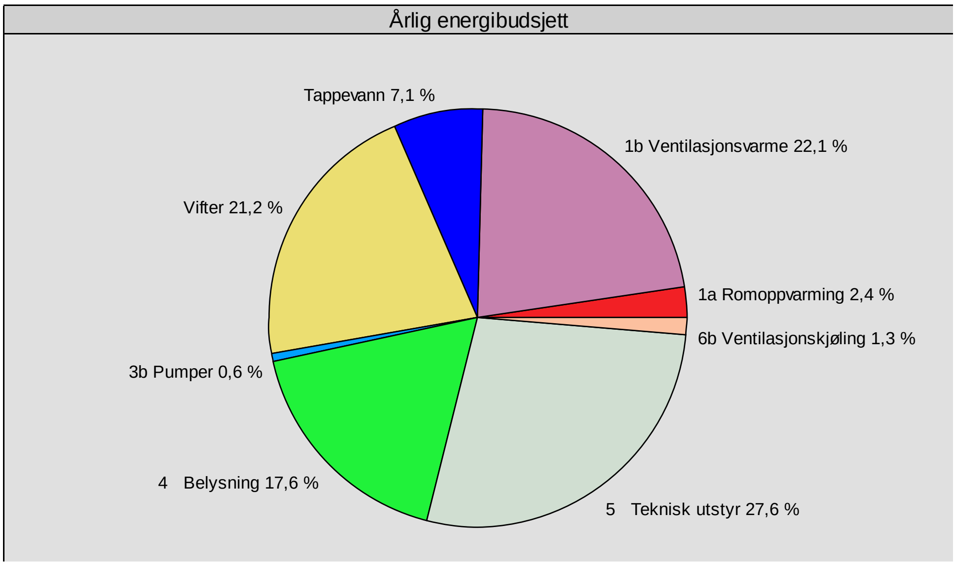


Table 4.13 Pie chart of energy budget in skylights roof sports hall.

The SIMIEN simulation of the two alternatives shows that both of them help saving lighting energy. But saw tooth roof results in higher heating energy consumption which is almost the same as the saved lighting energy. Skylights roof shows a better potential regarding energy saving.

5. Conclusion

Simulations showed that both of the alternatives give potential for increasing the daylight autonomy in the sports halls. More numbers of saw tooth and skylight openings will increase daylight autonomy and even daylight distribution within the building floor plan. Evaluation of the two kinds of roof shapes showed that skylights roof will have more uniform daylight distribution with less GFAR than saw tooth roof because of the roof shape and the light redirection of LCPs.

Analysis of the HDR Images found that saw tooth roof works better with north orientation while skylights roof has no influence from orientation. However, LCPs applied in skylights roof cause uneven and extreme high luminance values on the window. By calculating the luminance ratio it was found that although both daylit alternatives meets requirements for maximum contrast, the saw tooth roof creates slightly higher visual comfort than the skylights roof.

The results of SIMIEN simulation shows that applying both options can save almost half of the lighting energy consumed in a sports hall with no windows. However, the saw tooth roof has a much higher heat loss because of larger GFAR. Therefore, the total energy consumption saved by skylights roof is the most.

5.1. Future work

Due to time limitation, the studied design parameters and the physical models are not comprehensive for the daylight imitation in a sports hall. The study process and results represented in this research has potential to grow and expand even further with additional simulations and literature review.

This thesis only studied how the saw tooth roof and skylights roof affect daylight visual comfort in a standardized sports hall and their influence on energy demand. The results could be used by designer and employees who works on improving daylight condition in sports halls.

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Appendix A

Daylight simulation results of two alternatives in DIVA

The 3D models were made by Grasshopper which is quite efficient to change the design parameters, such as the number of saw tooth. The scripts are displayed in the pictures below.

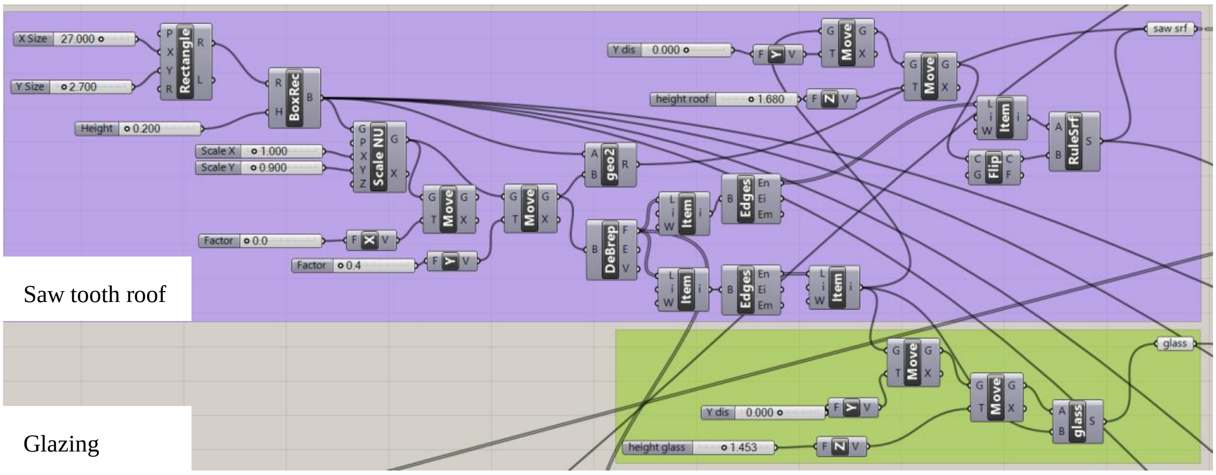

Figure A. 1 Saw tooth roof solid and glazing parts' script in Grasshopper.

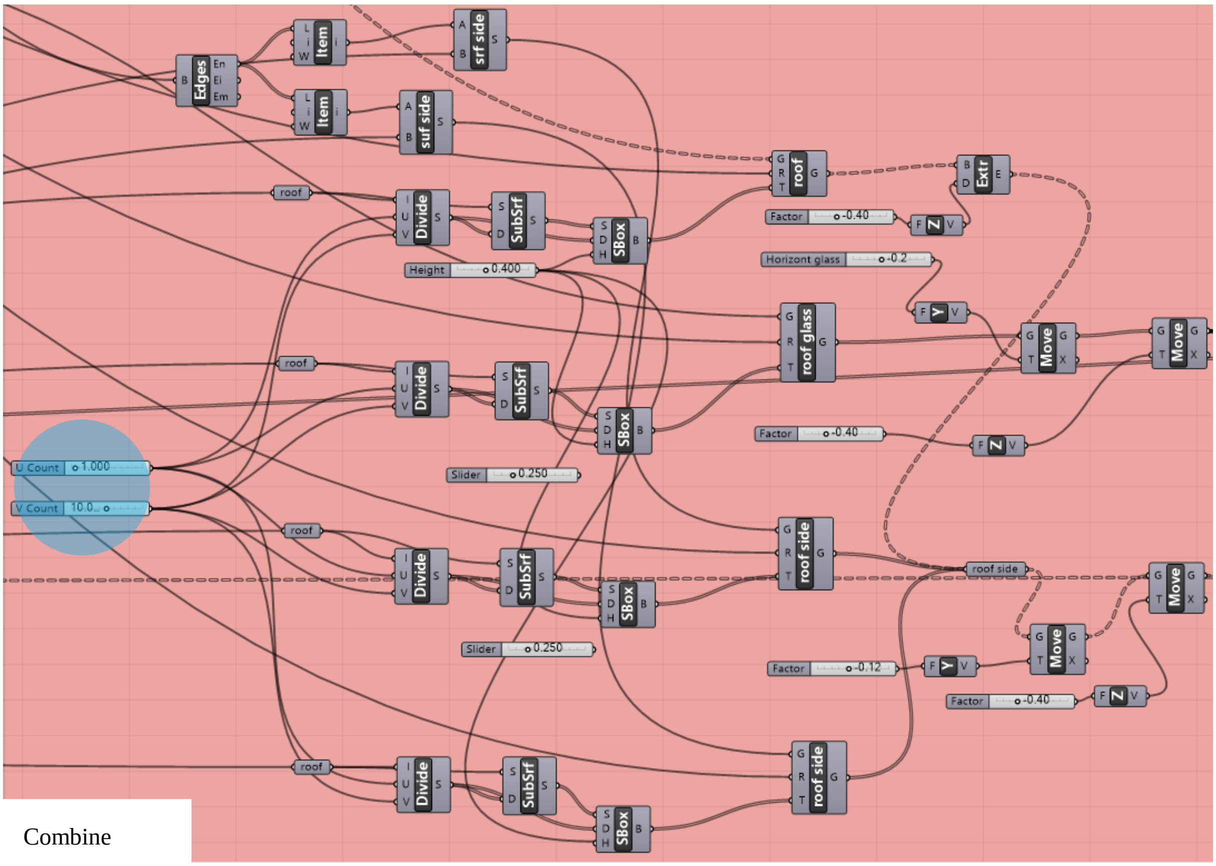

Figure A.0.1 Combine the opaque and glazing part of saw tooth roof.

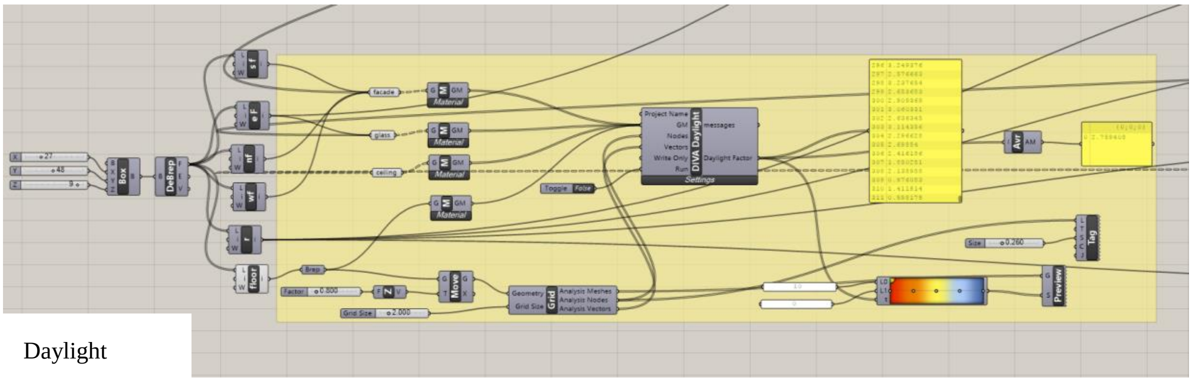

Figure A.3 Daylight analysis script.

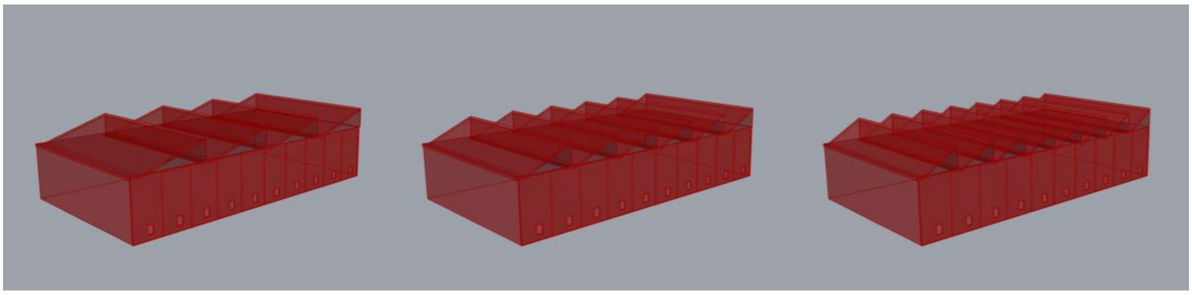

Figure A.4 3D models made by the scripts.

The figure below is the Grasshopper scripts for making skylights roof.

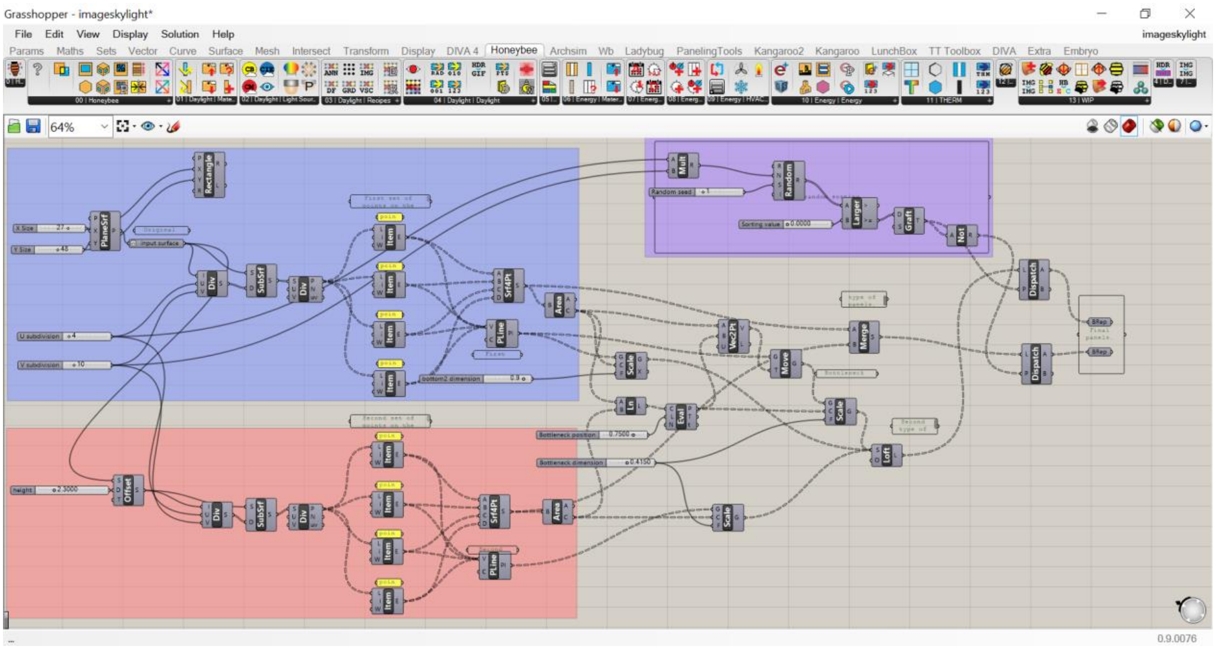

Figure A.5 Skylights roof scripts in Grasshopper.

To analyze the DF and DA, the weather data and material should be submitted in DIVA for Rhino. For adding a custom material open [project location]/ [project]- DIVA/ Resources/material .rad. Then write down the material's property as shown in the figure below. Save and proceed in Rhino.

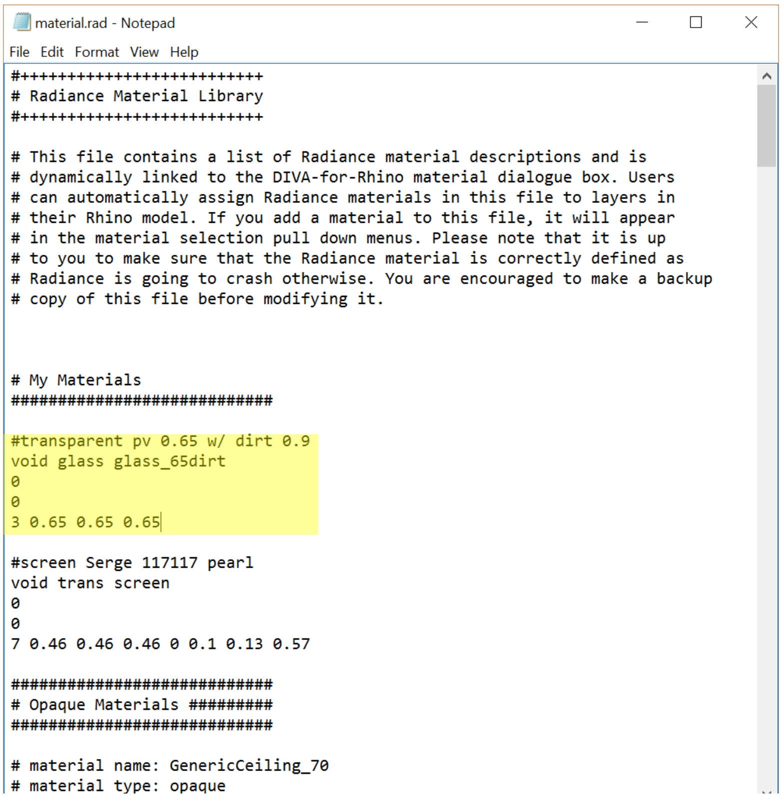

Figure A.6 Adding custom materials.

After materials assignment, DF simulation can be run.

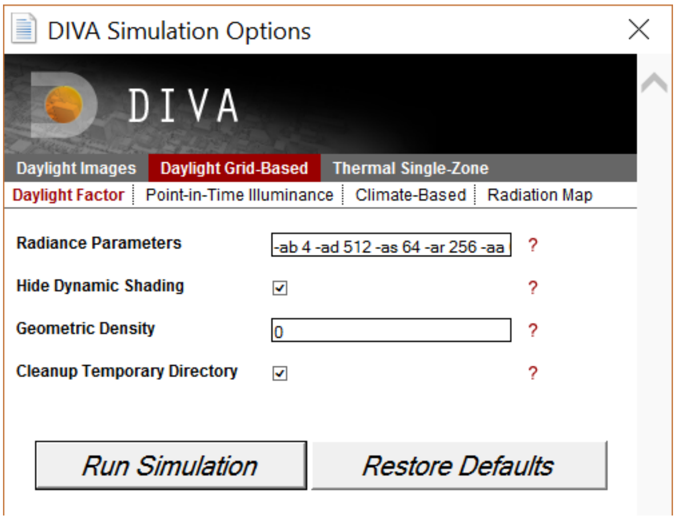

Figure A.7 Daylight factor metric.

The DA metric simulation needs an additional step which is lighting setting. Lighting power depends on lighting level and type. Table below is some recommended values:

	100lux	200lux	300lux	500lux	700lux

Fluor W/m^2	2.5	5	7	12	17
LED W/m^2	1.5	3	5	7	11

Table A.1 Recommended lighting power.

The lighting set point is 500 lux; the lighting power is 7 W/m^2~ 9072W. The standby power is 3W. And the ideal operation mode is dimming with occupancy on/off. The selected node is a node in the back of the room.

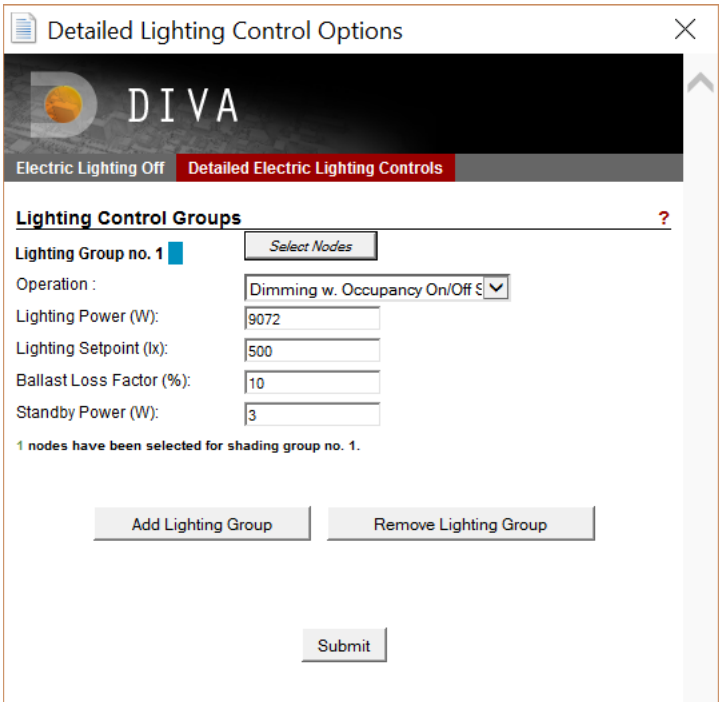

Figure A.8 Detailed electric lighting control setting.

When all the materials are assigned, it is time to start the DA simulation. Select "all (Dautonomy...)" for the metric. It is important to prepare the occupancy schedule which is a .csv file in advance. Since the sports facilities have a long operation time, the time schedule is set from 7 am to 10 pm on workdays.

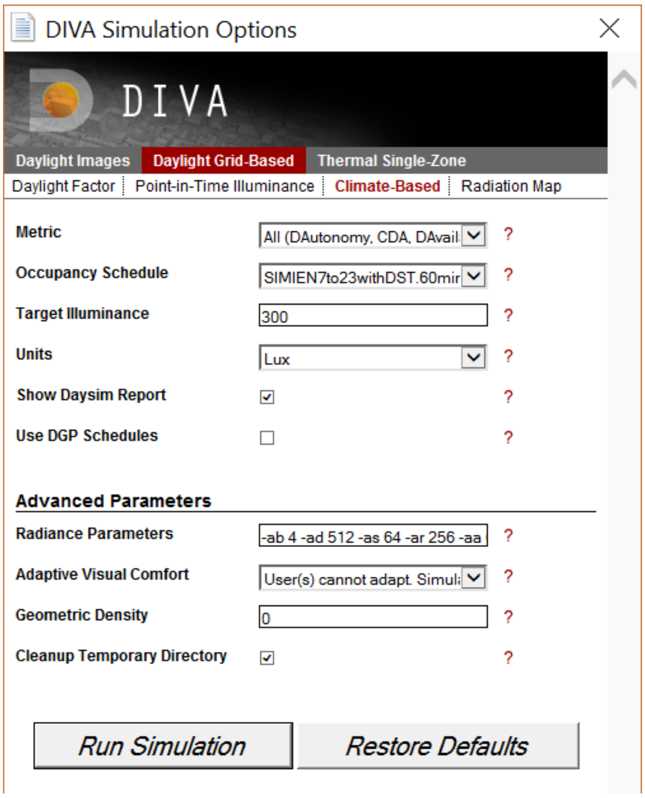

Figure A.9 Daylight autonomy simulation settings.

Appendix B

HDR Images converted to false color images

The HDR Images were converted to false color images by using Honeybee which is a program developed by Mostapha S. Roudsari. It is an environmental plugin which connects Grasshopper to EnergyPlus, Radiance, and Daysim for daylight simulations.

Honeybee appears as a tab in the Grasshopper interface, figure B.1, and since Honeybee is connected to Grasshopper, simulation results can be viewed directly within the 3D model in the Rhino interface.

Figure B. 1 Honeybee interface.

The plugin not only can create geometry and generate Radiance-materials18, it also allows users to convert HDR Images to false color images (Roudsari, 2017). In addition, it is possible to adjust the legend scale and steps. The script to covert HDR Images to false color images is shown in the figure below.

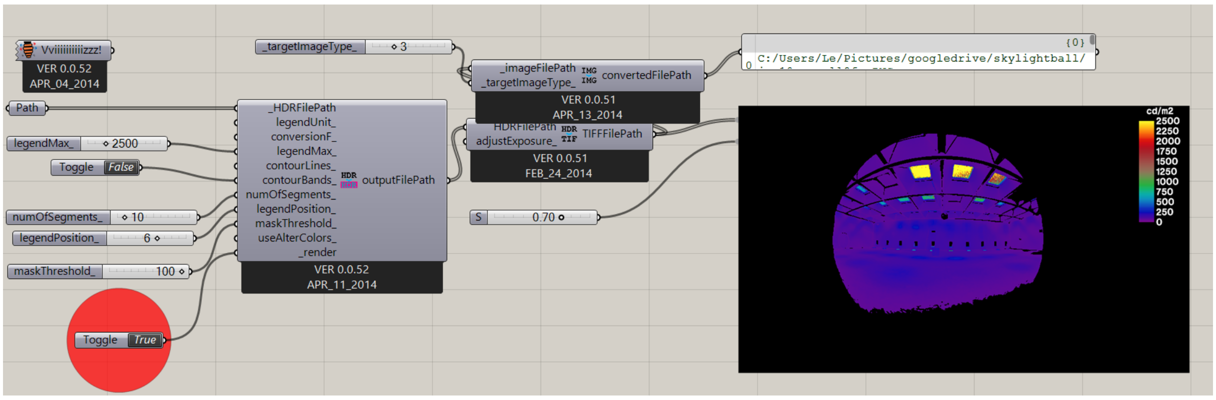

Figure B. 2 Convert HDR Images to false color images by Honeybee.

Appendix C

Lighting energy demand calculation

The lighting power demand was calculated based on the .csv file from the DA simulation performed in DIVA, as shown in table C.1.

A	B	C	D	E	F
Daysim schedule file (to be used in combination with a thermal simulation program)					
Daysim header file: C:\DIVA\te			Occupied	Lighting Group 1 - manual_dimming	
			Installed L	9075	No blind groups specified.
month	day	hour	occupanc	lighting [0=off...1=full on]	
1	1	0.5	0	0	0
1	1	1.5	0	0	0
1	1	2.5	0	0	0
1	1	3.5	0	0	0
1	1	4.5	0	0	0
1	1	5.5	0	0	0
1	1	6.5	0	0	0
1	1	7.5	1	1	0
1	1	8.5	1	1	0
1	1	9.5	1	1	0
1	1	10.5	1	0.97	0
1	1	11.5	1	0.78	0
1	1	12.5	1	0.88	0
1	1	13.5	1	0.89	0
1	1	14.5	1	1	0
1	1	15.5	1	1	0
1	1	16.5	1	1	0
1	1	17.5	1	1	0
1	1	18.5	1	1	0

Figure C.1 .csv file from DA simulation in DIVA

Then import the data to an Excel file with delimiter "," and decimal separator ".".Make a sum of the occupancy on/off dimming hours in the same month, table C.2.

Sum - lighting	hour											
month	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
1	0	0	0	0	0	0	0	21	21	20.9	18.92	17.33
2	0	0	0	0	0	0	0	20	19.19	16.59	13.93	12.84
3	0	0	0	0	0	0	0	18.56	14.34	11.25	9	7.54
4	0	0	0	0	0	0	13.15	8.66	5.4	3.9	3.14	2.97
5	0	0	0	0	0	0	4.19	3.22	2.57	2.23	2.61	2.1
6	0	0	0	0	0	0	4.07	3.37	3.7	2.97	2.89	2.2
7	0	0	0	0	0	0	4.75	3.32	2.59	2.84	2.24	2.2
8	0	0	0	0	0	0	10.92	7.47	4.87	4.07	3.19	3.2
9	0	0	0	0	0	0	19	14.52	10.46	7.41	6	4.97
10	0	0	0	0	0	0	21	19.8	16.28	14.02	12.28	11.08
11	0	0	0	0	0	0	0	22	21.91	20.2	18.19	17.24
12	0	0	0	0	0	0	0	23	23	23	22.54	20.71
Sum	0	0	0	0	0	0	77.08	164.92	145.31	129.38	114.93	104.38

month	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5	22.5	23.5	Sum
1	16.87	17.3	19.24	20.86	21	21	21	21	21	21	21	1.68	322.1
2	12.45	12.36	13.95	16.35	19.19	19.99	20	20	20	20	20	1.6	278.44
3	7.09	7.33	9.01	11.61	15.2	19.22	22.71	23	23	23	23	1.84	246.7
4	2.77	2.21	2.58	3.09	4.99	9.13	14.21	20.91	22	22	1.76	0	142.87
5	2.28	2.2	2.21	2.22	2.24	3.09	4	6.93	14.83	20.87	3.52	0.16	81.47
6	2.2	2.2	2.2	2.28	2.89	3.75	6.14	7.62	11.48	18.18	2.68	0.08	80.9
7	2.2	2.68	2.2	2.41	2.95	3.66	5.95	8.51	11.35	19.98	1.76	0	81.59
8	3.07	2.72	3.59	3.71	3.86	5.84	9.05	13.4	20.5	22	1.76	0	123.22
9	4.99	4.68	5.82	8.08	11.51	15.99	20.19	21.96	22	22	1.76	0	201.34
10	11.08	11.48	13.4	16.13	19.45	20.99	21	21	21	21	1.68	0	272.67
11	17	17.58	19.74	21.9	22	22	22	22	22	22	22	1.76	331.52
12	20.68	21.23	22.96	23	23	23	23	23	23	23	23	1.84	362.96
Sum	102.68	103.97	116.9	131.64	148.28	167.66	189.25	209.33	232.16	255.03	123.92	8.96	2525.78

Figure C.2 Summary of monthly and hourly lighting power

From clock 8.5 to 17.5 the electrical light can be dimmed off because daylight is available. The occupancy hour "*h_occ*" is calculated by multiplying the days of workdays in a month with 10h. The occupancy power "*on_occ*" is the sum of monthly occupancy on/off dimming hours from clock 8.5 to 17.5. Times the value of "*on_occ*" and lighting power which is 7 W/m^2 can get the occupancy lighting energy "*E_occ*".

AB	AC	AD	AE	AF	AG
h_occ	h_unocc	on_occ	on_unocc	E_occ	E_unocc
210	534	194.42	127.68	1361	894
200	472	156.84	121.6	1098	851
230	514	111.59	135.11	781	946
220	500	39.71	103.16	278	722
210	534	23.88	57.59	167	403
220	500	26.9	54	188	378
220	524	25.63	55.96	179	392
220	524	39.75	83.47	278	584
220	500	78.44	122.9	549	861
210	534	145	127.67	1015	894
220	500	197.76	133.76	1385	937
230	514	223.12	139.84	1562	979
2610	**6150**	**1263.04**	**1262.74**	**8844**	**8842**

Figure C.3 Lingting energy demand by occupancy

Dividing the occupancy lighting energy "*E_occ*" by the value of "*h_occ*" can get monthly lighting power demand with occupancy on/off.

模板专区 DF2_intgain.300lx no dynamic shading.csv sawtoothsimien.xls

	A	B	C	D	E
1	**Lighting zone 1**				
2	zone area:		1296	m²	
3	installed lighting power:		9072	W	
4	installed standby power:		3	W	
5	*total installed power:*		*7.00*	*W/m²*	
6					
7	*month*	*workdays*	*zone1,occ*	*zone1,unocc*	
8	Jan	21	**6.48**	**1.67**	
9	Feb	20	**5.49**	**1.80**	
10	Mar	23	**3.40**	**1.84**	
11	Apr	22	**1.26**	**1.44**	
12	May	21	**0.80**	**0.76**	
13	Jun	22	**0.86**	**0.76**	
14	Jul	22	**0.82**	**0.75**	
15	Aug	22	**1.27**	**1.12**	
16	Sep	22	**2.50**	**1.72**	
17	Oct	21	**4.83**	**1.67**	
18	Nov	22	**6.29**	**1.87**	
19	Dec	23	**6.79**	**1.91**	
20					
21	**total annual average power:**			**4.83**	**W/m²**
22	**total energy demand (LENI):**			**17.69**	**kWh/m²**

Figure C.4 Lingting power of every month with occupancy

Energy performance simulation in SIMIEN

SIMIEN settings of sports hall without windows

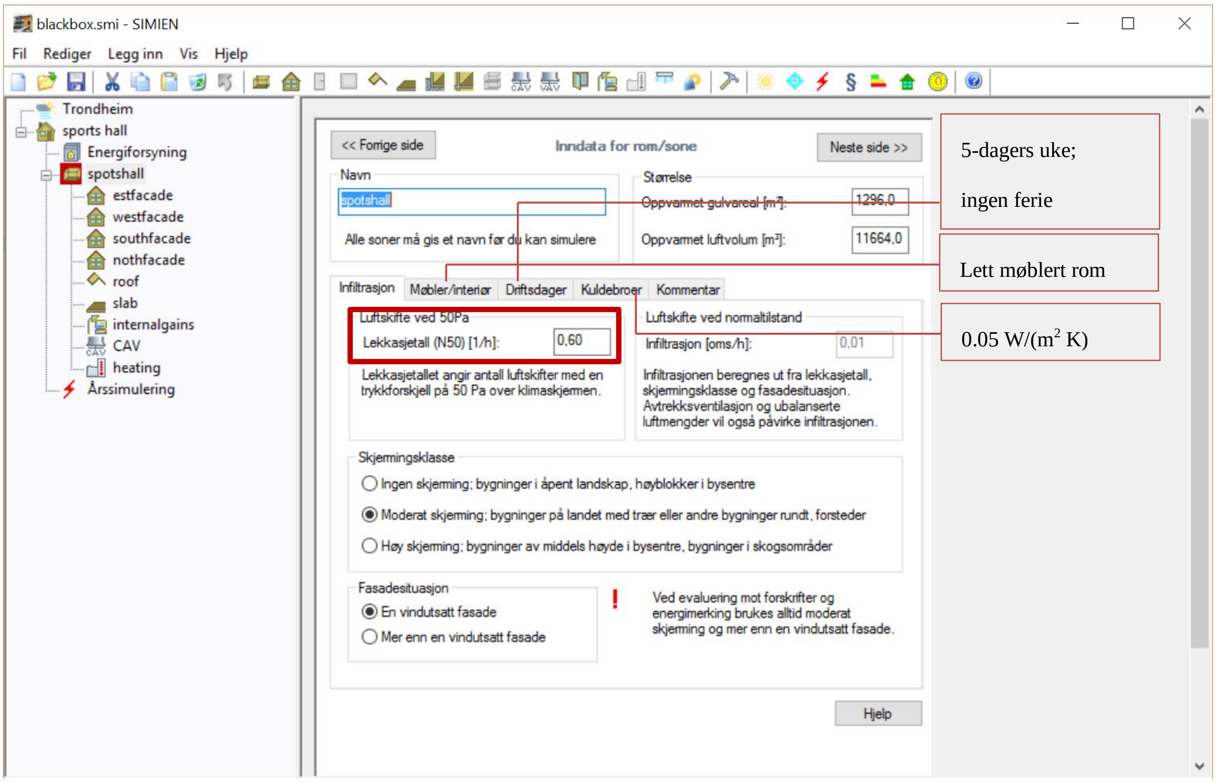

Figure C.5 Zone settings of sports hall

The U-value of walls, roof and floor were calculated according to the composite structures in a real project, which is called Bankgata idrettshall.

The wall is made of 70mm massive wood, 200mm insolation, wind barrier, 48mm studs and 25 mm planking.

The roof is made of 13mm plaster, 350mm mineral wool, wind barrier, 48mm air gap, 36mm studs and 25mm roofing.

The floor is made of 300mm concrete.

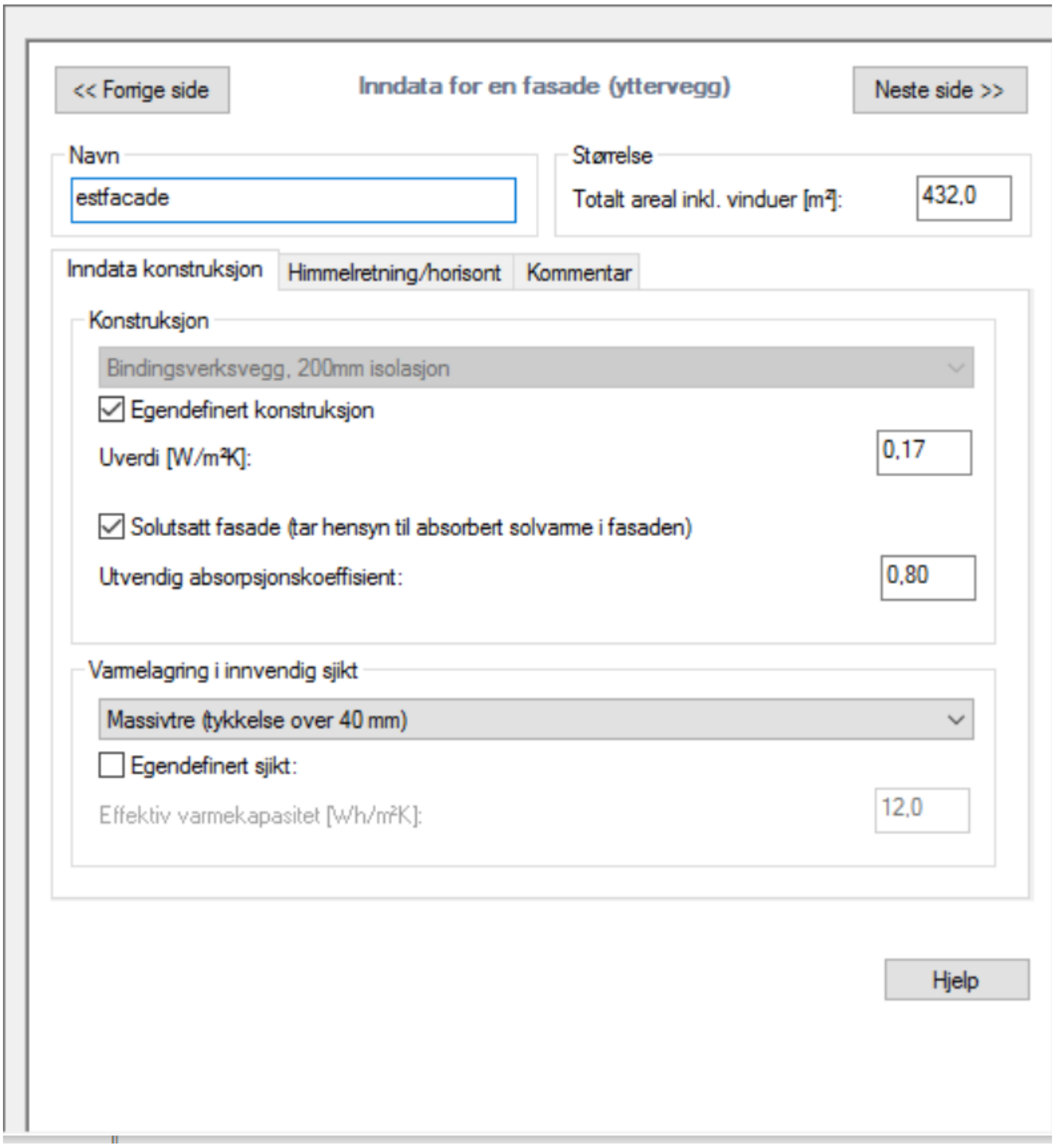

Figure C.6 Area and U-value of wall

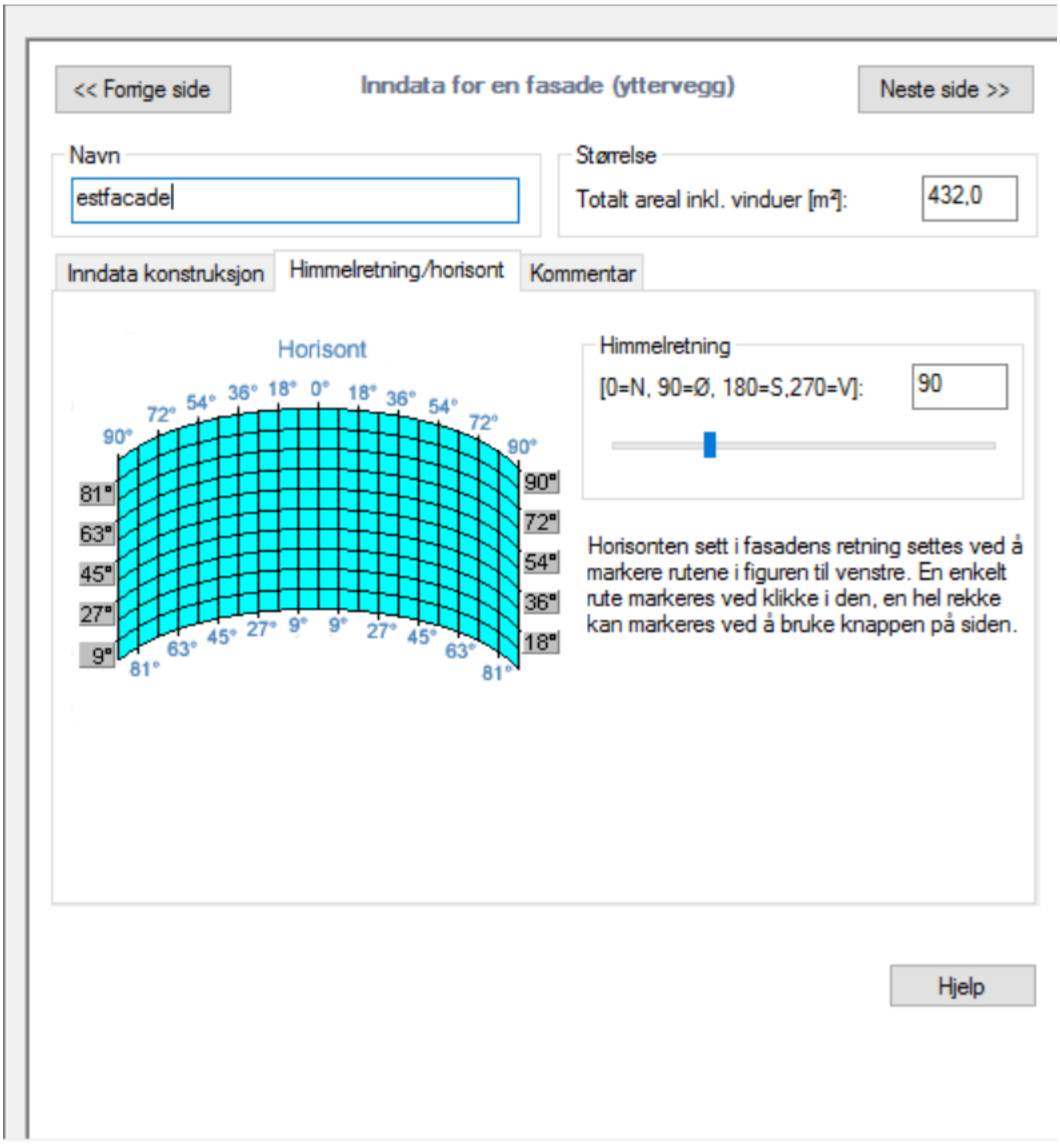

Figure C.7 Orientation of wall

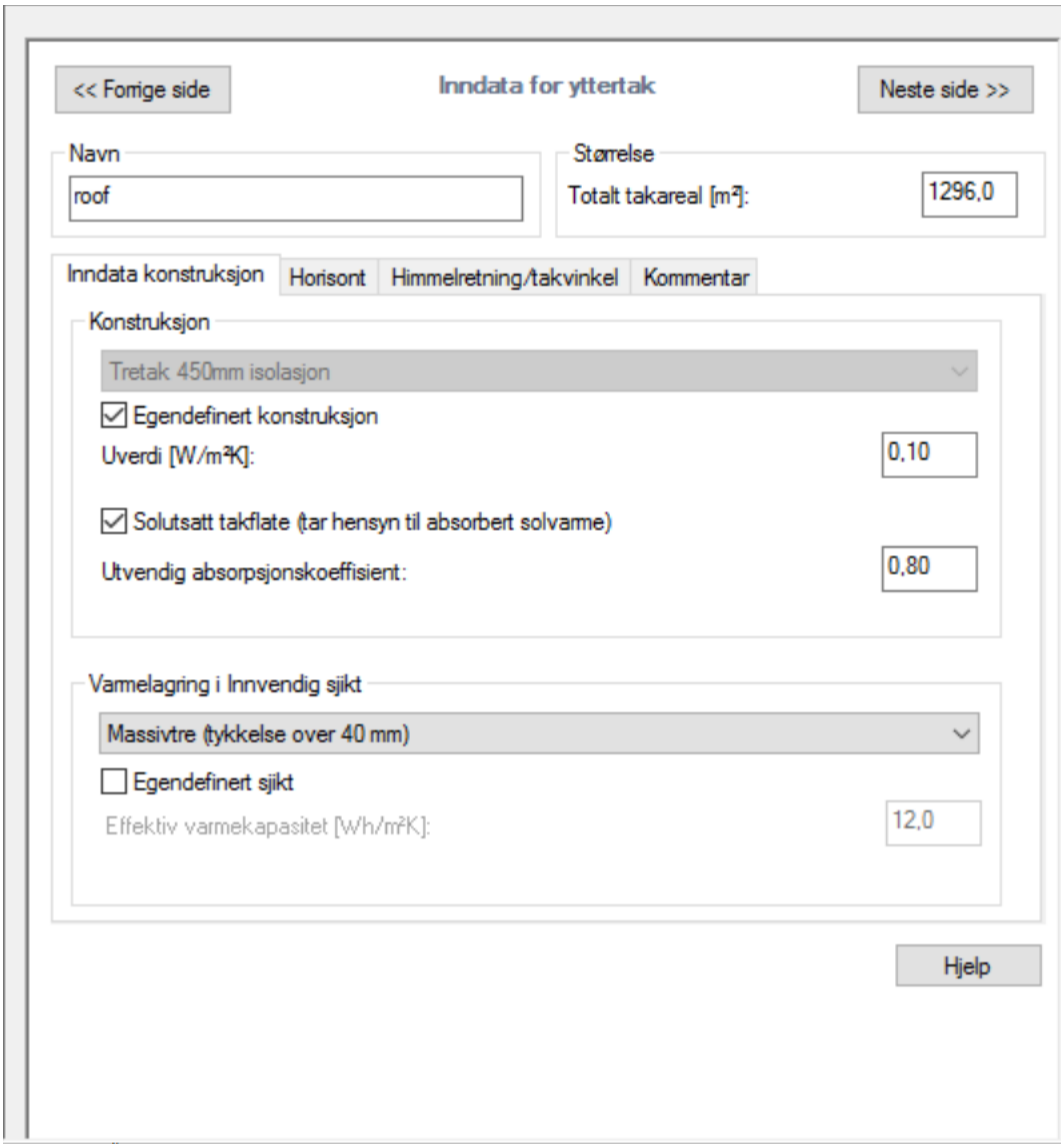

Figure C.8 Area and U-value of roof

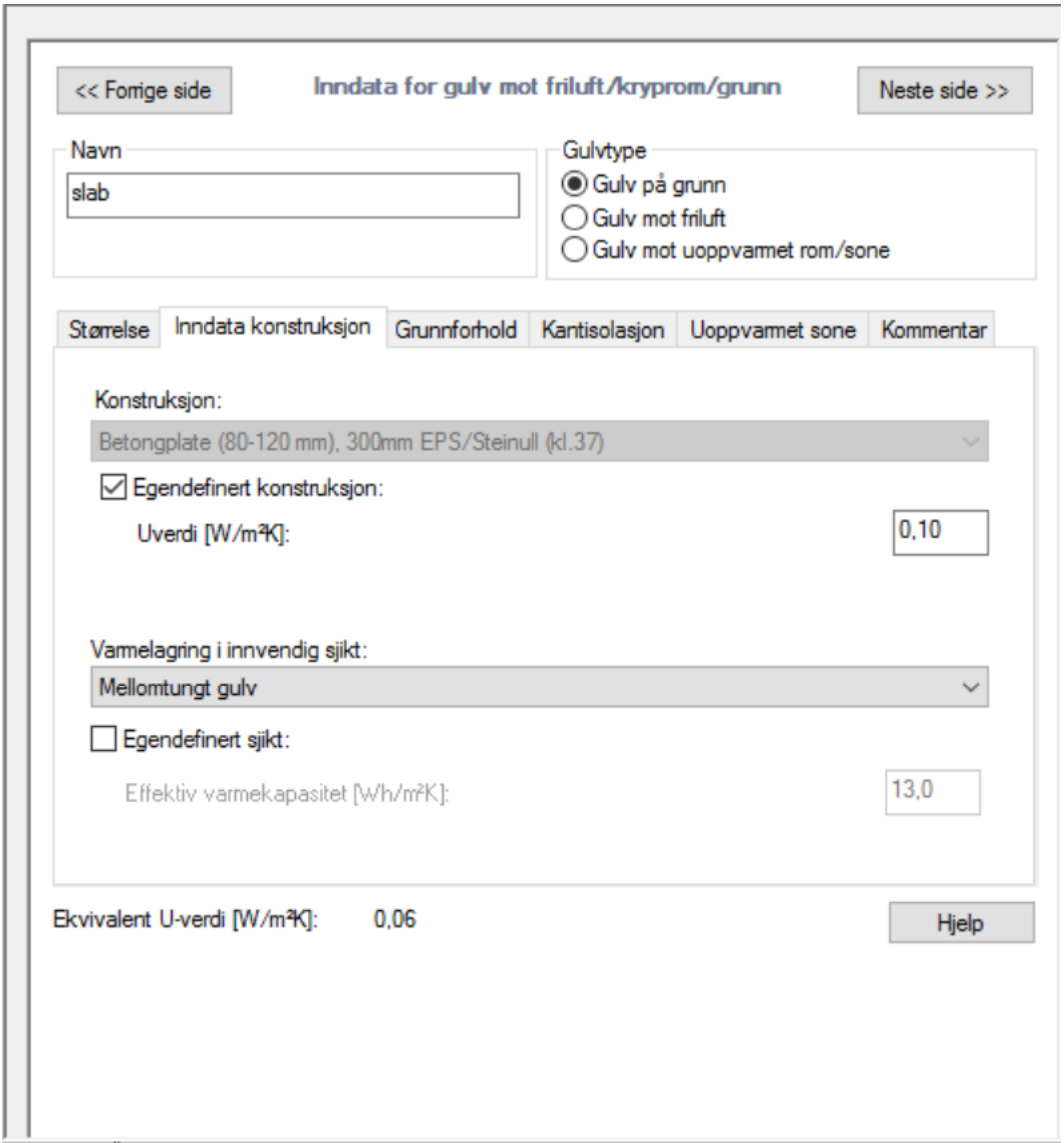

Figure C.9 U value of floor

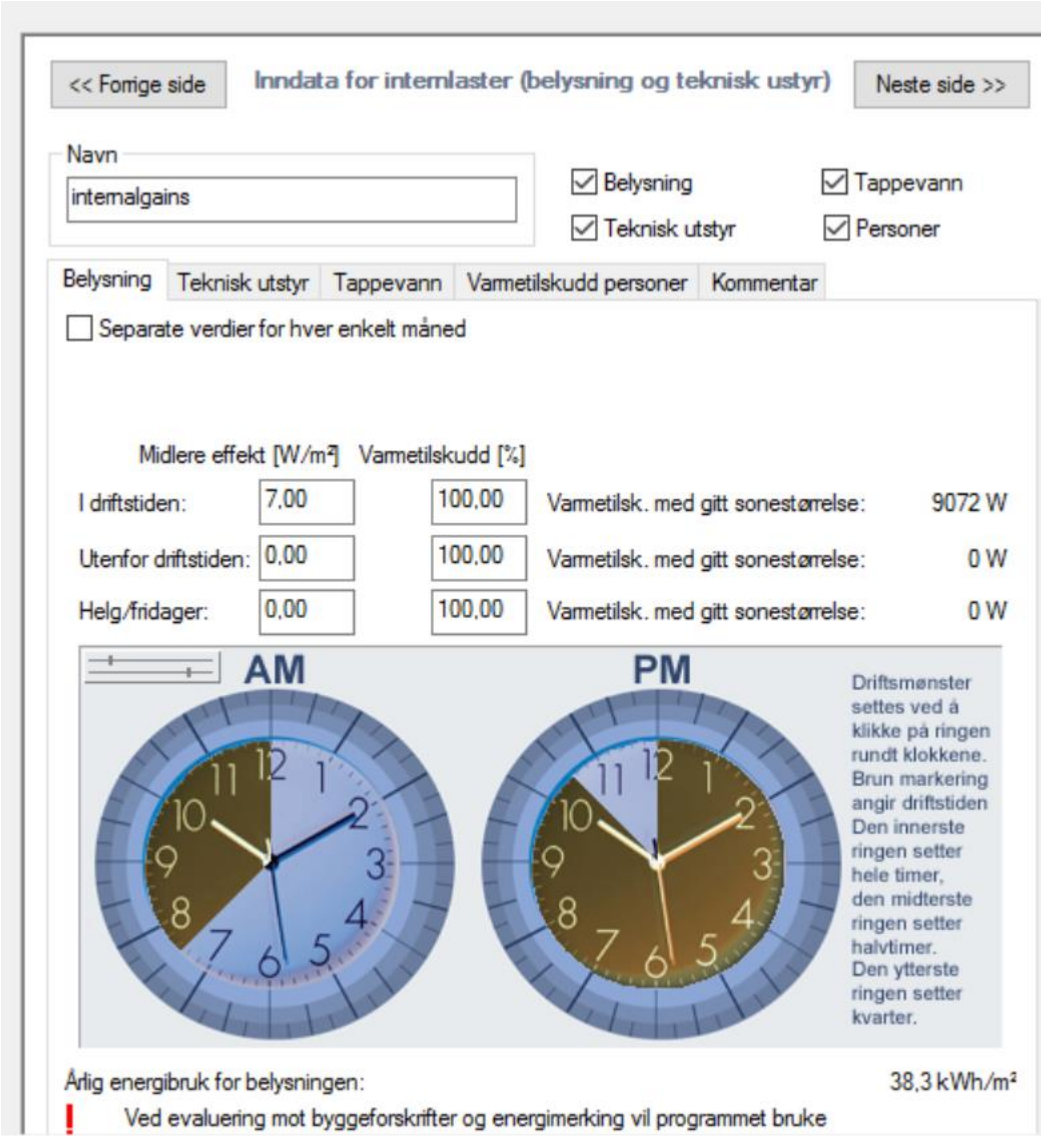

Figure C.10 Lighting setting

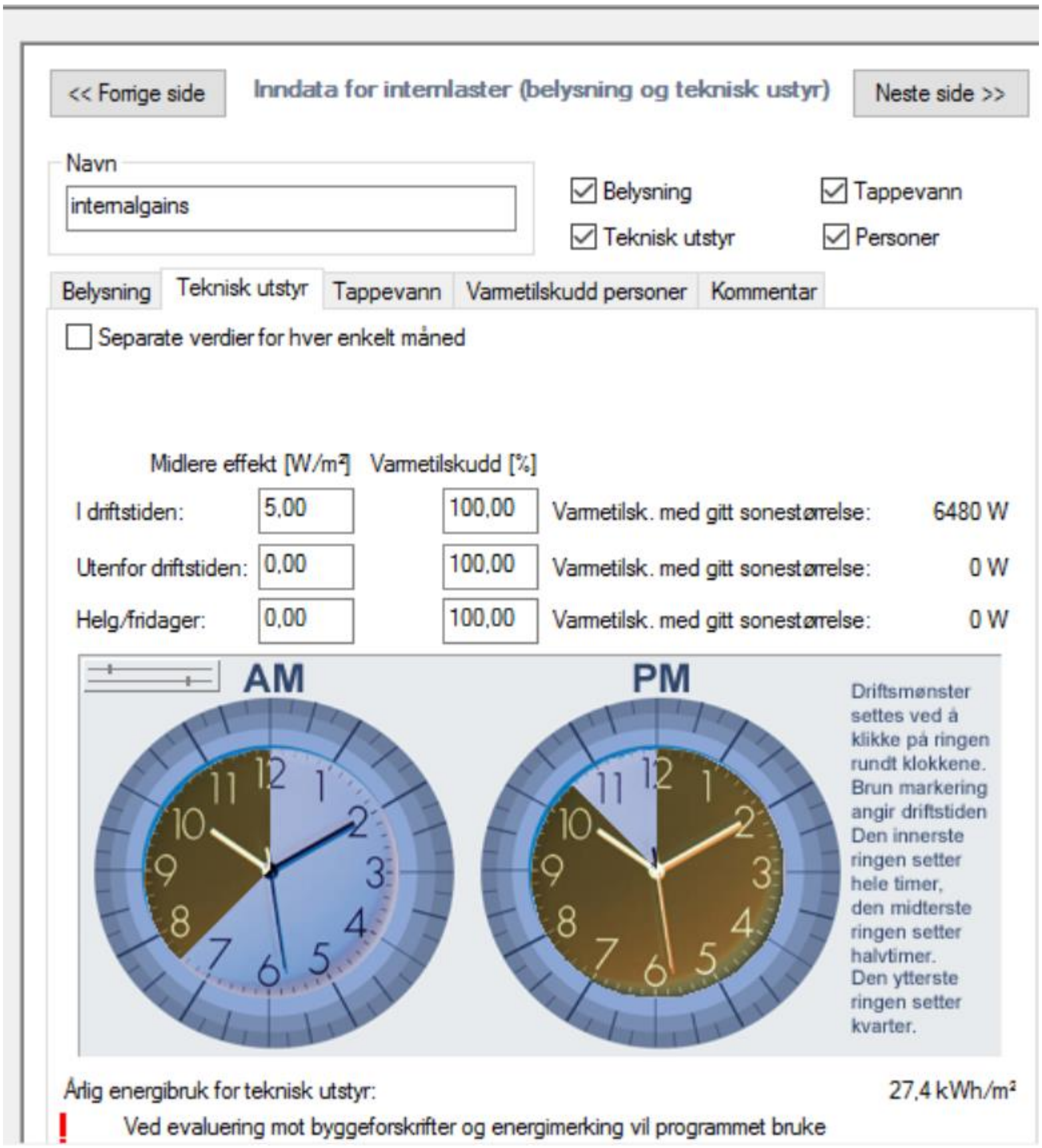

Figure C.11 technical equipment setting

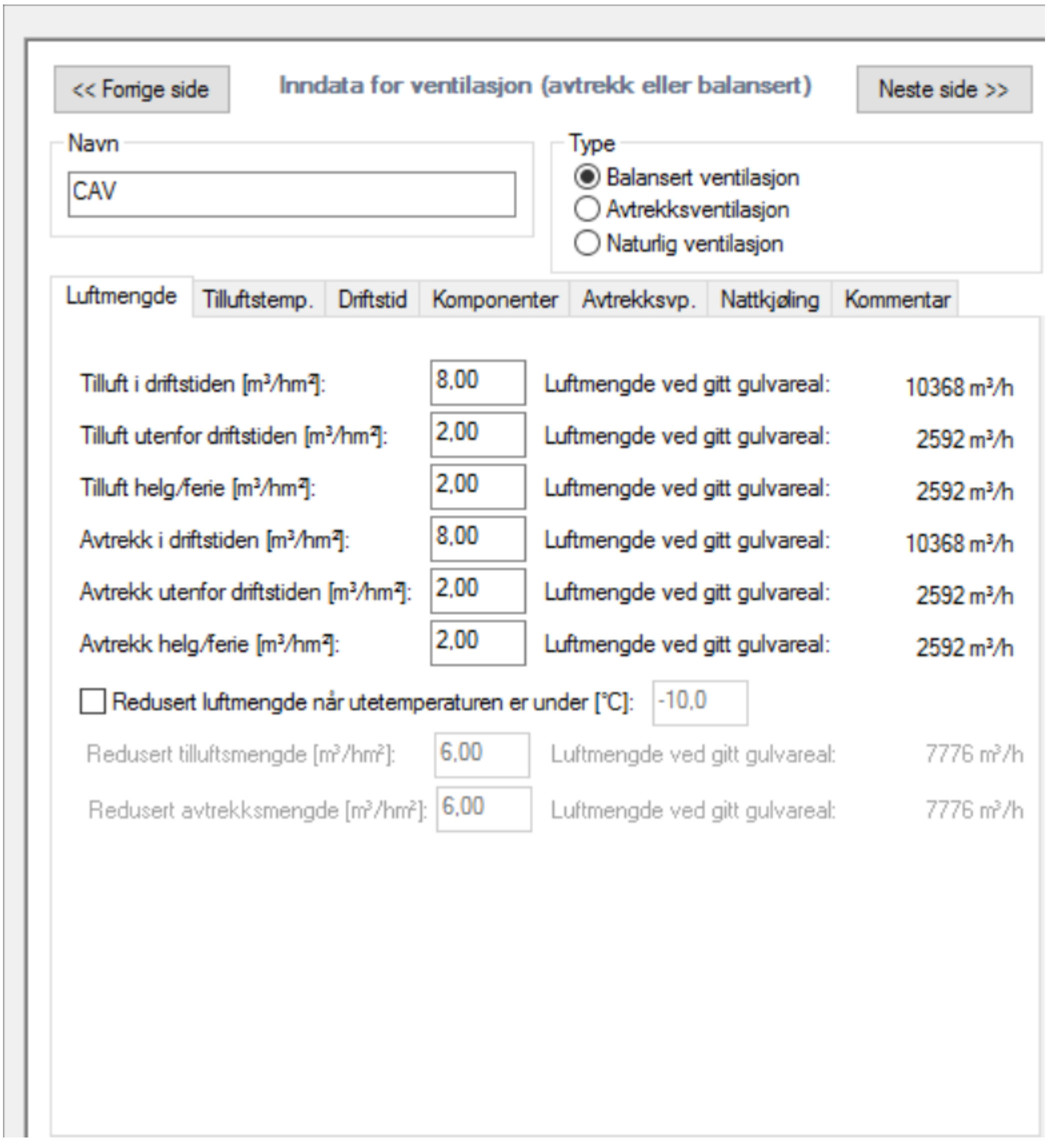

Figure C.12 Ventilation setting; airflow

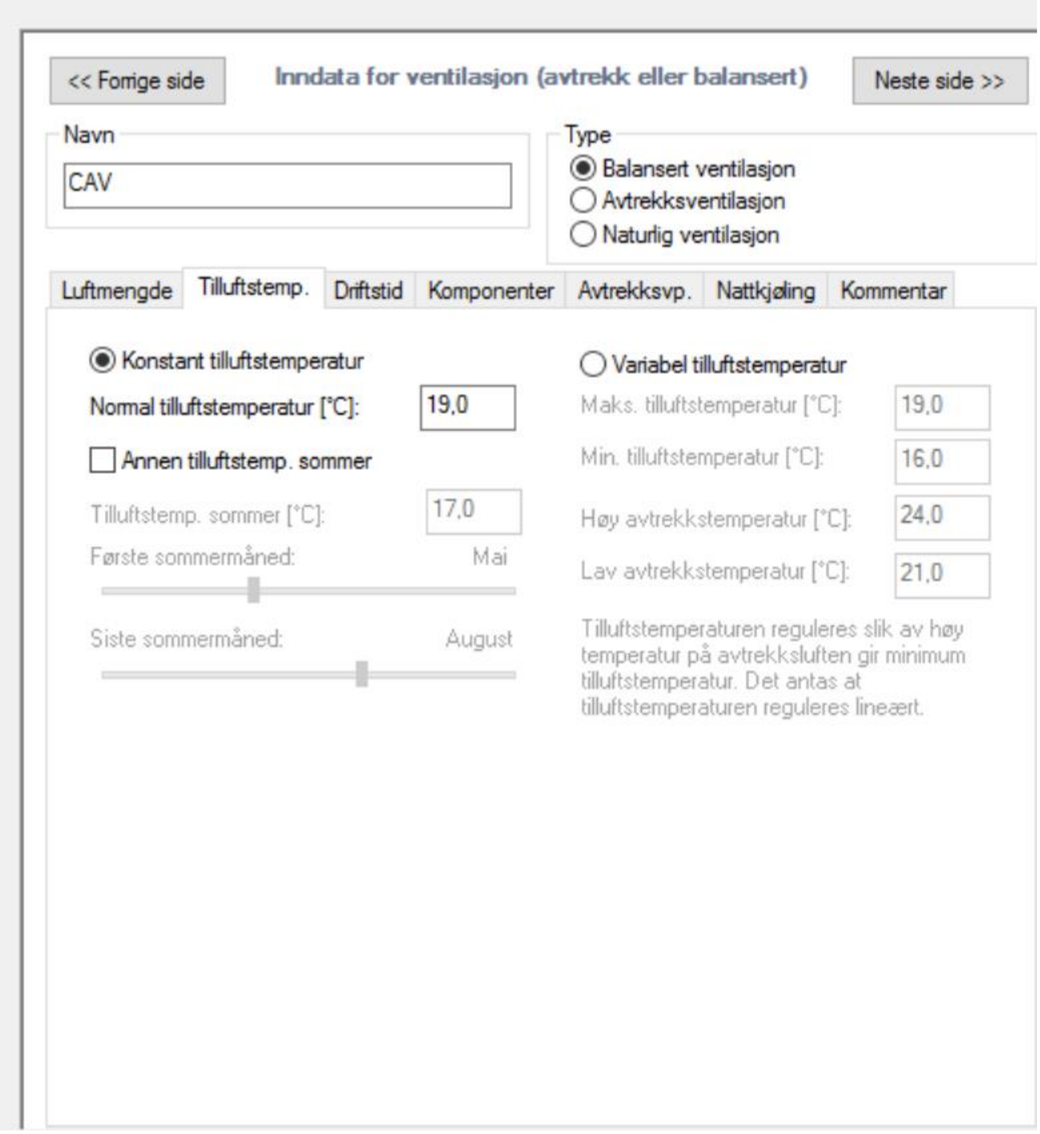

Figure C.13 Temperature of supply air

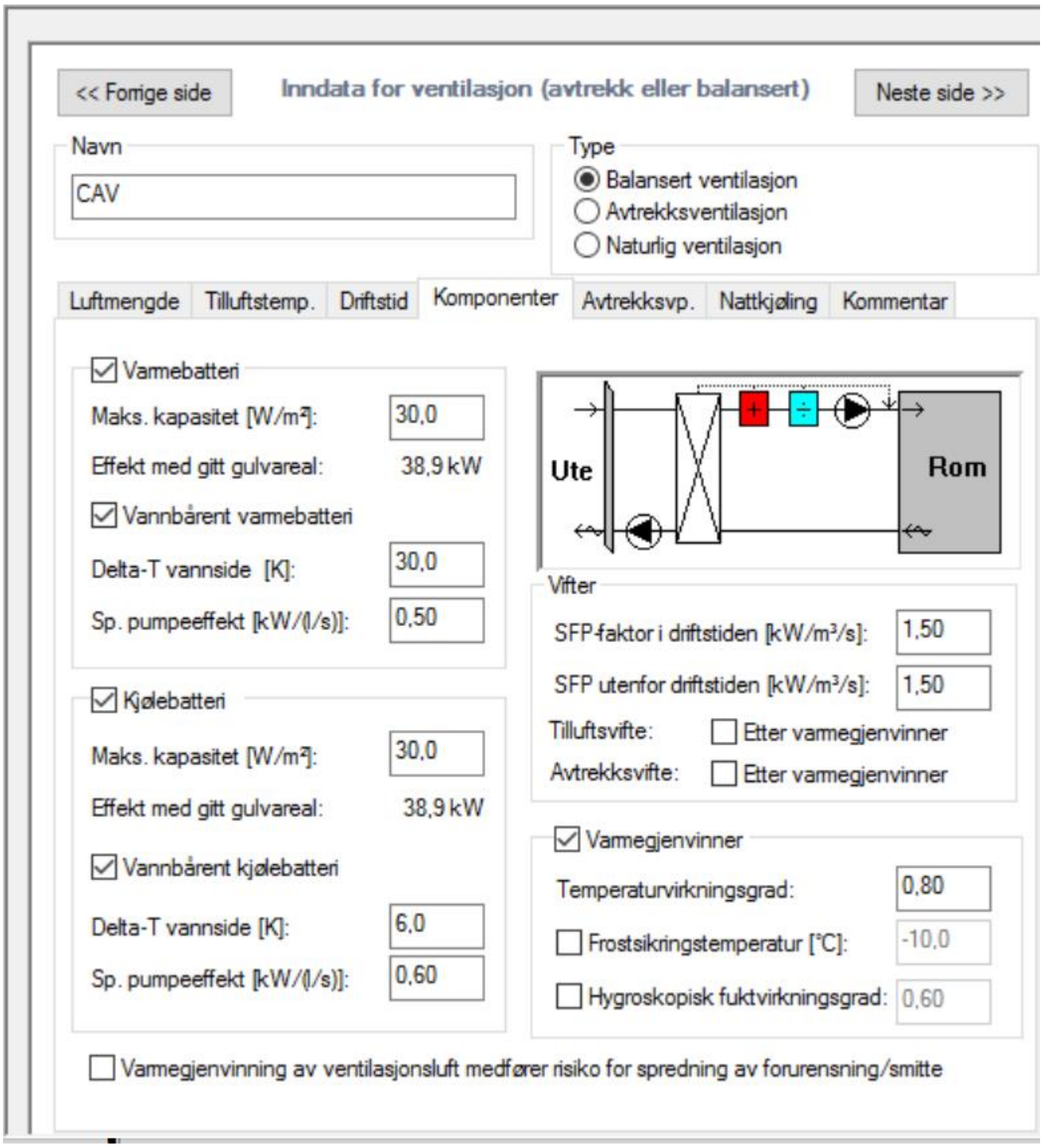

Figure C.14 SFP factor

Saw tooth roof sports hall

The saw tooth roof sports hall has glass and different wall and roof area. The method is adding the area of saw tooth glazing to the north facade, so the total area of the north facade including windows becomes 837 m^2. There are 100 pieces of north orientated window which is 2.5m wide and 2.5m high three layers glass with argon gas. And the total area of the pitched roof is 1553.4 m^2, the total area of east facade is 475.2 m^2.

Skylights roof sports hall

The different setting of skylight roof sports hall is only the roof windows. There are 32 pieces of triple glazing, argon gas filled window. Each is 2.4m wide and 3.8m long.