IMPROVING DAYLIGHTING UTILIZATION IN LTH STUDY CENTER

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

Lund University

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

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Abstract

Daylighting is a free source of light that fosters a direct connection to nature. It has a great potential to enhance the health and productivity of the building inhabitants, to improve thermal and visual comfort in indoor spaces, and to increase energy efficiency in buildings. LTH study center (Lund, Sweden) is a compact building that was originally designed as a library. The building is nowadays used as a study hub. Due to its compact building form, unsatisfactory daylight conditions occur. This study focused on improving daylighting utilization in LTH study center. Continuous and proportionally larger wall and roof apertures can provide enough uniform light for such building. However, as larger glazing area were needed to improve daylighting, the building's energy use assessment was also conducted to check if the increase in energy use is within an acceptable range. The improvement focused on side-lighting strategy, providing continuous side windows and more clerestories to allow daylight penetration deeper towards the building core. For the top-lighting system, the current position and size were kept, which resulted in negligible changes in daylighting level. Increased side-lighting measures yielded an overall increase in daylight level of the building. On the other hand, energy demand increased as expected, yet the increase was not significant. After adding more insulation to the building envelope, the reduction of energy use was marginal. Therefore, LCC analysis needs to be conducted to validate the necessity of adding more insulation layer. Moreover, by providing larger glazing area on the facade, the daylight level improved only in the peripheral zones but not in the core zones. To improve the daylight level in the core zones, further study of top-lighting solution is needed. In addition, with continuous side windows, the quality of the view out improved dramatically while the electric lighting dependency was significantly reduced.

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Abbreviations

ADF	Average daylight factor
BREEAM	Building Research Establishment Environmental Assessment Method
CDA	Continuous daylight autonomy
CIE	Commision Internationale de l’Eclairage
CBDM	Climate-based Daylight Modelling
DA	Daylight autonomy
DDM	Dynamic daylight metric
DF	Daylight factor
DGP	Daylight glare probability
IES	Illuminating Engineering Society of North America
sDA	Spatial daylight autonomy
SDM	Static daylight metric
SFR	Skylight-to-floor ratio
SGHC	Solar Gain Heat Coefficient
WER	Window-to-envelope ratio
WWR	Window-to-wall ratio
UDI	Useful daylight illuminance
UR	Uniformity ratio

1 Introduction

1.1 Background and problem motivations

Daylight is known as a free source of light that has positive effects on health, increasing occupant’s productivity, bringing thermal and visual comfort within the indoor area, and increasing energy efficiency in buildings. However, daylight is an unpredictable light source since it varies a lot depending on the solar position, geographical location, and weather conditions. Despite its great advantages, its unpredictability, variation in intensity, surrounding environment, users preference etc., results in the need of integration of daylight and electric lighting in building design. Daylight integration in building can also reduce dependency on electric lighting. As a bonus, daylight can bring a positive psychological effect on building user’s experience as it creates ambience for visual comfort (Ne’eman, 1984).

LTH Studiecentrum is a study hub for LTH students located in Lund (55.7047° N, 13.1910° E). It was first designed in 1976 as a research library, and then the building got renovated from 2005 until 2006 to be a study hub for LTH students (Akademiska Hus, 2019). The building is rather compact, with approximately 40 x 40 m^2 as the general building measurement, and has four floors in total: 1) Basement, 2) First floor, 3) Second floor, and 4) Mechanical floor. Due to the compact building form, the implementation of daylighting approaches could be difficult. From the side-lighting, it was experienced that not enough daylight could penetrate into the building. LTH Studiecentrum also has a top-lighting in form of roof monitor with the openings facing almost towards east-west orientation. However, the position of the skylight is not facilitating the daylight level inside the building. Due to an insufficient daylight penetration, it resulted in the building dependency towards electric lighting. The opening hours of the building can be divided to: 1) Monday-Friday from 08.00-17.00, 2) Saturday, Sunday, and holidays from 10.00-17.00, and 3) LTH students with access card can come to the building from 17.00-22.00, everyday. During the opening hours, the electric lighting is on all the time.

According to CIBSE Lighting Guide 5 (2011), special function-oriented buildings such as a library requires users to perform several visual tasks such as reading, studying, browsing books or journals, finding correct books, using computers, etc. It results in the need of optimized useful daylight to perform these tasks while avoiding glare and visual discomfort for the users. As recommended by BSI British Standard Light and Lighting (2011), the recommended illuminance level for library is 300 lux for general purpose and 200-500 lux for special purposes such as displaying, reading, etc. Beside its functional purposes, Moreover, a well daylit room or space provides a less stressful environment for students and staff and improves learning rates (CIBSE, 2011). A study by Pniewska and Brotas (2013) also concluded that as daylight brings a positive effect on human psychology, it results in happier and healthier users. In return, this provides various positive benefits such as increased attendance and learning rate of students or working of employees, and improved task performance due to higher and clearer visibility.

To optimize the daylight in LTH Studiecentrum, a combination of side-lighting and top-lighting strategies were used. This goes in line with a study conducted by Perera and Swaris (2017) which stated that side-lighting strategy combining side windows and clerestory provide adequate yet glare-free, uniform, good reading light, and it was also more spatial than other strategies. To increase effective use of daylight and visual comfort, innovative top-lighting strategies can be combined with side-lighting strategies as well to provide a better visual experience for the users. Varying side windows size and shape might be the solution to improve the daylight level inside the building. Also, different types of skylights might result in better visual comfort for user satisfaction in LTH Studiecentrum. Not only the daylight level, view out requirement according to Swedish Standard SS-EN 17037 can also be considered which provides more values and better experience for the users within the building.

While ensuring better quality of daylight inside a building, larger windows might affect the building's energy use at the same time. According to a study by Bülow-Hübe (2011), especially in Swedish climate, glazing size is considered as one of the most important factors that can influence the annual cooling demand of a bulding. In this aspect, solar energy transmittance plays a major role. On the other hand, the glazing type is considered as the important factor when it comes to the building's annual heating demand, as the U-value has an important role on this. However, both the glazing size and type have been proven to influence the thermal comfort of a building. Moreover, increase in total illuminance level heightens the possibility of having more useful daylight illuminance (UDI) inside the building, which reduces the dependency on electrical lighting. Therefore, a study to improve daylight penetration in relation to the building's energy consumption focusing in heating, cooling, and reduction in electric lighting dependency was conducted in this thesis.

1.2 Aims and assumptions

Combining side-lighting and top-lighting is a great strategy to amplify daylight level and enhance users' experience in the building, especially in compact buildings where daylight penetration could be very limited. The main objective of this thesis is to investigate the optimal window shape and size to improve the daylight level in a compact building, in this case, LTH Studiecentrum. Combining the side-lighting with top-lighting strategy was also considered, but the focus was more into the side-lighting strategy as the building was considered too enclosed, especially towards the outdoor view. With this idea, three research questions were used as the framework of this thesis:

- What window shape and size would be the best for side-lighting strategy in LTH Studiecentrum?
- How the current top-lighting position and condition would change the daylight level inside the building?
- After increasing the WWR, WER, and SFR, how much would the heating and cooling demand change?
- With improved daylighting how much electrical dependency could be reduced?

Considering all four questions, some hypotheses based on the literature review were deduced. The main hypotheses are stated below:

- Additional side window and clerestory per window pane would help to improve the daylight level inside the building. However, the scope of changing the top-lighting position and size was limited. This results in an insignificant change in overall daylight level of the building.

- As WWR, WER, and SFR go up, the heating and cooling demand would go up as well. The increase on the energy consumption would be considered when deciding whether having larger windows to improve the daylight level would be worth it or not.

1.3 Limitations

Varying the side-window size based on the window-to-wall ratio (WWR) and the window-to-envelope ratio (WER), and also the top-lighting based on the skylight-to-floor ratio (SFR), might have an impact on both the daylight levels and the energy balance of the building. A very common scenario would be the need to develop refurbishment towards the building construction due to less internal gains from electric lighting usage as the daylight level increases. However, this study was only focused on the overall heating and cooling demand, and a brief discussion on electric lighting dependency. The study did not consider any possible total price difference between the existing condition and the proposed improvements. The study solely focused on improving the daylight level inside LTH Studiecentrum, and see how the heating and cooling demand reacted to larger WWR, WER, and SFR. Any change of electric lighting design was not proposed. Moreover, although the energy consumption went up based on this study, the goal of the study was to improve the daylight level and view out quality.

2 Daylighting in libraries

2.1 Importance of daylight

There were times when incorporating natural light in architectural spaces only focused to aesthetic and psychological features. But now a days, architecture with intelligent daylighting design can lead towards building's sustainability by reducing energy consumption in artificial lighting.

However, light is essential to create vision. Vision connects both physiology and psychology. Daylight has a direct impact on users three-dimensional body as well as their psychological state like emotional response, cognitive performance and behaviour, as stated by Baron et al. (1992). In fact, it has a positive impact on users' physical mental and health which facilitates better performance, as studied by Heschong et al. (2002). A study by Pniewska and Brotas (2013) discussed that, as daylight facilitates the psychological condition of human beings, it results in healthy users which provides positive outcomes such as increased attendance and learning rate. They also stated that, as the staff salary covers most of a company's total cost, daylight can prompt more savings by improved productivity of the staff than the savings obtained from reduced energy demand.

2.2 Lighting requirements for libraries

Library is a confined place mainly for reading purpose along with storing and displaying books in shelves. Use of daylight requires smart and detailed light control strategies in library spaces, as they are supposed to provide the right amount of illuminance for the users' visual comfort, which is directly dependent on light and its interaction with architectural spaces and materials as stated by Lushington et al. (2014). As reading is the fundamental function of a library, legitimately required amount of light should be available without creating high contrast within the field of view. The high contrast might result in glare condition and cause visual discomfort. Work planes properly illuminated with glare-free uniform natural light help the users to develop their learning skill and attentiveness (Bellia et al., 2013). In addition, daylight variability should be ensured inside libraries to create a connection with the nature outside, which is generally appreciated by the users. Suitable size, shape of wall and roof apertures along with appropriate reflective surfaces can provide the ambiance mentioned here for a library. Moreover, consistency of light level is required for reading or writing, which can be achieved through incorporation of electric lighting associated with proper controlling system. Decorative or dramatic lighting systems are not convenient to use inside a library.

For daylighting design, it is necessary to provide the required quantity of light to perform different visual tasks recommended by standards. According to British Standard Light and Lighting (2011), minimum illuminance of 300 lux should be available in general spaces in libraries. For more intensive visual tasks like reading and writing, 500 lux should be provided. Moreover, 200 lux should be maintained vertically on the bookcases in the library. For good light distribution, a brightness ratio of 10:3:1 should be maintained between the general surrounding, immediate surrounding and visual task as recommended by IESNA (2011). Moreover, to properly read the name of the books, uniformity of light should be maintained along the height of the bookshelves where the ratio from top to bottom should be within 6:1 (IESNA, 2011).

Although users' visual comfort for reading and other tasks is variable regarding different individual, social, cultural, traditional, etc. aspects, as mentioned by Fridell Anter, (2014). Among other parameters such as temperature, ventilation, noise, etc., lighting was considered the most important parameter in aspect of productivity by most of the users in library.

2.3 Daylighting methods

Several daylighting strategies are being used worldwide to provide effective and sufficient lighting within library spaces considering location, climate, culture, user group, building volume, etc. Daylight can be provided through openings in the building envelope and roof apertures which are known as side-lighting and top-lighting strategies. To avoid the harsh effect of direct sunlight, convenient system should be installed along with these strategies as well. Moreover, these strategies associated with proper selection of indoor materials and intelligent distribution of functional spaces can provide a better result. Since the experimented building in this research is located in cold climates, the literature study was more focused on side-lighting and top-lighting strategies appropriate for similar type of climatic zones.

2.3.1 Side-lighting

Side-lighting strategy refers to openings like windows and clerestories. In smaller libraries which do not have very deep plans, side-lighting strategies can perform well by itself. According to M. Dean (2002), daylight can be provided adequately around six meter inside from the fenestration area by side-lighting. To penetrate daylight deeper towards the plan, windows should be placed at a higher position as stated by Dubois et al. (2019) in her book. On the contrary, windows at higher position do not provide a pleasant view outside. Therefore, windows can be combined with clerestories to ensure both daylight of better intensity and view out of satisfactory level.

Special concentration should be given to shading devices while designing windows for the library to avoid visual discomfort by glare. Generally, in south facade horizontal shading devices are used and in east and west facades vertical shading devices perform well. Moreover, fixed exterior overhangs reduces direct sunlight incident to a higher extent than the internal blinds. However, selection of exterior and interior shading devices completely depends on the location, climate and surrounding contexts.

2.3.2 Top-lighting

There are some top-lighting strategies for libraries in cold climatic zones. Roof monitors and skylights are more commonly used for smaller libraries. Skylights are horizontal apertures with various configurations such as sloped, sawtooth, conical, triangular, etc. Sloped skylights help to fetch more light than flat skylights when the solar angle is low. In Nordic countries, sloped skylights are considered more effective as it permits sunlight from zenith under overcast sky. Skylights should be smaller in size to avoid overheating and designed with deep adjacent diffused surfaces to reflect and diffuse the direct sunlight to provide a non-directional uniform light inside as mentioned by Dean. For more uniform light, using multiple smaller skylights like sawtooth or conical skylights in appropriate distance performs better. Famous architect Alvar Aalto introduced a conical skylight system to allow diffused daylight but not direct sunlight, which became a popular daylighting strategy for library. Roof monitors are two parallely placed vertical apertures. It evades direct light from overhead sun, creates more interesting lofty spaces within the vertical extensions and causes less water leakage than skylights. In many libraries use of both roof monitors and skylights can also be seen.

However, combination of both side-lighting and top-lighting strategies performs better than implementing them separately according to many studies.

2.3.3 Architectural components

The selection of materials for the library's interior walls, floors, ceilings and furniture can also have an impact on daylight level due to their reflectances. Generally, materials with higher reflectances create brighter and lively ambiance whereas materials with lower reflectances create a darker and gloomy ambiance inside. In addition, functional organization within spaces should also be considered regarding daylight. For instance, the reading, displaying, and working zones can be placed close to the openings. On the other hand, the services and other functions which do not require much daylight, can be placed in the zones far from openings.

2.4 Effects of daylighting in building energy consumption

2.4.1 Electrical lighting

Daylight is a free source of light which is more efficient in comparison to electrical lighting in terms of several aspects. As stated by Dean (2002), there are two basic advantages of using daylight instead of electrical lighting. Firstly, electrical lighting has far less efficacy than daylighting. It should be mentioned that, only one-third of the energy generated from fossil fuel is being used as electricity and the rest is being wasted during the whole process. Secondly, daylight is easily obtained and renewable whereas electrical lighting is not. Therefore, electrical lighting dependency should preferably be reduced by daylighting. However, as daylight cannot be used during night time, it can be used in such controlled way during daytime which might reduce electrical demand even up to 80% as mentioned by Pniewska and Brotas (2013).

2.4.2 Heating and cooling demand

Along with daylighting level, sunlight has impact on building’s heating and cooling demand. In general condition, larger openings reduce heating demand and increase cooling demand due to solar heat gain. The quantity varies according to location, orientation, and surrounding environment. On the south orientation, the solar heat gain is higher as it receives more direct sunlight for longer periods in daytime whereas on the north the heat gain is lower as it receives mostly diffused sunlight. On the east and west orientations, during early morning and late afternoon more direct solar radiation occurred. Therefore, the size, shape, and shading systems for the openings should be designed considering the heating and cooling demand as well.

3 Building precedence

After having a theoretical overview of daylighting strategies, we decided to study some built projects, to have an understanding about how the architectural interpretation of these strategical theories perform in reality and how are they perceived by the users. For more relevance to our research, mainly library buildings were studied. Among them some of the renowned and user friendly library buildings are discussed further down where distinctive daylighting strategies were implemented.

3.1 Library precedence in Europe

3.1.1 Stuttgart city library, Germany

This library was designed by Yi Architects and officially opened on October 2011. It is a cube-shaped building that has translucent roof over to create natural lighting inside the building. The library consists of nine-story with concrete and glass blocks on its façade that will give dynamic lights from the outside especially at night time. The interior surfaces are mostly using bright white color to maximize both the natural and artificial lighting.

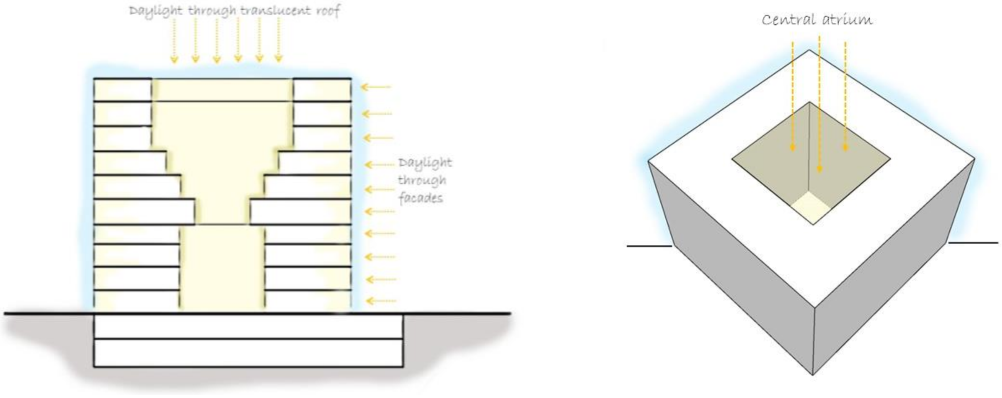


Figure 1: Stuttgart city library atrium section.

3.1.2 Porto School of Architecture library, Portugal

A school of architecture designed by Alvaro Siza during 1985-1996. The whole school were built of 10 pavilions surrounding a central plaza. The north side used reinforced concrete structures and have large openings along the walls and cantilevers. Commonly used interior materials are exotic woods for floors and paneling, also marbles in foyers and stairs. The library has a triangular skylight that enhances the daylight level inside the room.

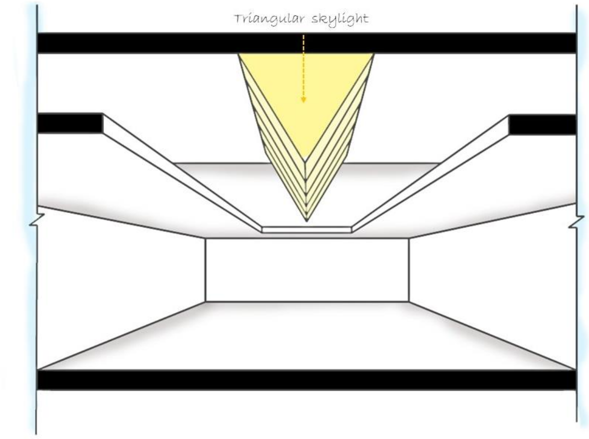


Figure 2: Triangular skylight in Porto School of Architecture library.

3.2 Library precedence in Nordic countries

3.2.1 Viipuri library, Viipuri, Finland

After winning the competition to design the library, architect Alvar Aalto experimented his ideas on natural lighting, in which he wanted to pursue his career. To provide appropriate light for reading rooms he introduced a conical skylight that projects down diffused uniform white light while avoiding direct, shadow-producing solar radiation. This systematically perforated roof with two-meter light wells creates a futuristic look. This effective lighting model became a feature of Aalto's design and became a popular strategy of daylighting for library design.

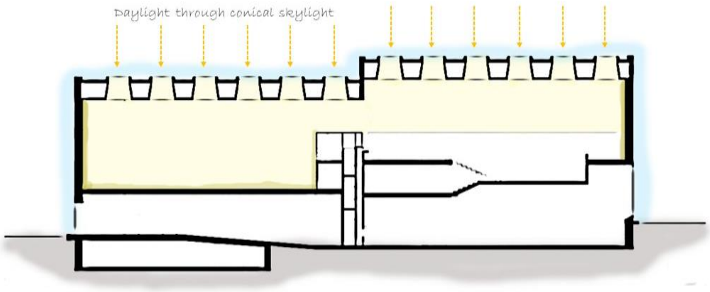


Figure 3: Conical skylights in Viipuri library.

3.2.2 Rovaneimi library, Finland

The conical skylight is used again in the library in Rovaniemi, 1961. They are used in public areas, such as smaller reading rooms, the periodical room and work areas. These lights are used in two ways. One is to balance the light levels provided by windows and other devices. The other is as the sole means of daylighting the room. In the Rovaniemi library, Aalto fragmented the north wall of the library into facets. The five facets are each illuminated by an u-shaped monitor. They are associated with the bookshelves rather than the reading areas.

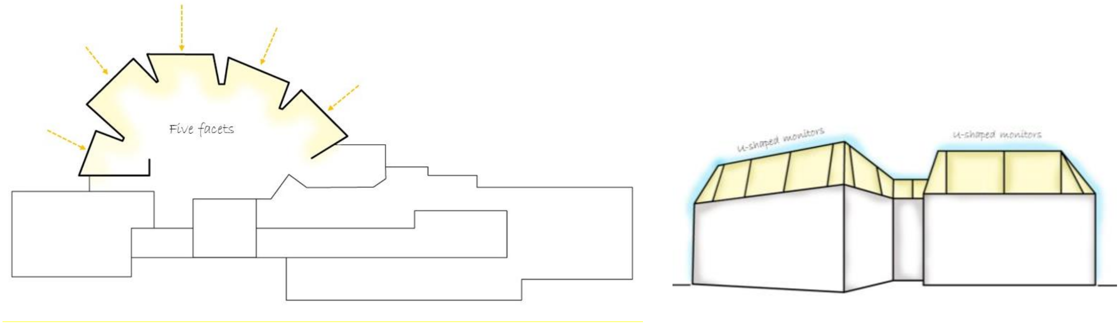


Figure 4: Facets and u-shaped roof monitor in Rovaniemi library

3.2.3 Malmo city library, Sweden

Malmo city library combines three buildings, a castle designed by the architects John Smedberg and Fredrik Sundbärg, central entrance and new library building designed by Danish architect Henning Larsen. In the new library building, mainly side-lighting strategy is used. The main reading zone is illuminated by large glazed facades through all the storey which allows the daylight variations all through the year. Therefore, this building is called ’calendar of light’.

Figure 5: Malmo city library interior (left- side-lighting in the new building; right- top-lighting in the old building).

3.2.4 Lund city library, Sweden

Lund city library was designed by Danish architect Flemming Lassen and introduced in 1970. It accommodates study zones, cafeteria, and an auditorium. The central zone is illuminated through a translucent roof. Clear glass walls and large clerestories close to the ceiling all around the building allows sufficient daylight and quality view outside.

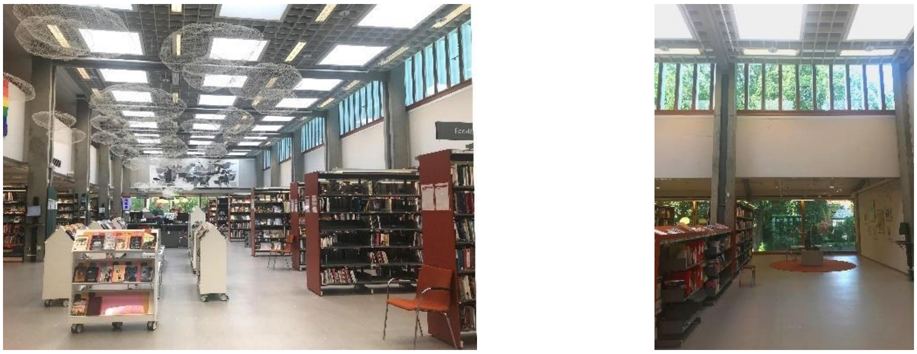


Figure 6: Top-lighing strategies in Lund city library.

4 Daylight Criteria

4.1 Daylight factor

International Commission on Illumination or CIE (International Commission on Illumination, 2019) defined daylight factor as “the ratio of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded”. It is calculated as a ratio between the average illuminance on an indoor surface and the outdoor illuminance under the CIE overcast sky. Note that the measurement should be done at the same time, on the same height if possible, and simultaneously. The calculation can be done using the following equation:

$$DF = \frac{E\ indoor}{E\ outdoor} \cdot 100\ [\%]$$

Where:

DF	:	Daylight factor of the measured point
E indoor	:	Indoor illuminance (lux) in the measured point or horizontal plane, placed at 0.8 m from the floor with the light sensor pointed upwards
E outdoor	:	Outdoor illuminance (lux) measured under a CIE Standard Overcast Sky

As stated by Nabil and Mardaljevic (2005), daylight factor has drawbacks of not taking light from the sun and non-overcast skies as well as not taking the impact of orientation to any building/room. In a further study, the same author also stated that DF has been used a lot in daylight evaluation because of its simplicity, although the realism of it was still questioned (Nabil and Mardaljevic, 2006). However, it is still used in many building regulations and environmental certification systems. (Dubois et al., 2019). For building design criterion, average daylight factor (ADF) is commonly used especially in the beginning of designing process, note that ADF value does not represent the space’s uniformity (Tregenza and Wilson, 2003). To calculate ADF, the measurement should be done according to a grid of points which will be averaged after all the numbers are obtained. The area 0.5 m from the wall periphery needs to be excluded.

Instead of ADF, median daylight factor (DF median) was considered to be able to represent more reliable value as it shows a specific DF value over its spatial distribution; half of the values are above the median and half are below (Mardaljevic and Christoffersen, 2017). DF median is included as one of the daylight criteria in Miljöbyggnad 3.0.

4.2 Daylight autonomy and useful daylight illuminance

As a lot of arguments regarding the accuracy in evaluating daylight with static daylight metrics (SDMs), i.e. DF, dynamic daylight metrics (DDMs) that use climate-based daylight modelling (CBDM) are more popular in recent times. CBDM takes into account the use of sun movement and dynamic sky condition that is generated from standardised climate data. DDMs are expected to provide better daylight evaluation.

Daylight autonomy was first defined by Reinhart and Walkenhorst (2001) as “the percentage of the occupied hours of the year when the minimum illuminance requirement at the sensor is met by daylight alone”. The calculation is based on illuminance threshold depending on the required amount of daylight to supply visual tasks for specific function. For educational building, the common threshold recommended by BREEAM-SE (2019) for DA calculation is 300 lux, considering the other 200 lux can be provided by electrical lighting. Here, the daylight illumination levels are dynamic and dependent on time, location, and orientation; and this fact allows DA to have more advantages in daylight evaluation in comparison to DF (Dubois et al., 2019).

There are several DA modification i.e. spatial daylight autonomy (sDA) and useful daylight illuminance (UDI). sDA value shows a percentage of the analysed area that meets the horizontal daylight illuminance level (in this case 300 lux) for a specific percentage of annual operating hours. The operating hours suggested by BREEAM-SE (2019) is 2000 hours. The Illuminating Engineering Society (IES) had approved sDA calculation method as a standardised method that can be used to evaluate daylight performance. Two criterias namely “Preferred daylight sufficiency” and “Nominally accepted daylight sufficiency” were defined by IES for area achieving a value of 75% and 55% respectively. Based on European Standard EN 12464-1 (2001), the suggested illuminance level for educational purpose (classroom) is 300 lux and circulation areas should be illuminated by at least 100 lux.

In a recent study by Nabil and Mardaljevic (2005), UDI is recommended as a method to evaluate daylight level in a building/room as it include the range that shows the comfortable range of daylight illuminance for the occupants. The illumination level were divided into three ranges: 1) UDI fell-short or insufficient daylight (< 100 lux), 2) UDI autonomous or useful daylight (between 100 – 2000 lux), and 3) UDI exceeded or daylight oversupply (> 2000 lux). The same study also stated that high value of achieved UDI might have a correlation with low energy use for electrical lighting, meaning that if the UDI range between 100 – 2000 lux is achieved for a fraction of time, the use of electrical lighting might not be necessary as the area is considered well-daylit.

4.3 Light uniformity and daylight glare probability

The uniformity ratio (UR) is a qualitative metric that is used to assess if a space is evenly daylit across the functional space or not. CIE (2019) defined UR as a ratio of minimum to average illuminance on a surface, or in short:

$$UR = \frac{E\ min}{E\ average}$$

The scale for UR ranged between 0 to 1. The higher the UR is, less contrast and less glare will be experienced on the space. However, complete uniformity (UR=1) could result in dull lighting conditions.

Daylight glare probability (DGP) was developed by Wienold and Christoffersen (2006) as an index that shows how the occupants that perform a functional task perceived the glare. To get a trustworthy result, no electrical lighting should be included in the calculation. DGP expresses the probability of an occupant feeling disturbed by glare in an exact situation. In this study, the level of DGP are presented as: 1) DGP < 0.35 imperceptible glare, 2) DGP 0.35 – 0.4 perceptible glare, 3) DGP 0.4 – 0.45 disturbing glare, and 4) DGP > 0.45 intolerable glare, as recommended by Swedish Standard SS-EN 17037 (Svensk Standard SS-EN 17037, 2019).

4.4 Standards or certification system

4.4.1 Miljöbyggnad

Miljöbyggnad (2015) is an environmental certification system used in Sweden with three certification levels: 1) BRONZE, 2) SILVER, and 3) GOLD. The certification system was issued by Swedish Green Building Council (SGBC) and has been used in the market since 2011 (Sweden Green Building Council, 2019). The certification consists three building aspects that cover: energy, indoor comfort, and materials. Daylighting is included in the indoor comfort part. More details about the criterion can be seen on Table 1.

Table 1: Criterion for daylighting from Miljöbyggnad 3.0 (2015).

	Bronze	**Silver**	**Gold**
Criteria 1 : Daylight factor			
DF median	DF ≥ 1.0%	DF ≥ 1.2%	DF ≥ 1.5%
Notes	*For simulations using software, a deviation of (– 0.2) % will be accepted*		
	Acceptable reflectance of surfaces: • *Wall areas → 0.80* • *Floor area → 0.30* • *Ceiling area → 0.90* • *Ground reflection → 0.20* • *Neighboring building's facade → 0.30*		
Criteria 2 : View out regarding neighboring building			
Window's area requirement	AF ≥ 10% if α ≤ 20° AF ≥ 10 + (α – 20) . 0.25 if 20° ≤ α ≤ 45°	AF ≥ 15% if α ≤ 20° AF ≥ 15 + (α – 20) . 0.25 if 20° ≤ α ≤ 45°	
	$AF = \frac{A_{glass}}{A_{floor}} \times 100$ A_{glass} = windows area (m^2) A_{floor} = room's area; including the area under furniture and service area (m^2) α = the angle from view windows towards neighboring building in front of the windows		

4.4.2 BREEAM-SE

BREEAM (BRE Environmental Assessment Method) is a certification system developed in the United Kingdom by the BRE (Building Research Establishment) group. Different versions had been in the market since 1990 and it is the most used international certification system in the world (BREEAM, 2019). In 2013, Swedish Green Building Council (SGBC) has adapted BREEAM to Swedish condition, the version is called BREEAM-SE. BREEAM-SE covers more aspects in comparison to Miljöbyggnad. The standard is divided into ten categories covering aspects from management to innovation. Based on BREEAM-

SE (2013), daylighting can achieve up to 4 credits, followed by providing adequate view out to achieve 1 additional credit. Both aspects are included in Health and Wellbeing, Visual Comfort section. The criterion details can be seen on Table 2.

Table 2: Criterion for daylighting from BREEAM-SE (2013).

Criteria 1 : Daylight factor	
Average daylight factor required at latitude 55 – 60°	2.1%
Minimum area to comply	1 credit → 60% 2 credits → 80%
One of the two in criteria 2 needs to be fulfilled (*criteria 2a OR criteria 2b*)	
Criteria 2a : Uniformity	
Uniformity ratio	General spaces → 0.3 Spaces with atria → 0.7
OR	
Minimum point daylight factor	General spaces → 0.3 times the average DF Spaces with atria → 0.7 times the average DF
Criteria 2b : View and room depth	
View out	
Table top height	0.85 m
View of sky from desk or table top height	80% of the room
AND	
Room depth	
Satisfying criterion	$d/w + d/HW < 2/(1-RB)$ *d : room depth* *w : room width* *HW : window head height from floor level* *RB : average surface reflectance*
Maximum credits for both criteria 1 and 2 fulfilled : 2 credits	
Criteria 3 : Average daylight illuminance	
Averaged over entire point space	At least 300 lux for 2 000 hours per year
Minimum area to comply	1 credit → 60% 2 credits → 80%
Criteria 4 : Minimum daylight illuminance	
At worst lit area	At least 90 lux for 2 000 hours per year
Minimum area to comply	1 credit → 60% 2 credits → 80%
Maximum credits for both criteria 3 and 4 fulfilled : 2 credits	
Highest possible credits to be achieved from daylighting : 4 credits	
Criteria 5 : View out	
Provided adequate view out	95% of the floor area space are within *X* meters of a window or a permanent opening
Window or opening size (the percentage of surrounding wall area) based on distance from window to work space	≤ 7 m → 20% 8 m – 11 m → 25% 11 m – 14 m → 30% ≥ 14 m → 35%
Maximum credits for criteria 5 fulfilled : 1 credit	

Lastly, glare control to avoid glare problem should also be installed. The installation should be designed to support maximization of daylight level, it also should not have any conflict with lighting control system operation (BREEAM-SE, 2013).

4.4.3 Swedish Standard SS-EN 17037

European Daylighting Standard EN 17037 was acknowledged in Sweden by Swedish Standard Institute (SIS) in 2018 as Swedish Standard SS-EN 17037 (Svensk Standard SS-EN 17037, 2019). The standard has been developed since 2010 and was focusing on target performance criteria. The standard consists of four recommendations which are: 1) minimum daylight provision; 2) recommendations for view; 3) exposure to sunlight; 4) minimum protection from glare. Each recommendation has three different level compliance MINIMUM, MEDIUM, and HIGH. More details on the criterion can be seen on Table 3.

Table 3: Criterion for daylighting from Swedish Standard SS-EN 17037 (2018).

Recommendation 1: Daylight Provision			
Level	**Types of Openings**	**Illuminance**	**Minimum value of DF for Sweden for 50% of daylight hours**
Minimum recommendations	From facade	300 lux over 50% of space, 50% of daylight hours	2.5%
		AND	
		100 lux over 100% of space, 50% of daylight hours	0.8%
	From rooflight	300 lux over 100% of space, 50% of daylight hours.	2.5%
Recommendations for medium daylighting of a space	From facade	500 lux over 50% of space, 50% of daylight hours	4.1%
		AND	
		300 lux over 100% of space, 50% of daylight hours	2.5%
	From rooflight	500 lux over 100% of space, 50% of daylight hours	4.1%
Recommendations for high daylighting of a space	From facade	750 lux over 50% of space, 50% of daylight hours	6.2%
		AND	
		500 lux over 100% of space, 100% of daylight hours	4.1%
	From rooflight	750 lux over 100% of space, 50% of daylight hours	6.2%
• *Illuminance should be calculated at 0.85 m above the floor* • *Grid cells should be between 0.5 – 2 m*			

Recommendation 2: View Out

Level	Width of view window(s), horizontal sight angle	Outside distance of the view	Number of layers to be seen from at least 75% of utilized area 1. sky 2. landscape (urban and/or nature) 3. ground
Minimum	≥ 14°	≥ 6 m	At least landscape layer is included
Medium	≥ 28°	≥ 20 m	Minimum two layers are included
High	≥ 54°	≥ 50 m	All layers are included

- *Minimum dimension of view window 1 m x 1.25 m*
- *$x + y = a/2$ (x, y = width of windows at same façade; a = depth of utilized area)*
- *$x + y + z = a/2$ (x, y = width of windows at same façade; z = width of windows at different façade a = diagonal of utilized area)*

Recommendation 3: Sunlight Exposure

Level	Sunlight Exposure
Minimum	1.5 hours
Medium	3.0 hours
High	4.0 hours

Recommendation 4: Glare Protection

Level	DGP$_t$	Maximum allowed exceedance during reference usage time
Recommendation for minimum glare protection	0.45	5%
Recommendation for medium glare protection	0.40	5%
Recommendation for high glare protection	0.35	5%

5 Methodology

5.1 LTH Studiecentrum

5.1.1 Location

LTH Studiecentrum is a study hub for students at Campus LTH of Lund University. It is located on John Ericssons väg 4 in Lund, Sweden (55.7047° N, 13.1910° E). The building is placed almost perpendicularly in relation to the north-south orientation. To integrate LTH Studiecentrum with other buildings in LTH, one entrance was placed on the north side of the second floor, which connects LTH Studiecentrum to Kårhuset on the other side of John Ericssons väg. On the first floor, another entrance is facing towards the south. This entrance creates a connection between LTH Studiecentrum and other academic premises located in the southern area.

5.1.2 Geometry

LTH Studiecentrum has a compact geometry with a square floor plan that has approximate dimensions of 40 x 40 m^2. The building consists of four floors: 1) Basement, 2) First floor, 3) Second floor, and 4) Mechanical floor, with a total area of 5030 m^2 and a total height of 12.9 m. The mechanical floor has a smaller and linear plan of 9 x 31 m^2 which is placed at the center of the building in parallel with north-south direction. The daylight simulations carried out in this thesis were focused only on the first and the second floor while the energy simulations took all floors into account.

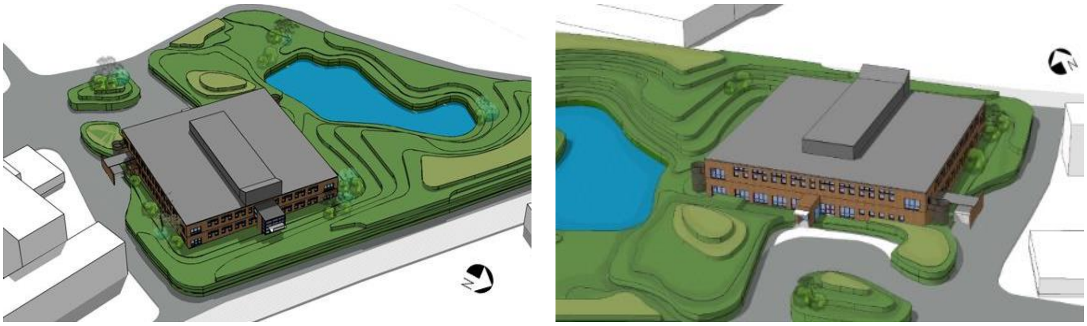
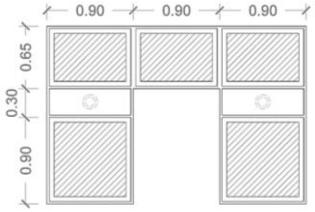
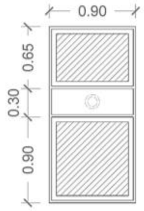
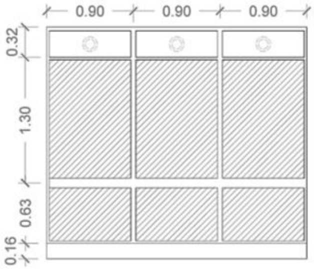
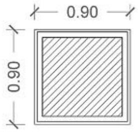
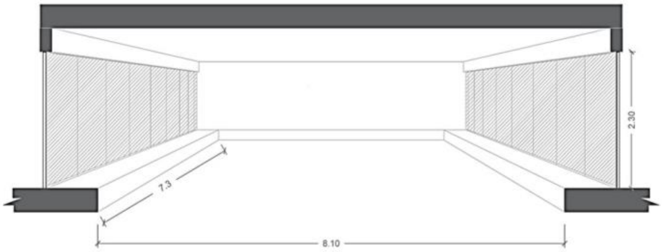


Figure 7: LTH study center illustration, left- north facade, right- south facade.

The building created a distinctive characteristics by using repetitive modules. All four facades of the building have almost similar appearance consisting of four types of windows. On the south part of the roof, there is one roof monitor with two openings towards east and west orientation, which creates a continuous atrium through the first and the second floor containing a spiral stair in the middle. The illustrations and dimensions of the windows and skylight can be seen in Table 4.

Table 4: List of existing side window types and skylight.

Window types	**Figure**	**Opening area (m²)**	**Number**	**Total opening area (m²)**
Type-1		3.4	50	170
Type-2		1.4	8	11.2
Type-3		5.5	23	126.5
Type-4		0.8	4	3.2
Roof monitor				33.5

5.1.3 Functional distribution

Although the building was initially designed as a research library, it was eventually redesigned for more general study activities in 2006. The first floor of the building consists of a library, a silent study room, common study spaces, a kitchen and a cafeteria. The second floor accommodates staff offices, a bookstore, a reception, a conference room and study areas. The third floor is mostly occupied with operation and maintenance service area for the HVAC system. The basement of the building is used for storage, workshops and technical services. Beside the two entrances, there are also two fire exits on the east and west sides of the building.

5.2 Research workflow

5.2.1 Analytical approach

The overall research to improve daylight condition and evaluate energy consumption was based on experimenting with the external glazing areas of the building, considering side-lighting and top-lighting. For this task, the analysis process was divided into five stages to investigate how the considered parameters affect energy use and daylighting. The first three stages of analysis were completely assigned to the side-lighting strategy, the fourth stage consisted of analyzing the top-lighting and the fifth stage was to assess the performance of the combination of both side and top-lighting. To avoid confusion about the terms that we used in this study, Figure 8 presents the parameters that will be altered.

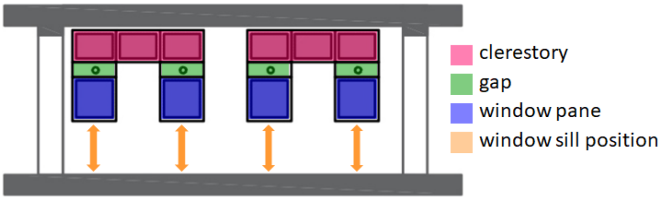


Figure 8: Illustration for altered parameters in side-lighting.

Firstly, we assessed the side-lighting strategy, focusing on side-windows and clerestory. The first three stages were conducted to investigate following features:
1) Reasonable vertical position of the windows and the glazing type,
2) Feasible window shape, and
3) Reasonable width for each window panes.

While conducting stage-1 to stage-3 simulations, the top-lighting was completely removed to simplify the problem. Selection of possible side-lighting approach was made from the analysis of first three stages. In the top-lighting investigation (stage-4), two different kinds of top-lighting strategies were assessed to determine the type, orientation and slope of the most suitable top-lighting approach for the given building. In the same way as conducting side-lighting simulations, in stage-4, the side-lighting was also completely removed. The last stage (stage-5) assessed the combination of the previously chosen side-lighting and top-lighting strategies. These two strategies were combined to achieve a configuration which is more comparable to the existing condition. In the end, the combination that obtained the highest daylight results while providing an energy-efficient solution for LTH Studiecentrum was selected.

In this building, as 55% of total window area consists of type-1 windows, it was assumed that type-1 windows had a major impact on overall daylight level and solar heat gain. Therefore, type-1 windows were considered for all possible alterations. Type-2 and type-4 windows were not taken into account for alterations, but were slightly modified to be aligned with type-1 windows due to their negligible window area of 3.6% and 1% respectively. Type-3 windows at the corners of the building were designed as fire exits, it was therefore decided to keep them in their existing condition for functional purpose. Furthermore, except the fire exits at the corners, all other type-3 windows were alternately replaced with suggested options of type-1 windows. It should be mentioned that, it was decided to change the windows on both floors in the same manner to respect the prevailing characteristics of the building.

5.2.1.1 Parametric scheme

The parametric scheme of all stages can be seen in Figure 9.

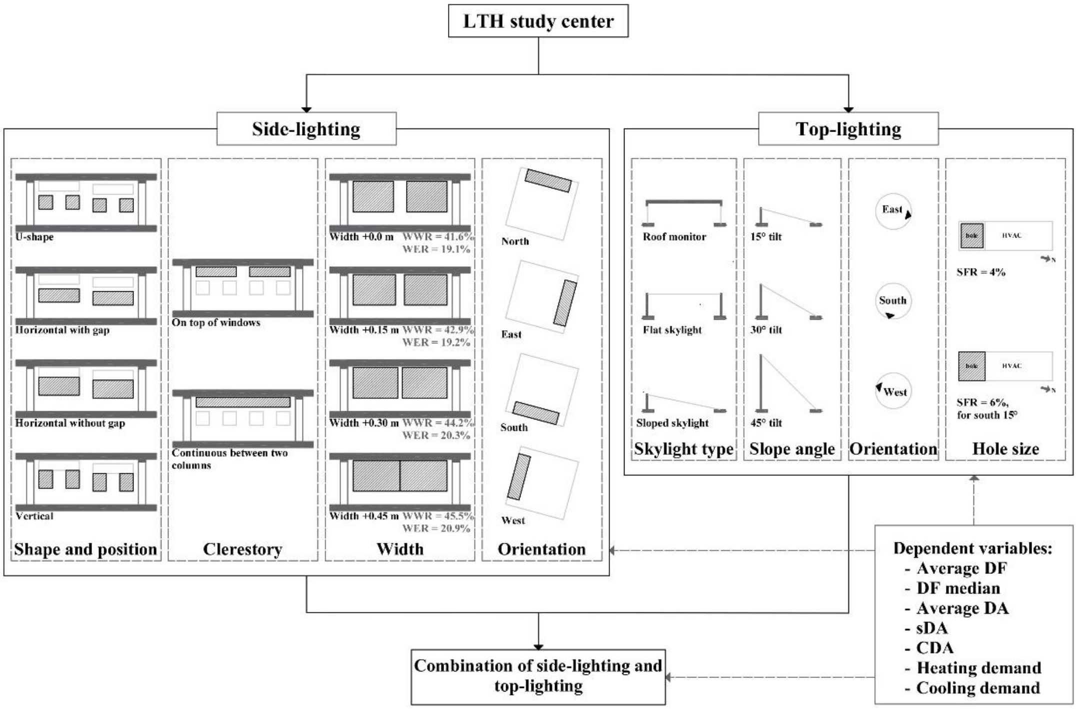


Figure 9: Parametric scheme of all stages.

5.2.1.2 Stage-1: Determining the reasonable vertical position of the windows and the glazing type

In the stage-1 analysis, all possible options to change the shape and position of existing type-1 windows were examined. For that, an outline alongside the existing U-shaped side windows and clerestory was assumed which produced a module of 5 m². Clear illustrations of this can be seen in Figure 10.

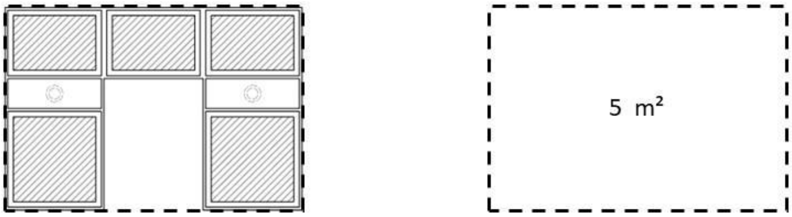


Figure 10: Illustration of existing U-shaped window and assumed module.

Within this existing module, two types of pane for side windows could be possible: 1) square (0.9 x 0.9 m²) and 2) vertical (0.9 x 1.2 m²) which can be seen in Figure 11.

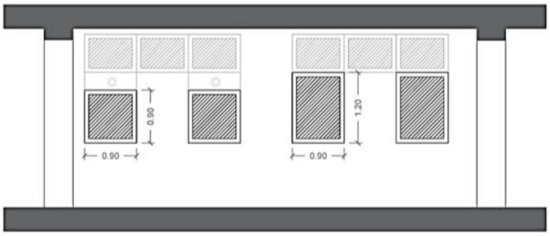
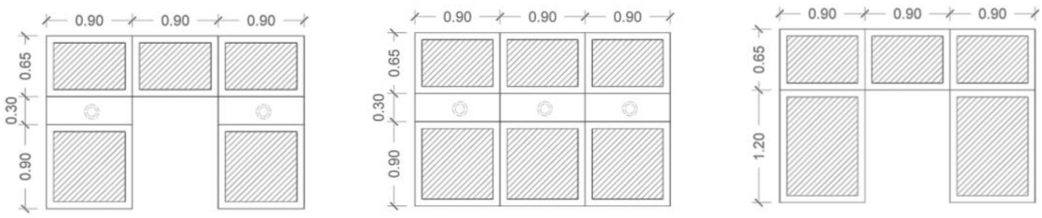


Figure 11: Different side window variation (left- square, right- vertical).

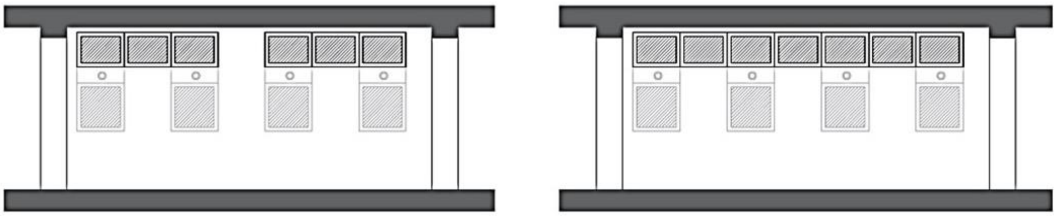
Combining these two types of view windows with the clerestory, three basic shapes were assumed for type-1 windows: 1) u-shape, 2) horizontal shape, and 3) vertical shape. Illustrations of the shapes studied are presented in Figure 12.



U-shape window *Horizontal window* *Vertical window*

Figure 12: Suggested basic shapes for type-1 windows.

Variations of clerestory within the existing facade were also considered, such as: 1) individual and 2) continuous clerestory between two columns, which can be seen in Figure 13.



Individual clerestory

Continuous clerestory

Figure 13: Variations of clerestory.

Based on these concepts, a total of 16 variations for both double and triple glazed windows, resulting in a total of 32 variations, were analyzed. The variations include:

- Changing window sill height from the finished floor. The two variables used were 1.1 m and 0.9 m. The simulations were conducted for the work plane height of 0.85 m. The openings lower than that level would not have a significant impact on daylight level but might increase heating and cooling load unnecessarily according to Dubois et al. (2019). Therefore, from the existing elevation of 1.1 m, the maximum downward movement of the window sill was kept very close to the working plane at 0.9 m. Note that, the current window sill height is too high to allow a preferable view out from sitting position (1.2 m), which is clearly unsatisfactory for the occupants.
- Keeping and removing existing 0.3 m gap between the side window and the clerestory.
- Inserting additional clerestory to create a continuous clerestory between windows within two columns.
- Using double glazed windows with a transmittance of 0.7 and triple glazed windows with a transmittance of 0.4.

The specification of 16 shapes and positions studied can be seen in Table 5 and the illustration can be found in Figure 14. A more detailed specifications can be found in Appendix A.

Table 5: Measurement details for the 16 windows.

Shape	**Name**	**Window pane no.**	**Window sill from finished floor (m)**	**Gap towards clerestory (m)**	**Clerestory**
U-shape	u-BC	2	1.1	0.3	Individual
	u-01	2	0.9	0.3	Individual
	u-02	2	0.9	0.3	Continuous
	u-03	2	1.1	0.3	Continuous

Horizontal	h-01	3	0.9	0.3	Individual
	h-02	3	1.1	0.3	Individual
	h-03	3	0.9	0	Individual
	h-04	3	1.1	0	Individual
	h-05	3	0.9	0.3	Continuous
	h-06	3	1.1	0.3	Continuous
	h-07	3	0.9	0	Continuous
	h-08	3	1.1	0	Continuous
Vertical	v-01	2	0.9	0	Individual
	v-02	2	1.1	0	Individual
	v-03	2	0.9	0	Continuous
	v-04	2	1.1	0	Continuous

Figure 14: Side-lighting illustrations for stage-1.

These 16 options were studied for both daylighting and energy use for the whole floor and the whole building respectively. After the simulations, the best performing solution from each shape was selected according to daylight results, resulting in three different options. These three options were compared to the base case (u-BC). Moreover, further analysis was carried out only for the double glazed windows since the triple glazed windows resulted to a very low daylight level.

5.2.1.3 Stage-2: Finding out the feasible window shape

Moving further to stage-2 analysis, we assessed which option performed better regarding a balance between daylighting and energy use among the three selected options. At this stage, a smaller room on north, south, east and west orientation was studied instead of the whole building, since a whole-building simulation was significantly heavier in terms of simulation time. This room was placed on both the first and second floor to see difference in performance due to the room orientation and floor height. More details about the dimensions can be seen in Figure 15 for the room placement on the first floor; and Figure 16 for the room placement on the second floor. The test rooms were modeled as surrounded by solid adiabatic walls so the openings of the external wall was the only source of light penetration and heat transfer. The simulations for u-BC and the three selected shapes from the previous stage were conducted only for the illustrated area of 240 m^2 on each floor. The mentioned area excluded the type-3 windows at both corners to avoid their impact as these are very specific windows. The width of the test rooms was taken as 8 m to keep the same width as two major functions on the first floor, which are the library and the silent study room.

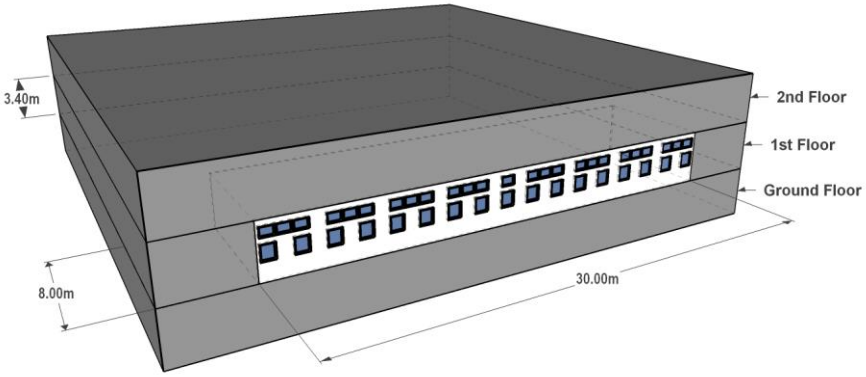


Figure 15: Illustration for the room placement on the first floor.

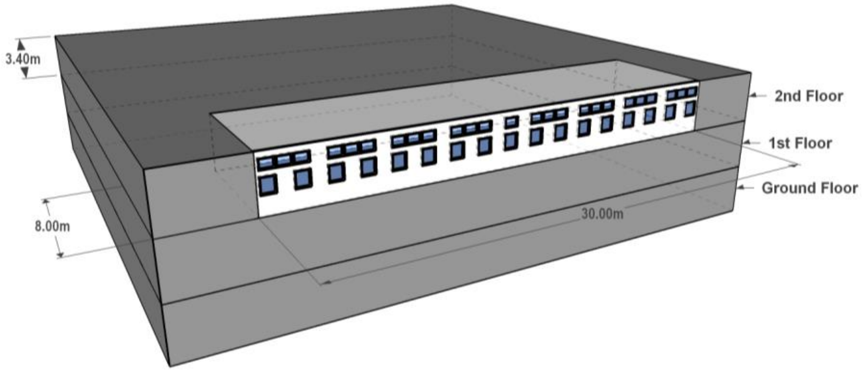


Figure 16: Illustration for the room placement on the second floor.

It should be mentioned that, on the south facade, all windows on the first floor are type-3 windows. In this simulation part, we also analyzed, what would be the impact of these windows if they were replaced with the three selected shapes of type-1 windows. From the simulation results, one window shape was chosen based on the daylight performance.

5.2.1.4 Stage-3: Determining ideal width for each window pane

In the stage-3 analysis, the chosen window shape was further analyzed to determine the reasonable width of each window pane. At first, two trials with the same window width but different window sill heights were investigated: 1) 1.1 m from the finished floor and 2) 0.9 m from the finished floor. These sill heights were studied to increase the daylight level and accessibility of the view out at eye level while seated (1.2 m). After that, the second series of simulations, with windows at 0.9 m from the finished floor, was kept constant and the width of the openings were increased with an increment of 0.15 m. The possible maximum width was 3.15 m as illustrated in Figure 17.

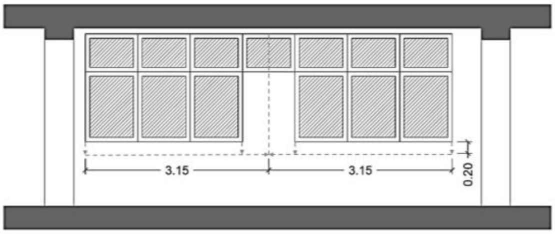


Figure 17: Maximum window width increment.

This process resulted in four different width variations per window pane: 1) w-1: 2.7 m, 2) w-2: 2.85 m, 3) w-3: 3.0 m, and 4) w-4: 3.15 m. The illustrations of all four width variations can be seen on Figure 18. As before, these four options were simulated at four cardinal orientations for an area of 240 m² on the first and second floor. After analyzing the results, two options were finally selected for stage-3 analysis.

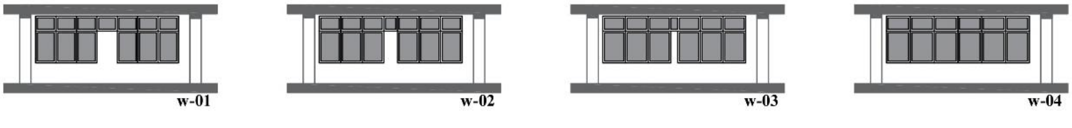
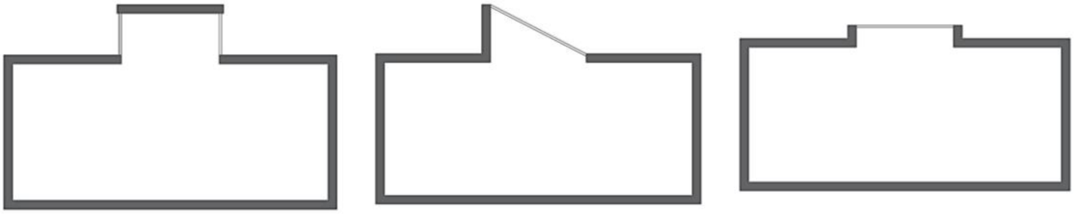


Figure 18: Window width variations.

5.2.1.5 Stage-4: Top-lighting

For top-lighting, three types of skylights were investigated: 1) roof monitor, 2) sloped skylight, and 3) flat skylight (Figure 19). The roof monitor was simulated for existing opening position on east-west orientation and an additional simulation with the opening only facing the south orientation. The north orientation was not analyzed as it was blocked by the existing HVAC service rooms. The reason behind selecting sloped skylight was that, in Nordic countries, sloped skylight is considered to perform better as it allows skylight from the zenith under overcast sky, which is three times higher than the daylight from the horizon. Besides, under a sunny sky, low-angled sunlight can penetrate through it (Dubois et al., 2019). For the sloped skylight, the existing area of the roof hole was kept constant and modeled towards south, east and west directions with three different angles of 15°, 30° and 45°. A flat skylight at an angle of 0° was also simulated to compare with the sloped one. This resulted in a total of 11 trials with the same hole area. One more possible option for sloped skylight was modeled, where the roof hole increased until the edge of the existing corridor in the periphery, which is currently not in function. This skylight was modeled with a 15° slope towards the south direction. As the results were analyzed, one top-lighting option was selected for the next stage regarding the best result in terms of daylighting.



Roof monitor skylight *Sloped skylight* *Flat skylight*

Figure 19: Three types of skylights.

5.2.1.6 Stage-5: Combining side-lighting and top-lighting

For the last stage of the analysis, the best results from stage-1 and stage-2 were combined. Two options for side-lighting and one option for top-lighting were chosen for this stage as mentioned before. These two combinations, namely combination-01 and combination-02 were then used for both daylight and energy simulations. Afterwards, these two combinations were compared to the existing building condition (u-BC + t-BC) to see the difference in daylighting and building energy performance.

5.3 Simulation tools

The main objective of this study is to improve the daylight level in LTH Studiecentrum and see how it affects the heating and cooling demands, and also the building’s dependency towards electric lighting. The results were evaluated as a function to their compliance to the Swedish building certification system Miljöbyggnad and several other certification systems. Both daylight and building energy consumption were analyzed based on steady state calculations and dynamic simulations using different softwares. To achieve the objective, parallel workflow between the daylight and energy assessment were conducted. The workflow of the whole thesis can be seen in Figure 20.

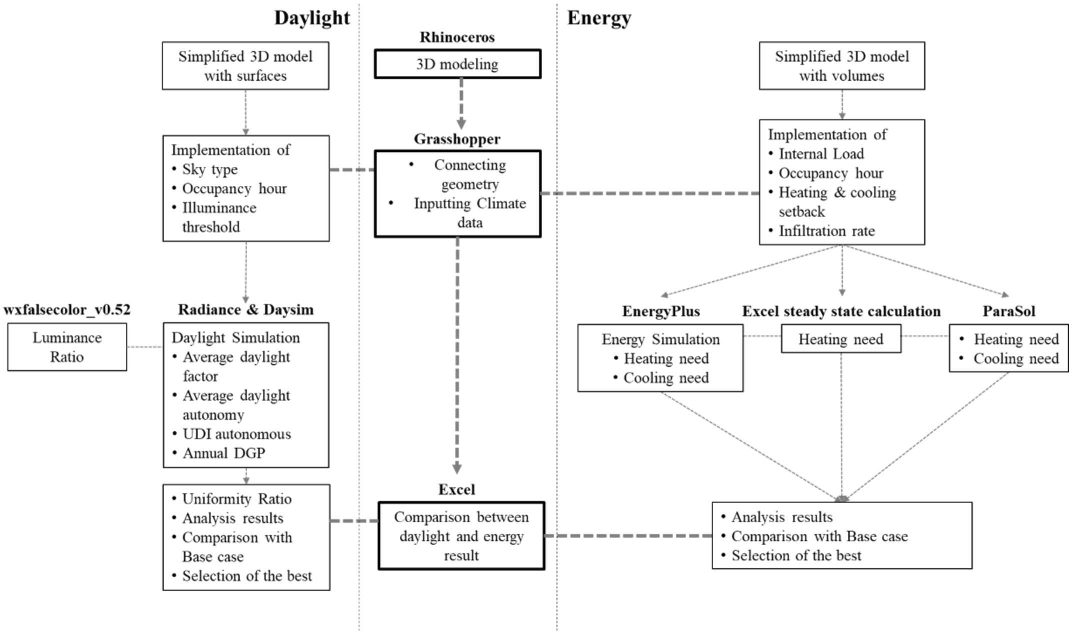


Figure 20: Computational workflow.

5.3.1 Rhinoceros

Rhinoceros (2019) is a modelling software used widely especially in architecture and building industry. It creates geometry based on curves and free form surface using a mathematical model. The geometry is generated by using different commands and menus. One of the plug-ins for Rhino 3D is Grasshopper, which is a visual programming tool that allows parametric investigations. By integrating Rhino 3D with Grasshopper, it is possible to analyze and investigate very large set of geometries and parameters. In this case, the building model was prepared with this software.

5.3.2 Grasshopper

Grasshopper (2019) is a visual programming software that creates environmental simulations developed by David Rutten at Robert McNeel & Associates on 2014. This software is commonly used to conduct parametric studies related to geometrical and material variations. The environment created in Grasshopper allows the user to use Honeybee and Ladybug plug-ins that were used to perform the simulations in this thesis. As Grasshopper is connected to Rhino 3D, all the changes that were made in Grasshopper will affect the model in Rhino 3D interface directly.

5.3.3 Honeybee and Ladybug

Honeybee and Ladybug are plugins allowing to run a wide range of environmental performance analysis. This software can be used as plugins to Grasshopper. Both Honeybee and Ladybug are mainly used at the early design phase. They could also be used to assess building environmental certification compliance. Both of tools played a major role for setting different parameters of daylight simulations in this study. Several other tools that were integrated and validated as simulation engines are OpenStudio, EnergyPlus, Radiance, and DAYSIM (Ladybug Tools, 2019).

5.3.4 Radiance and DAYSIM

Radiance (2019) has been known as a validated tool that could be used for architectural lighting simulation and rendering. This software is based on backward hybrid deterministic stochastic ray-tracing method to perform lighting calculations that produces high degree realism displayed for both numerical values and images. On the other hand, DAYSIM (2019) is a Climate Based Daylight Modelling (CBDM) tool that use Radiance as its core illumination engine. DAYSIM uses all Perez weather sky models combined with a daylight coefficient approach to analyze the annual daylight performance of architectural spaces. Some of the outputs that could be generated by DAYSIM are daylight autonomy (DA), useful daylight illuminance (UDI), and annual glare analysis.

5.3.5 wxfalsecolor_v0.52

wxfalsecolor (2019) is a graphical program that can be used to display Radiance RGBE images and to get a read of luminance/illuminance values. This plugin could also be used to export the Radiance RGBE images into bitmap images, that can further be displayed in printed documents. In this case, luminance at different points were measured using this program.

5.3.6 Excel steady state calculation

The steady state calculations were achieved by using a calculation sheet operated in Microsoft Excel. Steady state calculations take into account the building’s U-value of different materials, intentional and unintentional ventilation rates, and internal thermal mass. With this method, both solar and internal gains from equipment and occupants were not taken into account. The effect of thermal mass on thermal inertia and storage are not considered in the energy demand calculations with this method. Finally, this steady state method only estimates the heating demand since the cooling demand is mostly depending on solar and internal heat gains.

5.3.7 ParaSol-LTH

ParaSol-LTH (2019) is a simulation program that allows to predict a room’s annual energy demand (both heating and cooling). The program could simulate one room with five adiabatic surfaces and one facade with thermal exchanges through window and wall. This software could be used to examine the effect of different window (glazing) sizes on an adiabatic room, and how different shading devices could affect both the room’s thermal comfort and energy balance. The model takes into account the external wall and window U-value, the room’s orientation, solar and internal heat gain, and the building’s ventilation rates. The effect of thermal mass on inertia is also considered in the calculation.

5.3.8 EnergyPlus

EnergyPlus (2019) is a core energy simulation program compatible with Grasshopper. This program, which was developed by the U.S Department of Energy’s (DOE) Building

Technologies Office (BTO) since 1997, is a widely used building thermal load and energy simulation program. This software allows the user to create complex multi-zone energy modelling and computes the energy needed to maintain each zone at a particular temperature for each hour of the day. The software takes into account the building's shape, window-to-wall ratio, building construction, simple HVAC system, and shading to assess the building's energy demand and thermal comfort.

5.4 Daylight model

Both static (SDM) and dynamic daylight metrics (DDM) were explored throughout the research. Initially for some quick assumptions and decisions, the SDM, average daylight factor (ADF) was analysed. Although this metric does not consider orientation and occupancy hour, it allows to give an overview about the perceived daylight level of a space. Therefore, for more reliable climate-based results, simulations of daylight autonomy (DA) was performed, where the illuminance threshold was set to 300 lux. The values of this metric can influence luminous comfort to a great extent. During the calculation, major concentration was given to average daylight autonomy (DA_{300}) and spatial daylight autonomy ($sDA_{300, 50\%}$) to compare with different certification systems. Moreover, continuous daylight autonomy (CDA_{300}), useful daylight illuminance ($UDI_{100-2000}$) were assessed as well. Moreover, risk of visual discomfort at the task area due to glare was also investigated by using daylight glare probability (DGP). For annual glare prediction, annual DGP was simulated as well.

5.4.1 Simulation input and parameters

A weather file for Copenhagen, Denmark was used for the climate-based simulations. The Radiance parameters were set to obtain a good rendering performance of the simulations as reported in Table 6 (Radiance settings, 2019). According to Swedish Standard SS-EN 17037: 2018 requirements, the threshold for illuminance was fixed at 300 lux for functional spaces and 100 lux for circulation for DA simulations. The occupancy hours were from 09:00 to 18:00 hours everyday with an hour lunch break at 12:00. For all the simulations the grid size was 0.5 m, located at 0.85 m from the floor. Besides, CIE overcast sky was used for the simulations.

Table 6: Radiance settings (2019) for daylight simulations.

Ambient bounces (ab)	Ambient divisions (ad)	Ambient sampling (as)	Ambient resolution (ar)	Ambient accuracy (aa)
6	512	256	128	0.15

The reflectance of existing surfaces was measured with a luminance meter and the Hagner reflection reference plate using the following equation:

$$R\,surface\ = L\,surface\ \cdot\ R\,plate/L\,plate$$

Here, $R\ surface$ = reflectance of the surface; $L\ surface$ = luminance of the surface; $R\ plate$ = reflectance of the plate; and $L\ plate$ = luminance of the plate. The calculated values of the surface reflectance can be seen in Table 7.

Table 7: Surface reflectance.

Surface	Reflectance	Transmittance
Roof	0.6	-
Ceiling	0.6	-
Wall	0.2	-
Floor	0.3	-
Grey Column	0.6	-
Wooden Window Frames	0.5	-
Internal Brick Wall	0.2	-
Internal Wood Wall	0.5	-
Internal Grey Partition	0.1	-
Internal Green Wall	0.3	-
Ground	0.2	-
Adjacent Buildings	0.3	-
Road	0.3	-
Exterior Glazing	-	0.7
Interior Glazing	-	0.6

5.4.2 Parametric scheme

5.4.2.1 Stage-1: Determining the reasonable vertical position of the windows and the glazing type

At the beginning of the study, the first floor was identified as the critical floor because it resulted in 50% lower DF values than the second floor. Thus, during stage-1, DF simulations were conducted for the first floor for the 32 variations. The test surface was modeled for the whole floor at an offset of 0.5 m from the external walls. From ADF values, one option was selected as the best option in terms of daylighting from each shape. Triple glazed windows resulted in visibly a lot lower values than the double glazed windows, note that the visual transmittance of the triple glazed window selected was very low at 0.4. There are spectrally selective windows available today with a much higher visual transmittance and a low g-value (e.g. 0.69 Tvis and 0.35 g-value). However, it was decided to conduct the further research only for double glazed windows as mentioned previously.

5.4.2.2 Stage-2: Finding out the feasible window shape

In stage-2, smaller test planes were modeled with a length of 30 m and width of 8 m. The three selected shapes were simulated for this 240 m² for both DA_{300} and DF on the north, south, east and west orientations. For both floors, a total of 32 simulations were conducted. The reflectance of the test plane and the enclosing walls were taken as 0 (no reflectance) to avoid their impact on the result since in reality, light continues to travel in space in the open landscape situation. One of the important aspects of this research was to explore the view out quality of different window shapes. Accordingly, fisheye images of the windows were produced with image-based simulations by Honeybee, to assess the perceived view from the sitting position (1.2 m) for the three shapes. The best shape was chosen for next part after analyzing the average DA_{300}, $sDA_{300, 50\%}$, CDA_{300} values and view out qualities.

5.4.2.3 Stage-3: Determining reasonable width for each window pane

Moving further to stage-3, DA_{300} and DF simulations were conducted for the four width variations and four cardinal orientations for an area of 240 m² as in the previous part. Fisheye images of the openings were created to assess the overall visual perception of the openings as well. After analyzing the results and view qualities, two options were selected for further analyses.

Moreover, glare indices such as DGP and annual DGP were also evaluated in this stage for south and west orientation as glazing area increased. The degree of perceived glare was determined according to Swedish Standard SS-EN 17037. Considering DGP results, internal white roller shade and external light grey and dark blue awnings were applied in some extreme glare occurrences to see their impact and develop a suitable solution to the glare problem. The translucent radiance materials used for this three shading options can be seen in Table 8. Moreover, relative luminous ratio between the main task, immediate surroundings and remote surroundings in the visual field were calculated to check if it was in preferable (< 1:3:10), tolerable (< 1:6:20), or unacceptable (> 1:40) condition.

Table 8: Radiance materials (Radiance Material Notes, 2019) for shading.

Radiance materials	**White roller shade**	**Light grey awning**	**Dark blue awning**
Reflectance	0.786	0.570	0.0271
Specular reflectance	0	0	0
Diffuse transmission	0.1219	0.14	0.0006
Specular transmission	0.029	0.000	0.000
Roughness	0.01	0.01	0.01

Note that, the experimented shadings were considered as horizontal and flexible shading devices which would be operated by active users according to their preferences during glare hours. Therefore, these shading devices were not taken into account for energy simulations.

5.4.2.4 Stage-4: Top-lighting

For top-lighting assessments, both DF and DA_{300} simulations were performed for all three types of top-lights mentioned previously. A test plane was used which was offset 0.5 m from peripheral walls on the whole floor. Blind walls were considered for the facades to avoid the impact of side-lighting at this stage. A single top-light option was selected for the next stage as a result of this process.

5.4.2.5 Stage-5: Combining side-lighting and top-lighting

In the last part of the study, the best results from side-lighting and top-lighting strategies were combined. Two options for side-lighting and one option for top-lighting were chosen for this stage which yielded two final combinations. These two combinations were simulated for DA_{300} and DF for the twelve existing functional zones on the first and the second floor. For the first floor, the simulated zones were the library, the silent study room, the computer space, the open study area, and the cafeteria. On the second floor, the studied zones were the three open study areas, the two staff offices, the conference room and the book store. The simulated zones can be seen in Figure 21. Test planes for all the zones were offset 0.5 m from the external walls. It should be mentioned that, all the service areas of both floors were excluded from daylight simulations. The results were compared to the ones obtained for the existing building (u-BC and t-BC). In addition, compliances with two applicable certification systems were also checked for all the combinations.

Figure 21: Daylight zones on each floor.

5.5 Energy model

5.5.1 Simulation input and parameters

Although the daylight simulations only examined the first and second floor of LTH Studiecentrum, the energy simulations took into account all floors of the building. The reason for this was, even though there are several areas that are not being used for functional purposes, the ventilation system still needs to supply air towards these areas to fulfill the Swedish building requirement.

In general, the building envelope was constructed with brick masonry and all the external openings are double glazed. It was found that there is an insulation layer inside the external wall construction. The assigned building properties for energy simulations can be seen in Table 9.

Table 9: Building properties U-value.

Building properties	**U-value (W/m^{2}K)**	**SGHC**
External wall	0.2	-
Ground slab	0.13	-
Roof	0.32	-
Double glazing window	2.88	0.76
Triple glazing window (for stage-1)	1.00	0.54

For energy simulations, both steady state calculations and dynamic simulation software were used. As the dynamic simulation allows multi-zones simulations, the building was divided into several functional zones. These functional zones can be seen in Figure 22. More details about different load inputs on each functional zone can be seen in Table 10. The ventilation flows were taken from Miljöbyggnad BRONZE (Miljöbyggnad, 2015) to fulfill CO_2 requirement. On the other hand, the infiltration rate was following ASHRAE Handbook (ASHRAE, 2009) recommendation for average building. For the lighting and number of people, manual on-site calculation was conducted. It seems like the lighting in the building is relatively efficient. While running the simulations for existing building conditions, both the side-lighting and top-lighting solutions were taken into account. To simulate the existing case, the combination of u-BC and t-BC was used.

Table 10: Load inputs for energy simulation (Miljöbyggnad, 2015; ASHRAE, 2009)

Zone	**Loads**					
	Equipment (W/m^2)	Infiltration (l/s/m^2)	Lighting (W /m^2)	Person per area (person/m^2)	Ventilation per area (l/s/m^2)	Ventilation per person (l/s pp)
Study area + skylight	15	0.3	8.5	0.4	0.35	7
Library	15	0.3	8.5	0.1	0.35	7
Kitchen	15	0.3	8.5	0.05	0.35	7
Conference	15	0.3	8.5	0.4	0.35	7

Office	15	0.3	8.5	0.05	0.35	7
Service area	0	0.3	4	0	0.35	7

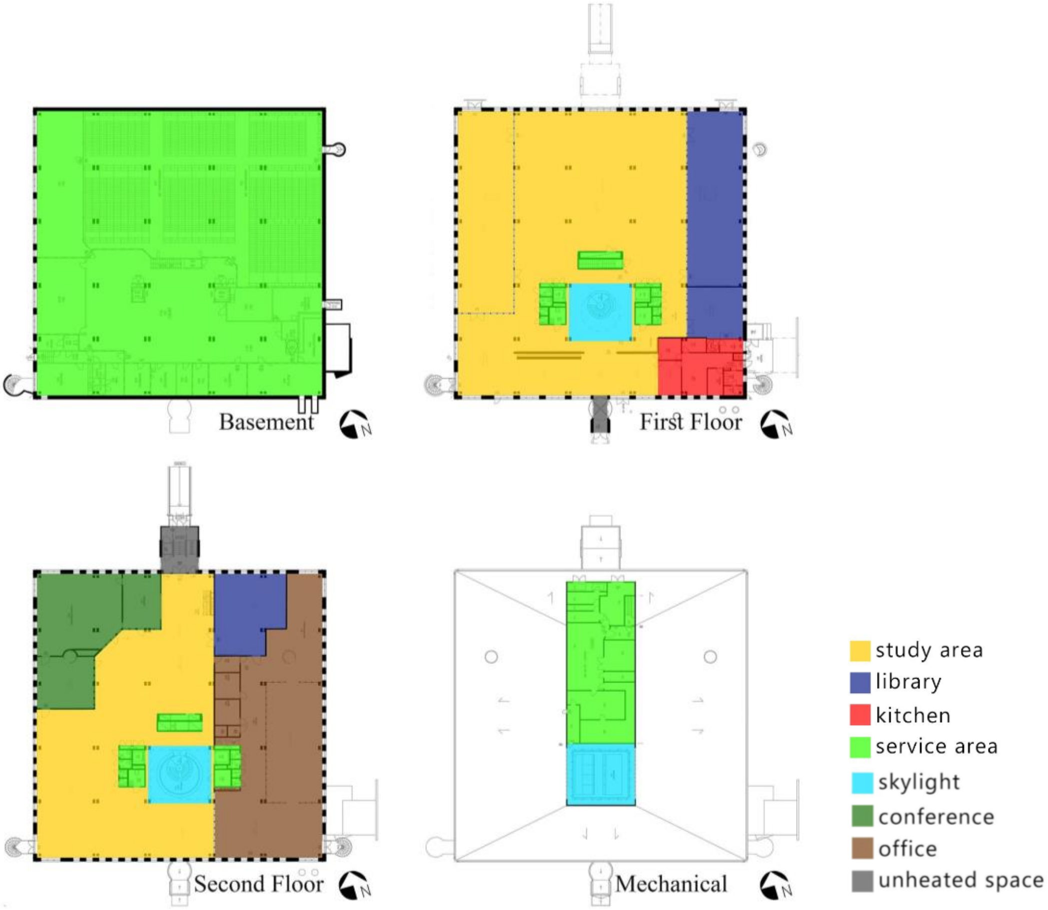


Figure 22: Thermal zones on each floor.

It should be mentioned that, the goal of this project was to increase the daylight level. Adding more insulation layer to the external wall and roof construction was considered to compensate for the increase in heating demand resulting from increased window areas.

5.5.2 Parametric scheme

5.5.2.1 Stage-1: Determining the reasonable vertical position of the windows and the glazing type

To understand how the building energy consumption varied according to WWR and WER, the internal gains such as equipment, lighting, and people occupancy were removed to simplify the problem, but the building properties from Table 9 were kept constant. The building indoor condition for the simulations can be seen in Table 11.

Table 11: Building indoor conditions for stage-1 energy simulations.

Infiltration	0.6 l/s/m^2
Ventilation per area	0.35 l/s/m^2
Heating set point	21 ºC
Cooling set point	26 ºC

As stated previously in the research workflow part, the side-lighting approach was conducted in three stages. In stage-1, 32 variations including different window shapes, positions, and glazing types were assessed. The building was considered as one zone per floor. In this stage, energy simulations were performed using only EnergyPlus.

5.5.2.2 Stage-2: Finding out the feasible window shape

Energy simulation is considered as a complex dynamic simulation and it takes into account many parameters at the same time. Based on this condition, sometimes it is hard to detect if there is a problem with either the energy model or script while simulation with EnergyPlus. As a validating process to both energy model and simulation, a comparison of three methods: 1) steady state calculation, 2) ParaSol simulation and 3) EnergyPlus simulation, were carried out in stage-2, where the simulations were carried out only for a 240 m^2 room oriented towards four cardinal directions. However, ParaSol has a limitation that only one adiabatic zone can be simulated, in this case it would be the room that was placed on the first floor. To simplify the comparison process, the steady state calculation was conducted only for the room placed on the first floor as well. Because of this limitation, the comparison between steady state calculation, ParaSol and EnergyPlus simulations can only be applicable for the room placed on the first floor. To ensure that the results are reliable, two weather files were used for EnergyPlus simulations: 1) CPH_nosun (a Copenhagen weather file where solar radiation has been removed) and 2) DNK_Copenhagen. The simulation results from CPH_nosun weather file should be comparable with the steady state calculations, and the simulation results from DNK_Copenhagen results should be comparable with the ParaSol simulations. The comparison was made between u-BC and each window solution, resulting in a total of four variations. As only four window variations were studied for each orientation, this part resulted in 16 simulations. By doing these comparisons, the goal is to gain confidence in conducting the energy simulation in further stages.

5.5.2.3 Stage-3: Determining reasonable width for each window pane

After the shape was decided, stage-3 was conducted to identify the ideal window width. Following the comparison method in stage-2, the simulations were carried out only for a 240 m^2 room oriented towards four cardinal directions. The comparison was also made between the selected window shape with four different window widths. To complete the process, all four width variations were then simulated in the whole building condition. This part resulted in 25 simulations.

5.5.2.4 Stage 4: Top-lighting

As mentioned in the research workflow part, the top-lighting assessment explored 12 variations in total. For the energy simulation, the skylight zone was modelled as one continuous zone from the first floor until the mechanical floor. The boundaries between the skylight zone and the study area was then modelled as airwalls, meaning that the airflow between two zones would be mixed and result in the same indoor temperature.

5.5.2.5 Stage 5: Combining side-lighting and top-lighting

As the best results from side-lighting and top-lighting simulations were unfolding, the building's dependency on electrical lighting might diminish, which may lead to lower internal heat gains from lights. Besides, larger glazing areas might result in more energy demand as well. To ensure that the energy consumption of the building would not increase, one more insulation layer on the external wall and roof was added. The new U-value for the external wall and the roof after adding the insulation layer can be seen in Table 12. The comparison was then made between: 1) Existing building condition (u-BC and t-BC), 2) Combination-01 without added insulation, 3) Combination-01 with added insulation, 4) Combination-02 without added insulation, and 5) Combination-02 with added insulation.

Table 12: U-value of the building properties after adding one more insulation layer.

Building properties	Old U-value (W/m^{2}K)	New U-value (W/m^{2}K)
External wall	0.2	0.13
Roof	0.32	0.2

5.6 Electrical lighting dependency

Along with higher daylight level inside a building, the dependency on electrical lighting goes down. Therefore, in this research, it was also studied how the improved daylighting yielded by selected two combinations facilitated to reduce annual energy demand for lighting. For this purpose, an annual daylight metric, UDI was used to calculate electrical lighting dependency.

As stated in a study by Nabil and Mardaljevic (2005), illuminance between 100 lux – 2000 lux is useful to perform different visual tasks. However, 100 lux can be used as the minimum threshold for switching on the electrical lighting. Accordingly, electrical lighting dependency was calculated using $UDI_{100-2000}$ for selected combinations which were later compared with the existing combination. The $UDI_{100-2000}$ values were obtained from DA_{300} simulations of the whole areas of the first and the second floor.

6 Results

6.1 Parametric study for daylighting

6.1.1 Stage-1: Positions and glazing types for side-lit rooms

As mentioned in the methodology chapter, three possible shapes for side-lighting were investigated, 1) u-shape, 2) horizontal and 3) vertical shape. Four parameters were altered for each shape, such as- the position of window sill, number of window panes, 0.3 m gap between the side window and clerestory, and individual and continuous clerestory. From these alterations, a total of 16 variations were obtained for side-lighting with four variations for the u-shape including the base case (u-BC, u-01, u-02, u-03), eight variations for the horizontal shape (h-01, h-02, h-03, h-04, h-05, h-06, h-07, h-08) and four variations for the vertical shape (v-01, v-02, v-03, v-04). Moreover, these 16 variations were simulated separately for both double and triple glazing windows.

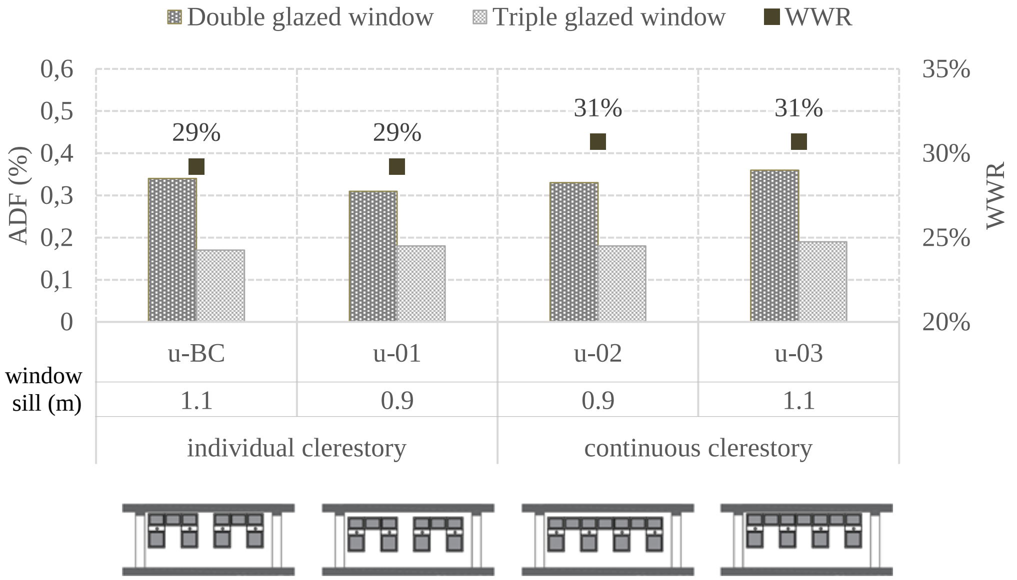


Figure 23: ADF (%) for u-shape variations on the first floor.

In Figure 23, the ADF results are presented for four variations of u-shape. The base case, u-BC had a window sill height of 1.1 m from the finished floor, two window panes and individual clerestories on top of two windows between two columns. This configuration resulted in an ADF of 0.34%. As the window sill height was changed to 0.9 m (u-01), the ADF decreased to a value of 0.31%. For u-02, an extra pane in the clerestory was added between two windows where the window sill height was 0.9 m. This alteration increased the WWR from 29% to 31% with respect to u-BC. Yet, u-02 presented a slight decrease of ADF to 0.31%. The window sill height was subsequently altered to 1.1 m resulting in a new variation u-03, for which ADF increased to 0.36%.

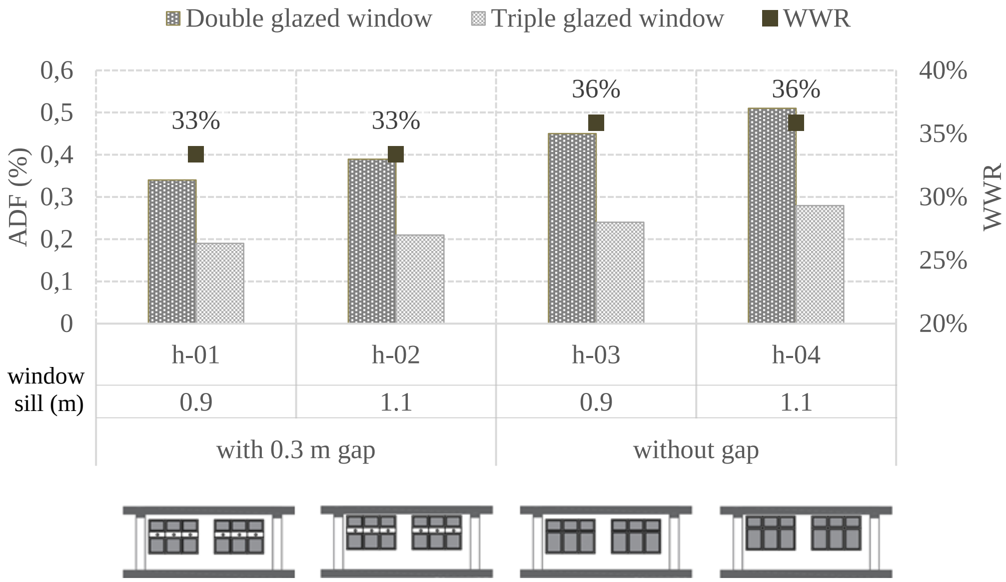


Figure 24: ADF (%) for horizontal shape variations with individual clerestory on the first floor.

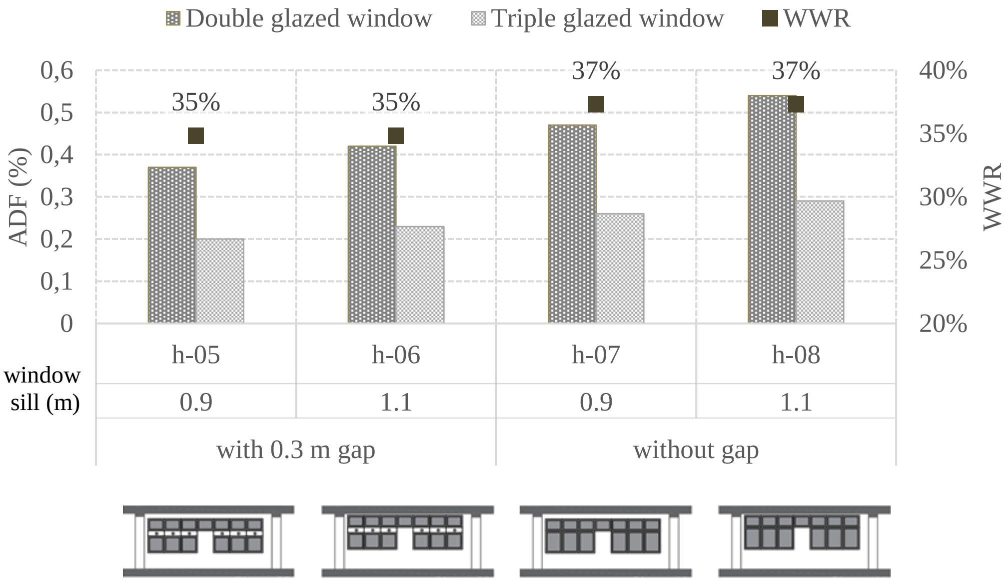


Figure 25: ADF (%) for horizontal shape variations with continuous clerestory on the first floor.

For the horizontal shape, the major alteration from the u-shape was an extra pane in each window. However, the eight variations of the horizontal shape were divided into two groups to simplify the analysis process. Four of the variations had individual clerestories while the other four were modeled with continuous clerestories. Figure 24 shows the four variations (h-01 to h-04) of horizontal shape with individual clerestory. The first variation, h-01 had three window panes with the window sill height at 0.9 m. Although adding an extra window pane increased the WWR from 29% to 33% in comparison to u-BC, the resultant ADF was the same as the base case. In variation h-02, changing only the window sill height to 1.1 m resulted in a higher ADF than h-01. In the next variation h-03, the window sill height was again changed to 0.9 m and 0.3 m gap with the clerestory was removed, which raised the WWR to 36% and ADF to 0.45%. In variation h-04, the only difference from h-03 was the higher window sill height. For h-04, the result was the best among these four variations with an increased ADF to 0.51%.

In Figure 25, ADF values for the four variations of horizontal shape with continuous clerestory can be seen. These four variations resulted in higher ADF values than the previously mentioned four variations although the pattern of the results were similar. By adding an extra pane in the clerestory, the WWRs were increased from 33% and 36% to 35% and 37% with respect to the previous four variations. Between the two groups, the resultant value of ADF increased from 0.34% to 0.37%, 0.39% to 0.42%, 0.45% to 0.47% and 0.51% to 0.54% for h-05, h-06, h-07 and h-08 respectively. Evidently, h-08 outperformed the best performing case of previous group, h-04. Therefore, among the eight variations of horizontal shape, h-08 was considered as the option yielding the highest ADF.

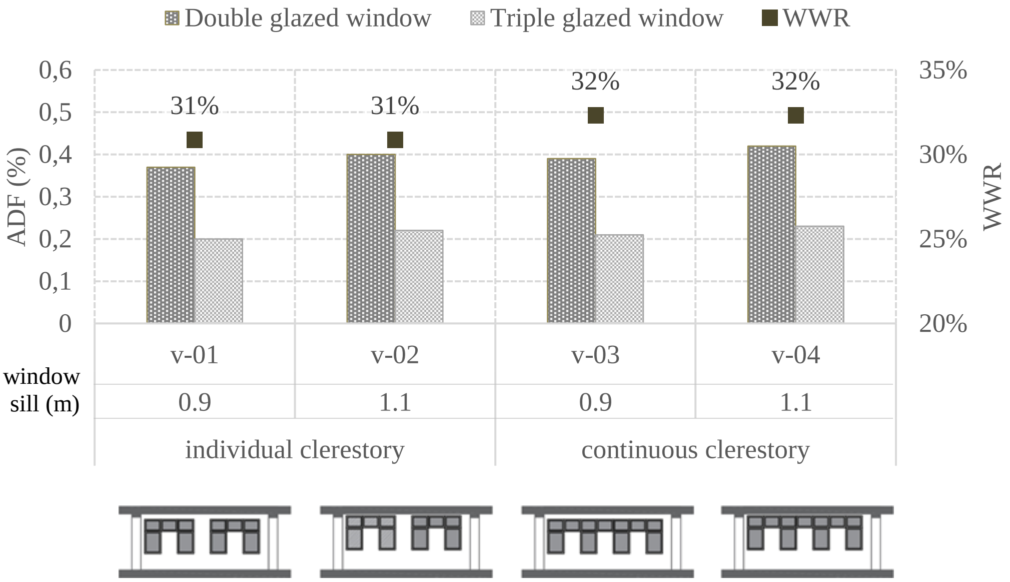


Figure 26: ADF (%) for vertical shape variations on the first floor.

The ADF results of the four variations for vertical shape are presented in Figure 26. For vertical shape, the major alteration from the u-shape was to remove the 0.3 m gap between side-window and clerestory. Unlike horizontal shape, each window was modeled with two window panes. The first option, v-01, had a window sill height of 0.9 m which resulted in an ADF of 0.37%. The ADF increased to a value of 0.40% for the following option v-02, where the window sill height was increased to 1.1 m. By adding an extra pane in the clerestory, v-03 experienced a reduction in ADF to 0.39% and v-04 had an increased ADF of 0.42%. Note that, the window sill height for v-03 and v-04 was 0.9 m and 1.1 m respectively. Therefore, according to the results v-04 was the best performing vertical shape.

Among the 16 variations, the highest ADF value was obtained by the case h-08, which had the largest WWR. It can be deduced that, not only the WWR but also the position of the openings had a significant impact on the results since all the options with window sill placed 0.2 m higher than their alternative options resulted in 9% – 14% relative increase in ADF values.

In addition, the results between the double and triple glazing windows were compared, see Figure 27. It shows- that for double glazing windows, ADF ranged from 0.31% to 0.54% whereas for triple glazing windows, ADF ranged from 0.17% to 0.29%. Undoubtedly, there was a considerable reduction in daylight penetration for triple glazing windows. Therefore, it was decided to continue the analysis further only for double glazing windows. However, note that the glazing visual transmittance of the selected three-pane window was low compared to products available on the market for spectrally selective glazing (Tvis = 0.69 is possible for a three-pane).

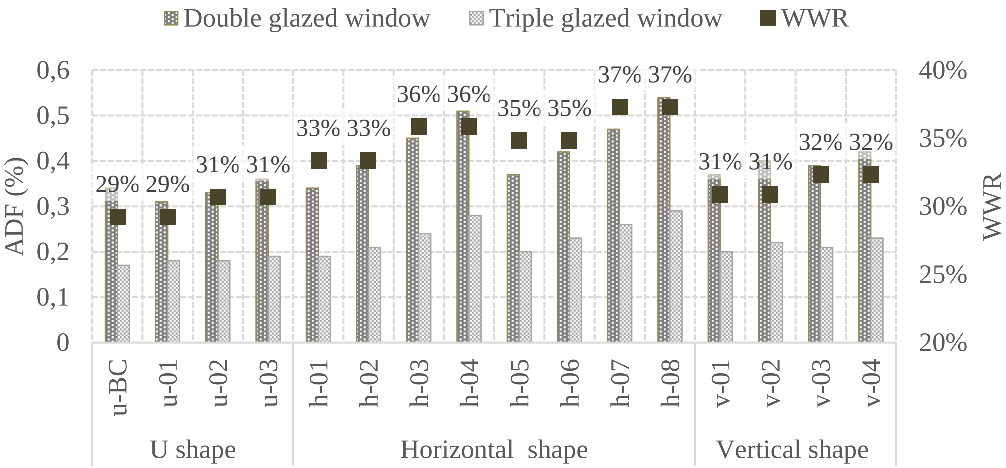


Figure 27: ADF (%) for different shapes, positions and types of glazing.

After analyzing all results for double glazing windows, the best option with the highest ADF value for each shape was chosen for the next stage. u-03 with WWR 31%, h-08 with WWR 37%, and v-04 with WWR 32% were selected for u-shape, horizontal, and vertical shape respectively.

6.1.2 Stage-2: Feasible shape for side-lighting

6.1.2.1 Static daylight metric (SDM) and dynamic daylight metrics (DDM)

Figure 28 shows the percentages of the area with sDA_{300} for 50% of annual occupancy hours for the three selected variations in comparison to the base case (u-BC) on the first floor for a smaller 240 m² room. The selected shapes had the same window sill height of 1.1 m and continuous clerestory between two windows. Only the horizontal shape had three window panes among the four variations.

At four cardinal directions, a distinct pattern of effects for different shapes can be observed. The south direction received the maximum natural sunlight which was followed by the west direction. On the south orientation, the base case (u-BC) had an sDA of 38%, from which it dropped to 31% for u-03. On the contrary, h-08 and v-04 increased to a sDA of 52% and 40% respectively. It should be noted that, on the south orientation, the type-3 windows from the base case were replaced by type-1 windows with the chosen three shapes. A considerable increase in daylight level on the north orientation was obtained for h-08, where the sDA value of 4% in u-BC reached a sDA value of 21%. Moreover, h-08 experienced the highest increase of sDA on the east and west facades by a value of 28% and 46% respectively. However, for all orientations except south, the sDA value did not reach the benchmark of 50% recommended by Swedish Standard SS-EN 17037 (Svensk Standard SS-EN 17037, 2019).

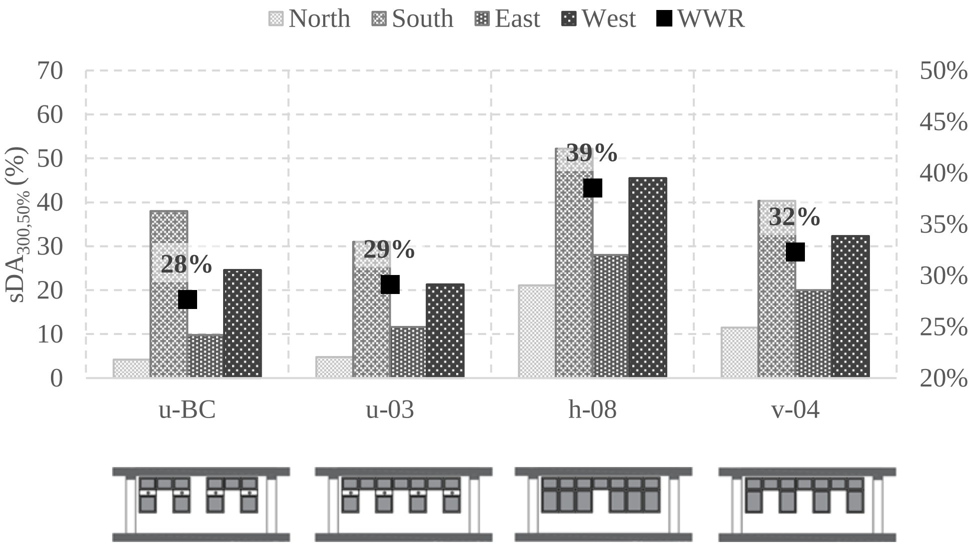


Figure 28: Effect on $sDA_{300,50\%}$ (%) of different shapes at four orientations on the first floor.

On the second floor, the sDA values on the four orientations for the four shapes increased more than on the first floor, see Figure 29. The only exception can be seen on the south facade of u-BC, where sDA of 38% on the first floor, was decreased to sDA of 31% on the second floor. Note that, on the south facade, the second floor had type-1 windows whereas the first floor had type-3 windows. The case, h-08 performed the best compared to other shapes on the second floor as well. For h-08, on the north orientation sDA increased three times more and on the south, east and west orientation sDA increased twice more in comparison to u-BC. Moreover, for h-08, the sDA values increased from 21% to 28% on the north; 52% to 61% on the south; 28% to 37% on the east and 46% to 48% on the west orientation comparing the first floor with the second floor.

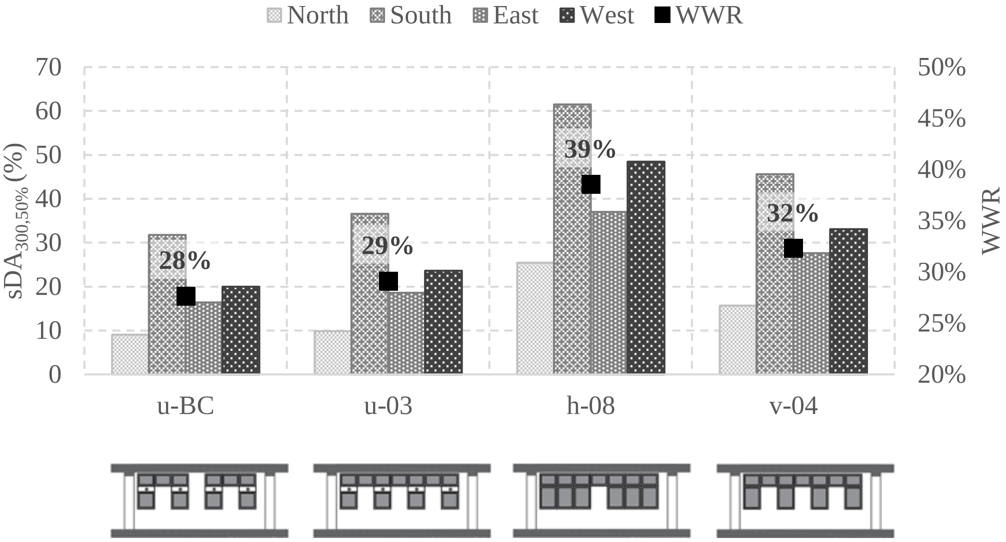


Figure 29: Effect on sDA$_{300,50\%}$ (%) of different shapes at four orientations on the second floor.

Figure 30 for SDMs exhibit similar effects as DDMs on the first floor. On the south and the west orientations the ADF values were higher than on the north and east orientations. Note that, the surrounding conditions (adjacent buildings, terrains, trees) on the four orientations were different. Only h-08 achieved ADF higher than 1%. On the south and west facades, h-08 reached an ADF of 2%, which is the minimum threshold for satisfactory daylight level (BSI, 1992). From u-BC to h-08, ADF increased from 0.6%, 1.3%, 0.6% and 1.3% to 1.5%, 2%, 1.2% and 2.3% on the north, south, east and west orientations respectively.

With the second floor, as the surrounding condition was slightly changed on the second floor, the highest ADF was obtained on the west façade and followed by the south façade. On the second floor, both h-08 and v-04 were reached ADF of 1% although h-08 had greater effect on improving daylighting level than v-04. On the north, south, east and west orientations, the ADF of 0.7%, 1%, 0.7% and 1% of u-BC, was respectively increased by v-04 to the ADF of 1%, 1.3%, 0.9% and 1.5% whereas by h-08, to the ADF of 1.6%, 2.1%, 1.6% and 2.2%. Evidently, h-08 outperformed the other shapes for all orientations.

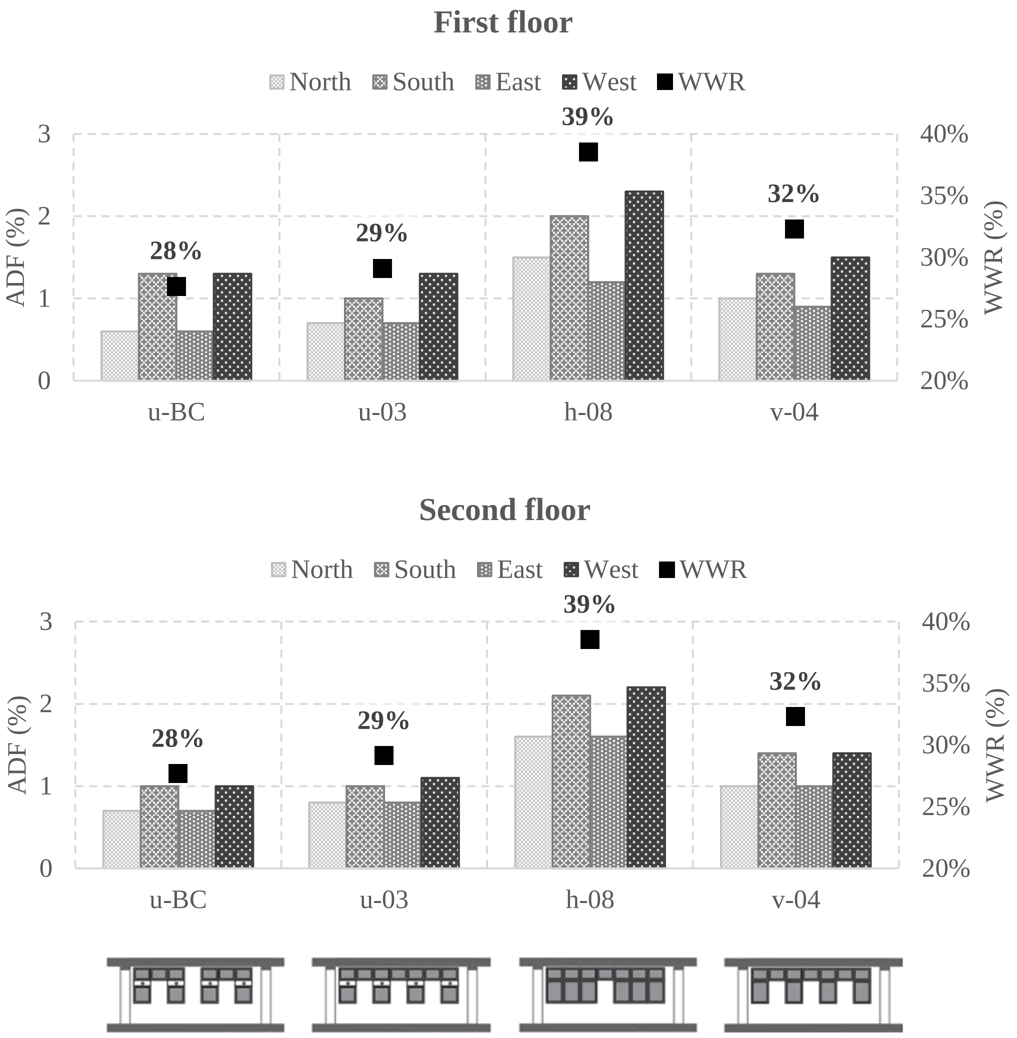
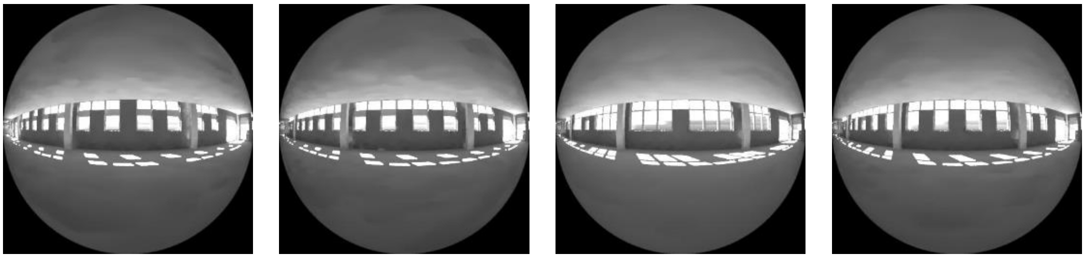


Figure 30: Effect on ADF (%) of different shapes at four orientations on the first and second floor.

6.1.2.2 View out

After the daylighting analysis, the quality of view out from indoor workplaces was also analyzed for the three shapes. Figure 31 presents the perceived view out at 1.2 m height for some workplaces located deep in the buildings plan (7 m) in the 240 m² room. Among the presented four shapes, h-08 provided an unobstructed horizontal view angle of 22° from the mentioned point. In comparison, the other three shapes provided a horizontal view angle of 7°. However, the Swedish Standard SS-EN 17037 (2019) recommends a minimum of 14^o horizontal angle for view. According to this, h-08 was preferred in comparison to u-03 and v-04. Consequently, from daylight quantity and view out quality, h-08 was selected as the best performing shape.



u-BC *u-03* *h-08* *v-04*

Figure 31: Effects in the view out by having different shapes.

6.1.3 Stage-3: Reasonable width for side-lighting

6.1.3.1 Static daylight metric (SDM) and dynamic daylight metrics (DDM)

At the beginning of this stage, the height of the selected shape h-08 was increased by 0.2 m for better visual accessibility. This was considered as a new variation, which was named w-01. Note that, from this stage the variation h-08 was addressed further as the base case of width variation (w-BC). Due to the increased height of w-01, the WWR reached to 42% from 39% of w-BC. From this new variation w-01, three more variations, namely- w-02, w-03 and w-04 were studied. A gradual increase of the window width by 0.15 m, resulted in the increase of WWR to 43%, 44% and 45% respectively for w-02, w-03 and w-04.

In Figure 32, it can be seen how the sDA changed according to four variations in window width on the first and second floor. On the first floor, an overall gradual increase of sDA was observed while the width was increased at an increment of 0.15 m. From w-BC to w-01, sDA values increased from 21% to 22%, 52% to 55% and 46% to 48% on the north, south, and west directions respectively while no change in values were experienced on the east orientation. However, in comparison to the w-BC with 0.2 m less in height, the increase of the sDA of w-01 were not significant. In comparison to w-01, the sDA increased for w-02 to 22%, 57%, 29%, 50% and for w-03 to 24%, 59%, 30% and 52% respectively on the north, south, east and west orientations. The highest increase in sDA was observed by w-04, where the sDA reached to a value of 26%, 62%, 31% and 55% respectively for north, south, east and west orientations. Clearly, there was no steep changes in the increased values of sDA within the four proposed width variations.

On the second floor, the increase of sDA from w-01 to w-04 was similar as for the first floor. Although on the second floor the sDA values were considerably higher than the first floor. The sDA increased in w-BC from 21% to 25%, 52% to 61%, 28% to 38% and 46% to 48% from the first floor results on the same orientations mentioned before. Similarly, for w-01, w-02, w-03 and w-04 the increase in sDA was observed on the second floor where w-04 performed the best. However, in w-04 the sDA reached to 33%, 71%, 43%, 58% on the north, south, east and west orientation respectively. On both floors sDA values complied to the Swedish Standard SS-EN 17037 only for the south and west facades.

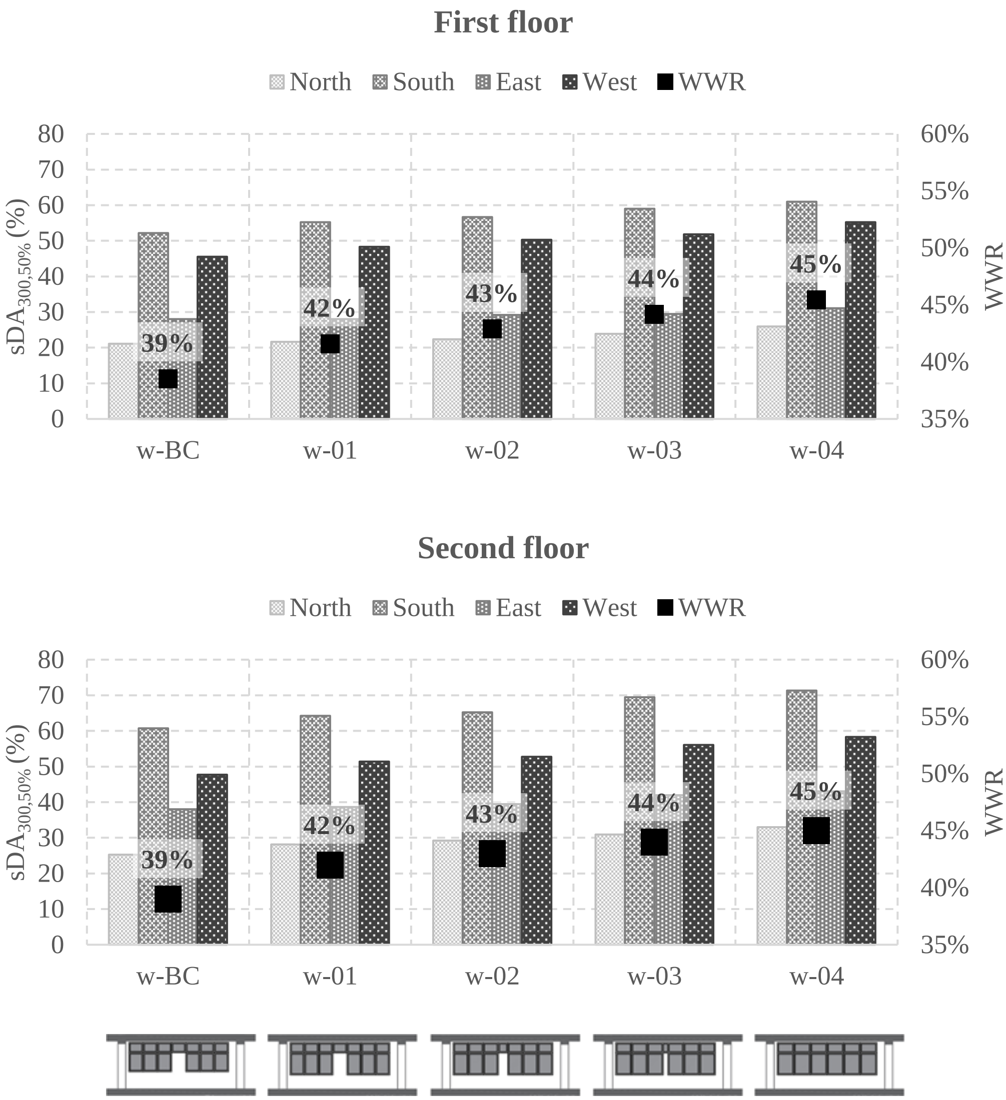


Figure 32: Effects on $sDA_{300,50\%}$ (%) of different width at four orientations on the first and second floor.

For the ADF metric in Figure 33, the pattern of increase was similar as observed for the sDA metrics on the first floor. However, SDMs increased more uniformly in comparison with DDMs although the changes were small. From w-01 the ADF of 1.5%, 2%, 1.2% and 2.4% were increased to the ADF of 1.8%, 2.3%, 1.4% and 2.8% for w-04 on the north, south, east and west orientations respectively. Note that, for all the width variations, the west facade achieved the highest ADF values on the first floor. Figure 33 also shows the ADF values on the second floor where the ADF increased similarly as on the first floor. However, west facade reached to the highest ADF on the second floor as well. In contrast to the first floor, a new feature can be noticed in the results of the second floor where on the north and the east orientations, the ADF resulted in the same values for all four variations.

From the lowest width variation (w-01), ADF values of 1.7%, 2.3%, 1.7% and 2.9% were increased to 2%, 2.7%, 2% and 2.9% in the highest width variation (w-04) for the north, south, east and west orientations respectively.

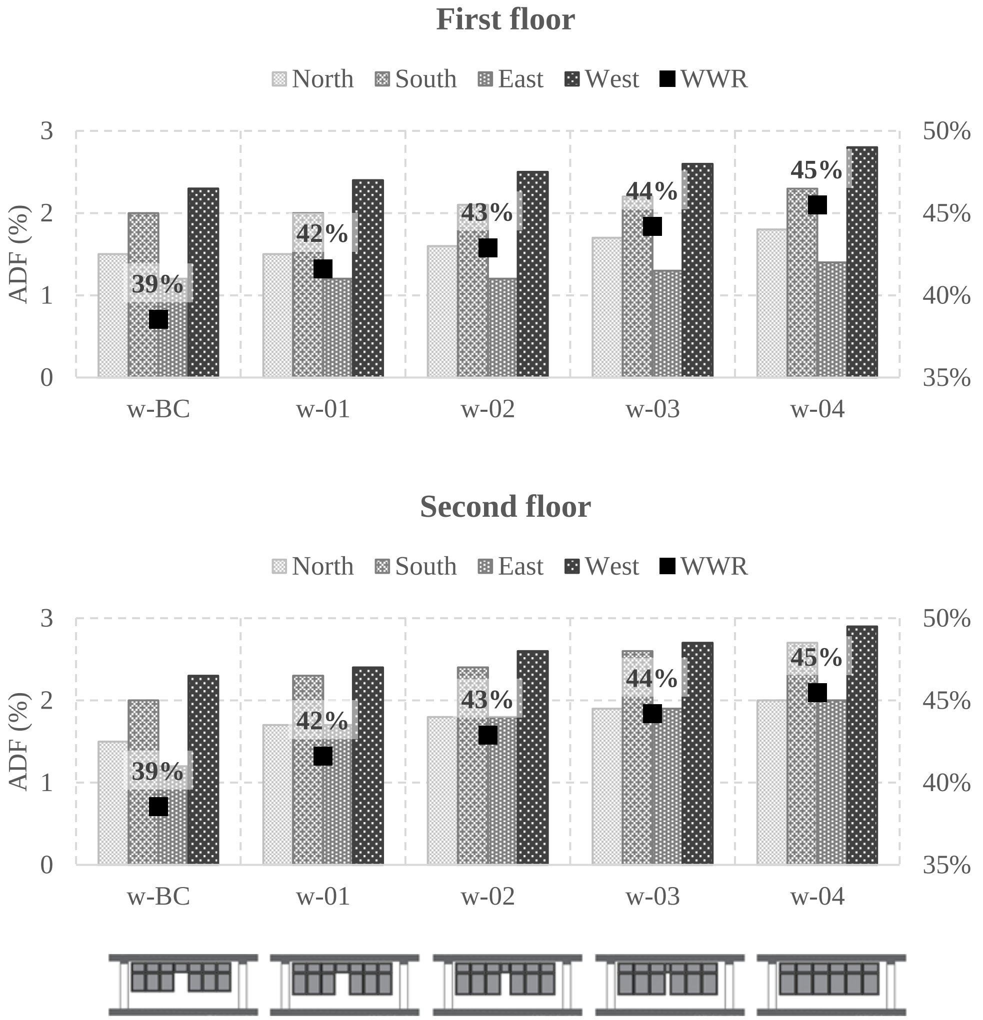
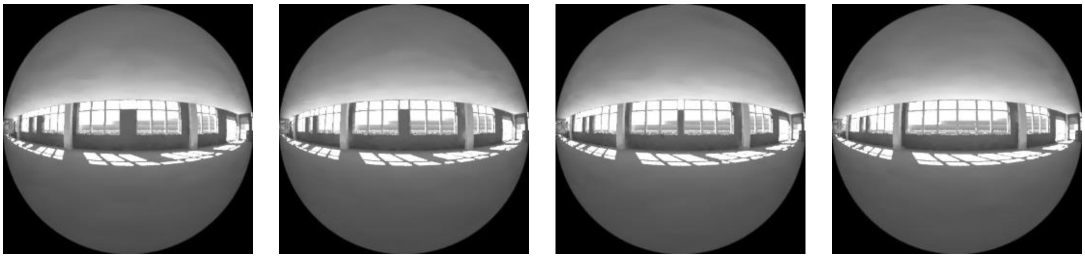


Figure 33: Effects on ADF (%) of different width at four orientations on the first and second floor.

6.1.3.2 View out

The view out was analyzed in this stage as well. In stage-2, the changes in the view quality were quite remarkable. However, the unobstructed horizontal view angle provided by the four options were 22°, 23.5°, 24.7°, and 49° respectively from the same viewpoint as the previous stage. It should be mentioned that, w-04 was in compliance with the medium requirement of view out by Swedish Standard SS-EN 17037 (2019) for visual comfort. At the end of this stage, two width options with lowest and highest results, were selected to continue the experiment to decide which one is worth to apply.



w-01 *w-02* *w-03* *w-04*

Figure 34: Effects on the view out of different widths.

6.1.3.3 Glare probability and luminance ratio

Although daylight quantity improved remarkably, a potential glare risk was observed due to the increased WWR. Figure 35 shows, with the selected options (w-01 and w-04), that 2.6 and 3 times more glare hours occurred annually in comparison to the existing condition. The presented values in the figure were studied at a workplace located close to the south facade on the second floor which can be seen in Appendix B. It should be mentioned that, on the west facade,the annual glare was around three times lower than on the south facade for both base case and chosen options.

To prevent potential glare occurrences in the visual field, one internal and two external shading were studied for the above mentioned workplace.The effect of these solutions can be seen in comparison to no shade situation in Figure 36 and Figure 37. Without any shading device, the relative luminance ratio between the main task, immediate surroundings and remote surroundings was in between preferred and tolerable level, i.e. 1:0.6:12 (IES, 2011). Yet, DGP resulted in 1, which corresponds to intolerable glare (Svensk Standard SS-EN 17037, 2019). In following Figure 36 and Figure 37, it can be seen that, the three solutions had a similar effect for both w-01 and w-04. The first internal system- white roller shade reduced DGP to 0.4 and 0.48 for w-01 and w-04 respectively. However, they still created a perception of disturbing and intolerable glare as stated in Swedish Standard SS-EN 17037 (2019). It provided a luminance ratio around 1:0.3:10 for both width variations which was within preferred benchmarks based on IES (2011). An improved comfort was created by external light grey awning for both options, as it lowered the DGP to 0.2 (imperceptible glare) and the luminance ratio was around 1:0.3:10. On the other hand, another external dark blue awning created a visible contrast within the workplace with a DGP of 0.02.

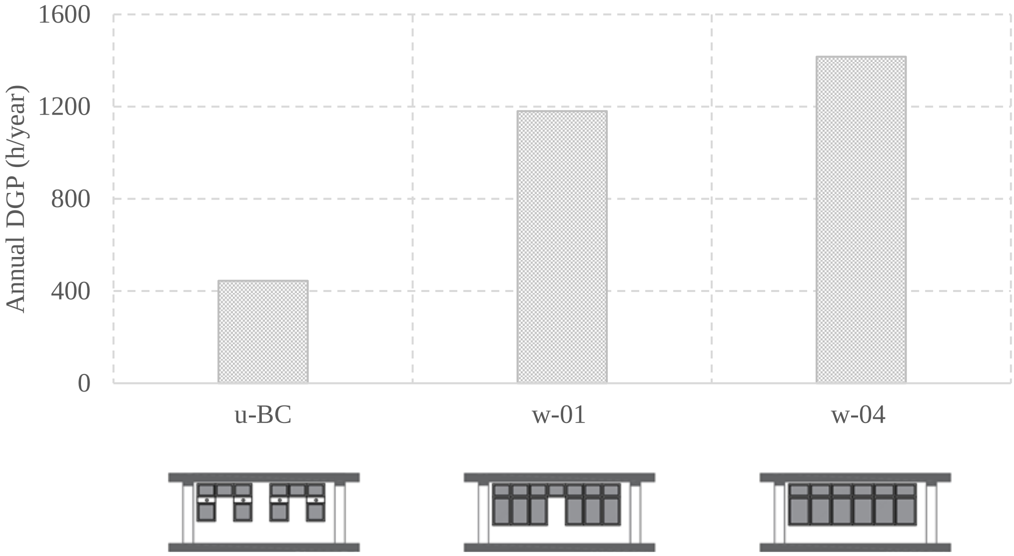
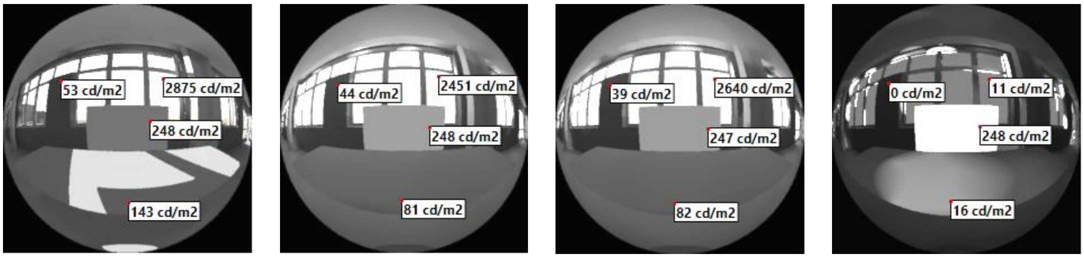
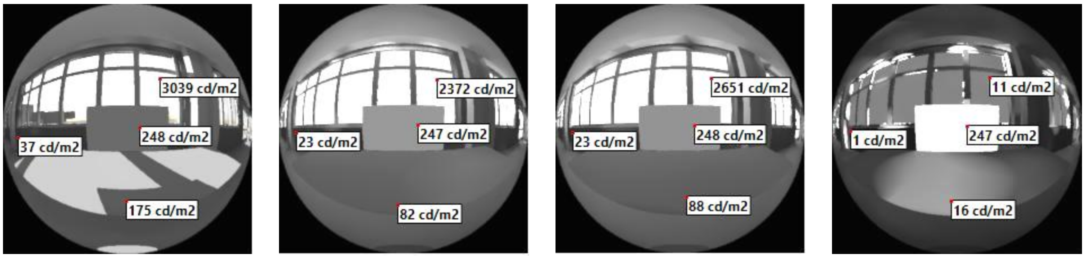


Figure 35: Annual DGP of Width-01 and Width-04 in comparison with base case.



No shade *2 February: 12 PM*	*White roller shade* *2 February: 12 PM*	*Light-grey awning* *2 February: 12 PM*	*Dark-blue awning* *2 February: 12 PM*

Figure 36: Luminance ratio and DGP with different shading for w-01.



No shade *2 February: 12 PM*	*White roller shade* *2 February: 12 PM*	*Light-grey awning* *2 February: 12 PM*	*Dark-blue awning* *2 February: 12 PM*

Figure 37: Luminance ratio and DGP with different shading for w-04.

In Figure 38, three solutions are presented with their annual performance for w-04. It should be mentioned that, the pattern of their performance was almost identical as for w-01. Hence, it was more reasonable to choose the light grey awning for both variations as it reduced glare occurrence while keeping an acceptable visual contrast within the workplace.

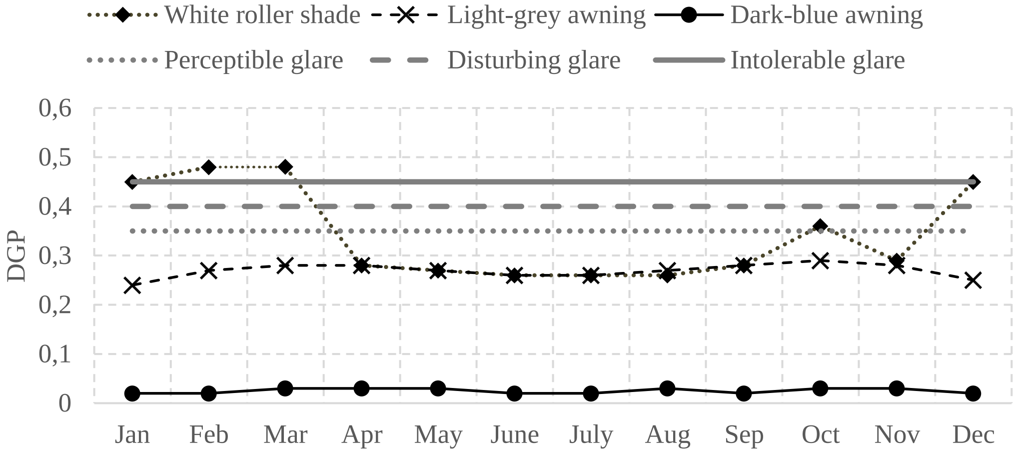


Figure 38: DGP provided by three different shadings for a year for w-04.

6.1.4 Stage-4: Different type, orientation and slope for top-lighting

Figure 39 shows annual metric, sDA for different top-lighting strategies as this stage of analysis took the orientations into consideration. According to the results, flat and sloped skylights provided 3.6 and 5.2 times higher sDA values in comparison to the existing monitor skylight (t-BC). However, for sloped skylights, the results did not show much variations for 15°, 30° and 45° slopes on different directions. Especially for both east and west orientations, the values remained constant. Nonetheless, for the south direction, the increase in daylighting was negligible in comparison to the other two directions; it was sDA of 4.3 % for 15° slope (t-03), and sDA of 4.2% for both 30° and 45° slope (t-04 and t-05). Due to the same SFR for all the sloped options from t-03 to t-11, significant changes cannot be seen. On the other hand, for t-12 (Sloped-S, 15^{o}), as SFR increased from 4.9% to 5.9% the resultant sDA was 4.7%. Therefore, t-12 was chosen as the best top-lighting strategy for the given building. Naturally, the skylight had much greater impact on the second floor than the first floor. Figure 40 shows that the top-lighting system raised sDA from 0.82% to 7.3% on the second floor from the first floor with the existing monitors. Moreover, with the chosen sloped skylight (t-12) the second floor achieved a sDA of 16.7% which was significantly increased from the sDA of 4.7% on the first floor.

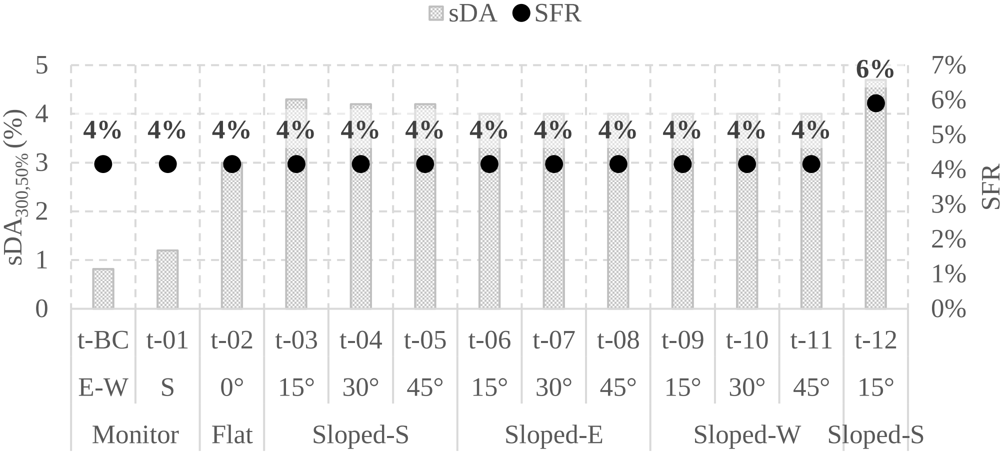


Figure 39: sDA (%) for different type, orientation, tilt angle of top-lighting at first floor.

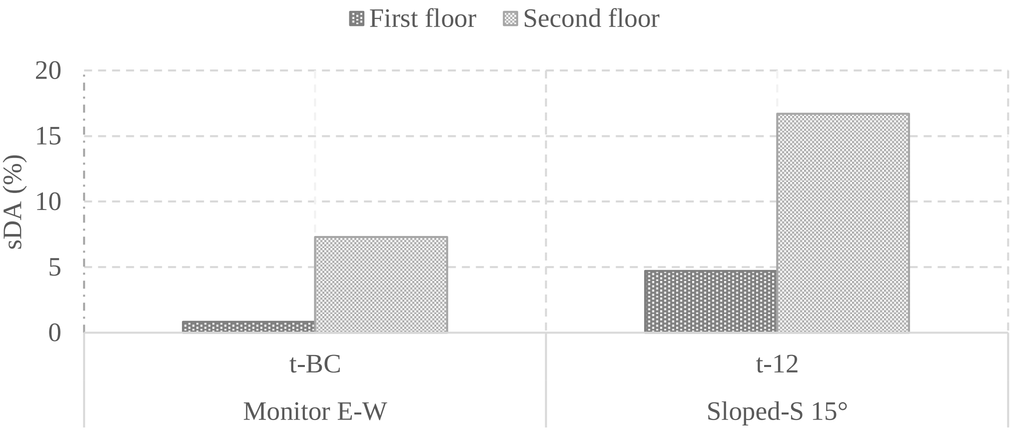


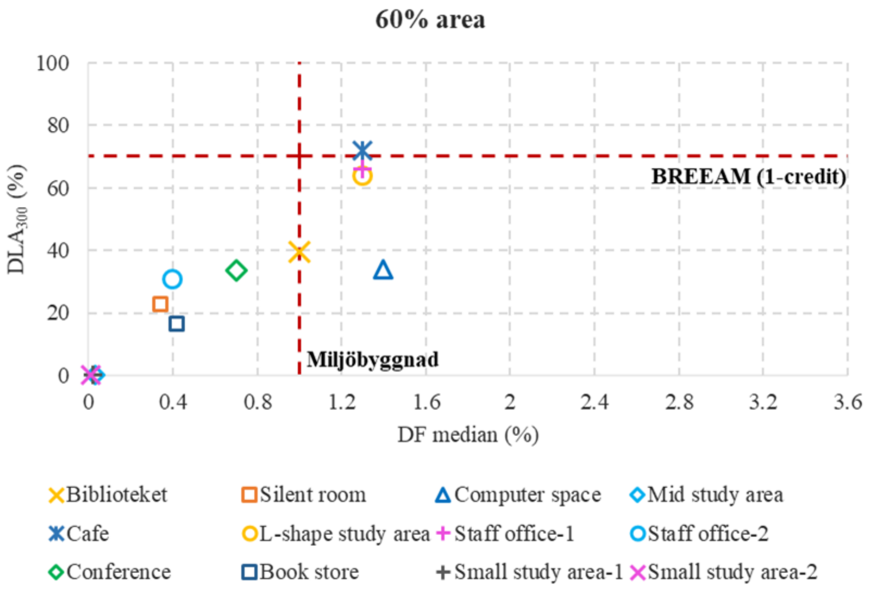
Figure 40: Difference of sDA (%) between first and second floor.

6.1.5 Stage-5: Combination of side-lighting and top lighting

6.1.5.1 SDMs and DDMs for internal functional zones and comparison with BREEAM-SE and Miljöbyggnad

In this stage, the selected top-lighting option (t-12) was combined with the selected side-lighting options w-01 (combination-01) and w-04 (combination-02). These two combinations were compared with the existing condition, (combination-BC). Figure 41 shows the CDA$_{300}$ for 12 internal zones on the first and the second floors for combination-BC. Both SDMs and DDMs for 12 internal functional zones on the first and second floors were evaluated to have a clear overview of daylighting and verify the compliance with Miljöbyggnad 3.0 and BREEAM-SE 2013. Since Miljöbyggnad requires a minimum DF median of 1% and BREEAM-SE requires a DA of 300 lux for 2000 hour of the occupancy hours (70% DA for the given building), the thresholds were set accordingly. The results of three combinations for both 60% and 80% evaluated areas (for BREEAM 1-credit and 2-credits requirements) can be seen in Figure 42.

Figure 41: *CDA$_{300}$ by combination - BC of internal zones: 1.Cafeteria; 2. Biblioteket; 3. Computer space; 4. Silent study area; 5. Mid study area; 6. L-shaped study area; 7. Staff office-1; 8. Staff office-2; 9. Book store; 10. Conference; 11. Small study-1; 12. Small study-2.*



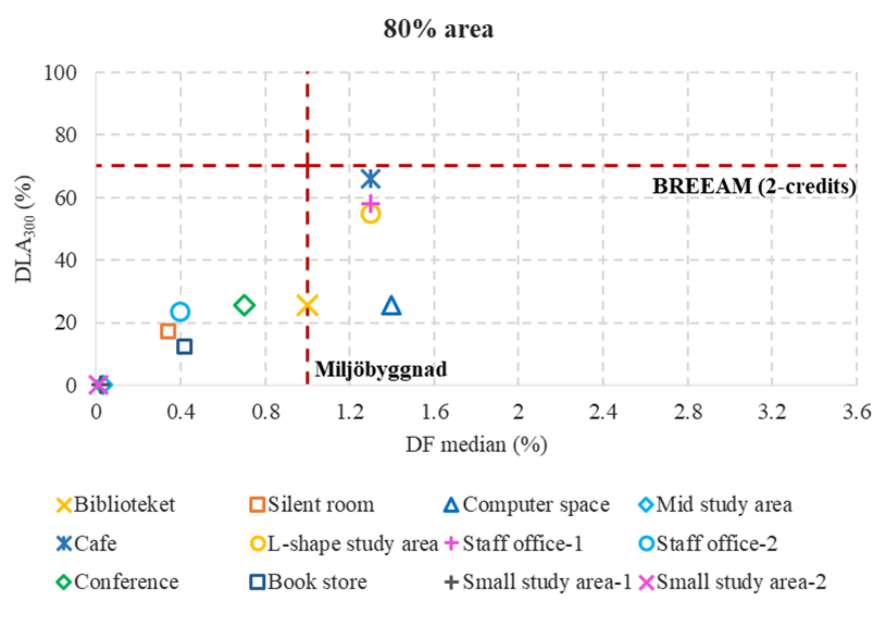
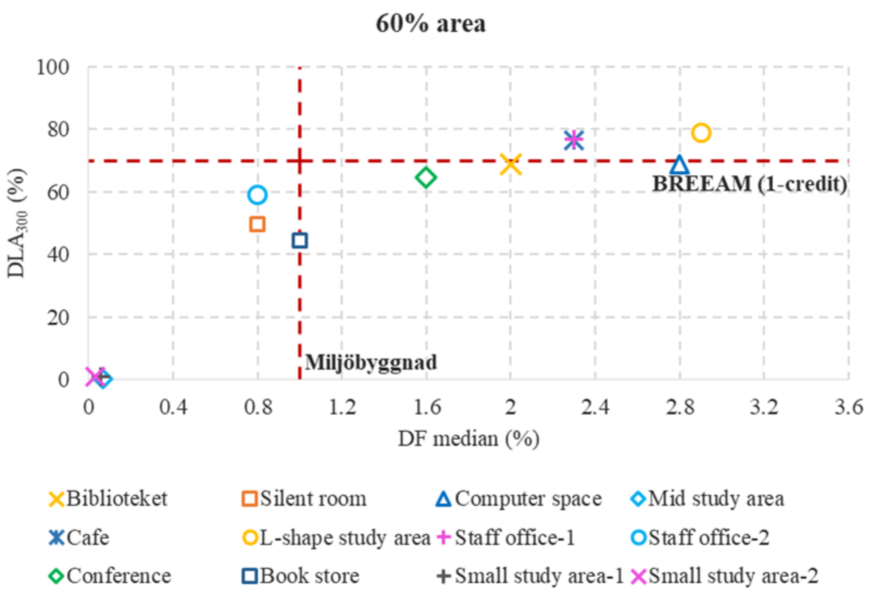


Figure 42: DDM and SDM of internal zones for 60% and 80% evaluated areas in existing combination (u-BC and t-BC).

Figure 43 presents the overview of daylight level for combination-01 where seven functional zones complied with Miljöbyggnad. On the other hand, for BREEAM-SE, five zones complied with 1-credit, and one third of the zones reached the 2-credits standard. Two of the major functions of the building, the silent room on the first floor and staff office-2 on the second floor could not meet any certification benchmark, but the DA increased from 23% to 50% and from 31% to 59% respectively considering 60% of the occupied area.

With combination-02 (Figure 45 and Figure 46), further improvements were obtained, where only one-third of the zones could not achieve DF median value of 1%. At the same time, half the zones complied with 1-credit and one-third of the zones complied with 2-credits from BREEAM-SE. The DA_{300} of the silent room was enhanced as well, with an DA of 50% in combination-01 increasing to DA of 52% in combination-02. It should be noted that, in both improved combinations, the daylight level remained extremely low in the three study areas at the core of the building. Regardless of the best side-lighting and top-lighting strategies, the results stayed constant with the existing combination for these three zones.

Figure 43: CDA$_{300}$ by combination-01 of internal zones: 1.Cafeteria; 2. Biblioteket; 3. Computer space; 4. Silent study area; 5. Mid study area; 6. L-shaped study area; 7. Staff office-1; 8. Staff office-2; 9. Book store; 10. Conference; 11. Small study-1; 12. Small study-2.



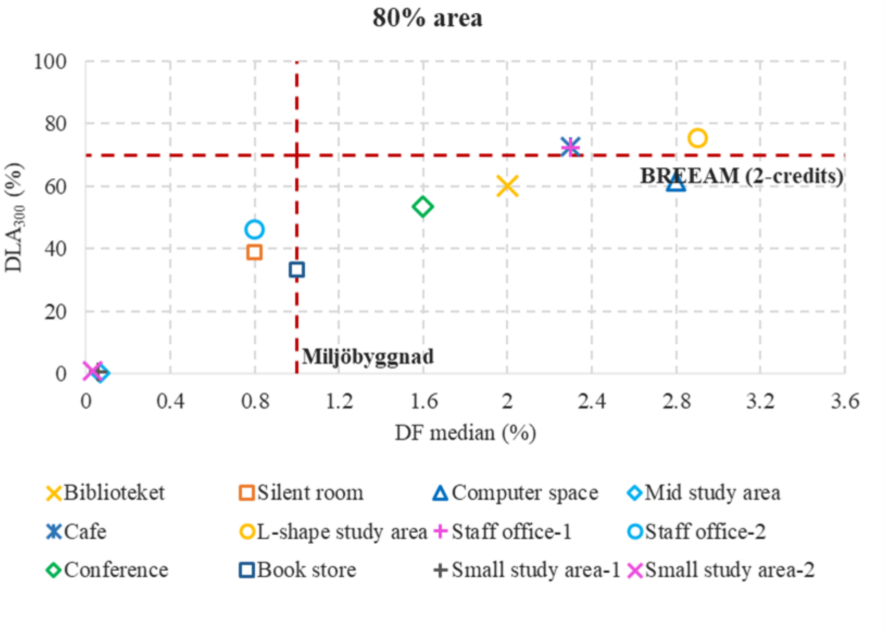


Figure 44: DDM and SDM of internal zones for 60% and 80% evaluated areas in combination-01.

Figure 45: CDA$_{300}$ by combination-02 of internal zones: 1.Cafeteria; 2. Biblioteket; 3. Computer space; 4. Silent study area; 5. Mid study area; 6. L-shaped study area; 7. Staff office-1; 8. Staff office-2; 9. Book store; 10. Conference; 11. Small study-1; 12. Small study-2.

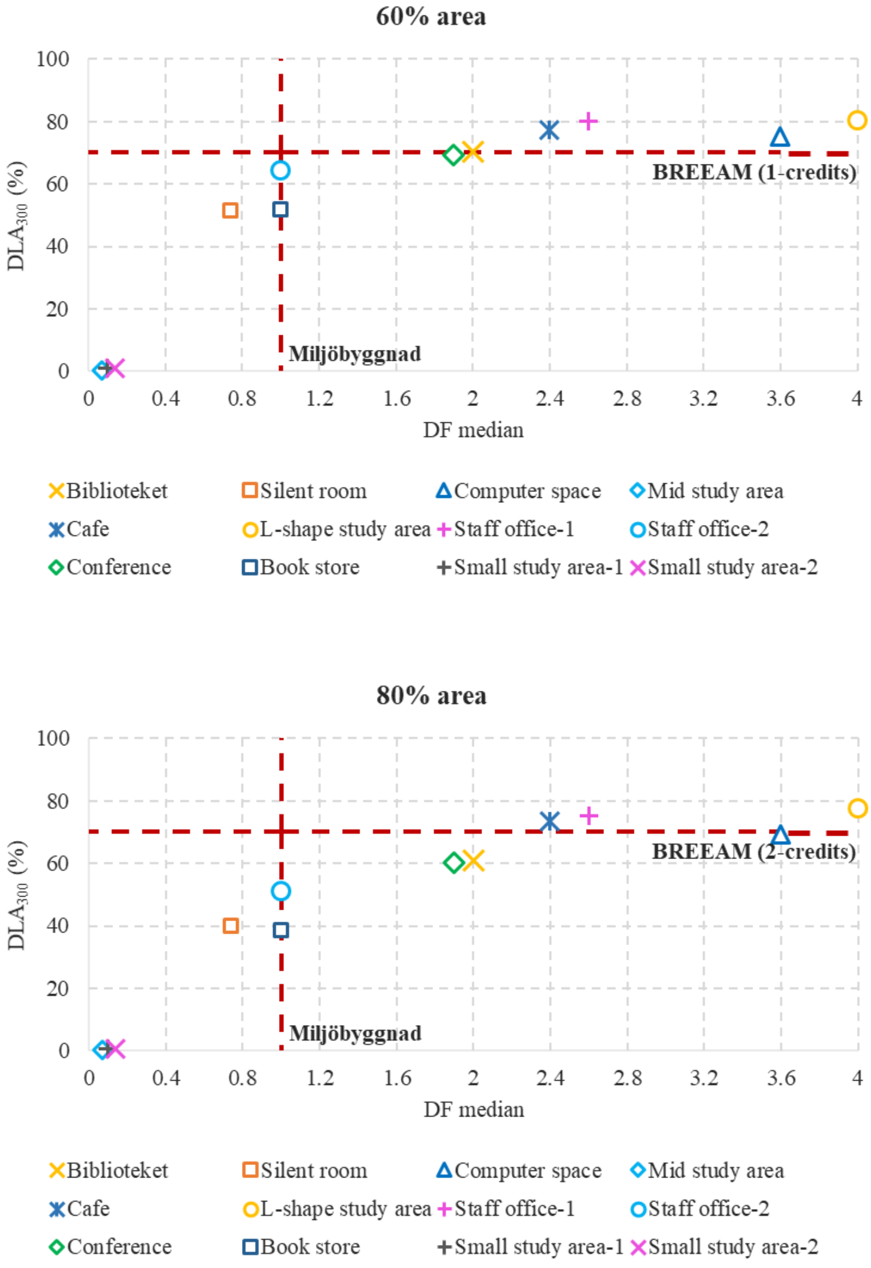


Figure 46: DDM and SDM of internal zones for 60% and 80% evaluated areas in combination-02.

According to BREEAM-SE, a simulation was conducted with DA_{90} for the worse lit zones, which resulted in a DA of 12% in mid study area on the first floor and a DA of 7% in two small study areas on the second floor whereas minimum 70% DA was required for 60% of evaluated areas. From the visualization of CDA_{300} results of all the combinations, it can be seen that even with partial credits daylight level was very poor in these zones.

The analyses were also carried out for different areas, with and without toplight considering DDMs (Figure 47). It was found that, the top-lighting system did not significantly improve daylight levels on the majority of the functional areas. However, it provided improvements to the circulation areas. The only zone that experienced the impact of skylight was the L-shaped study area on the second floor. Figure 47 shows that the addition of skylight increased the sDA of that space from 41% to 53%, from 76% to 87% and from 83% to 90% for the existing combination, combination-01 and combination-02 respectively.

Moreover, Figure 48 shows the contribution of the top-lighting system towards the daylighting quantity on the central circulation area of the building considering instead DA_{100} for the three combinations according to Swedish Standard SS-EN 17037. The three combinations resulted in a good daylight level in the central atrium when considering the benchmark for circulation area.

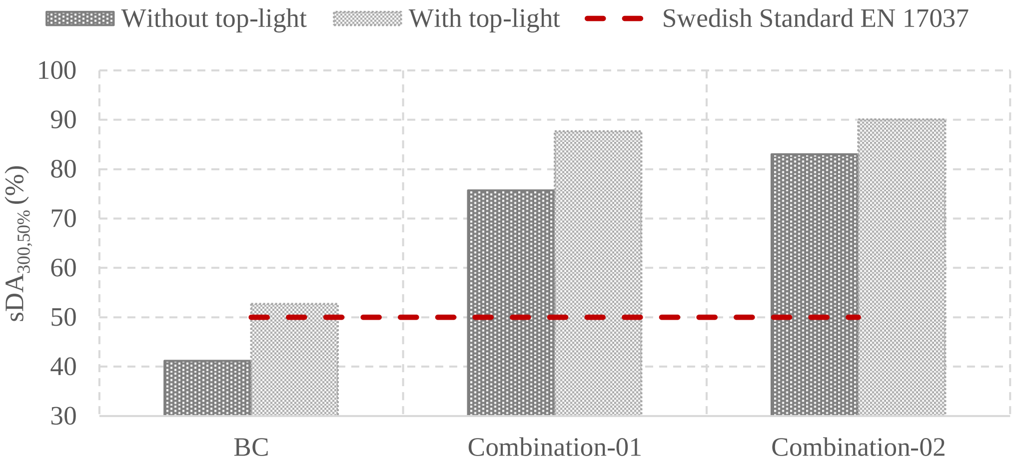


Figure 47: Effect of top-lighting system on the L-shaped study area on the second floor.

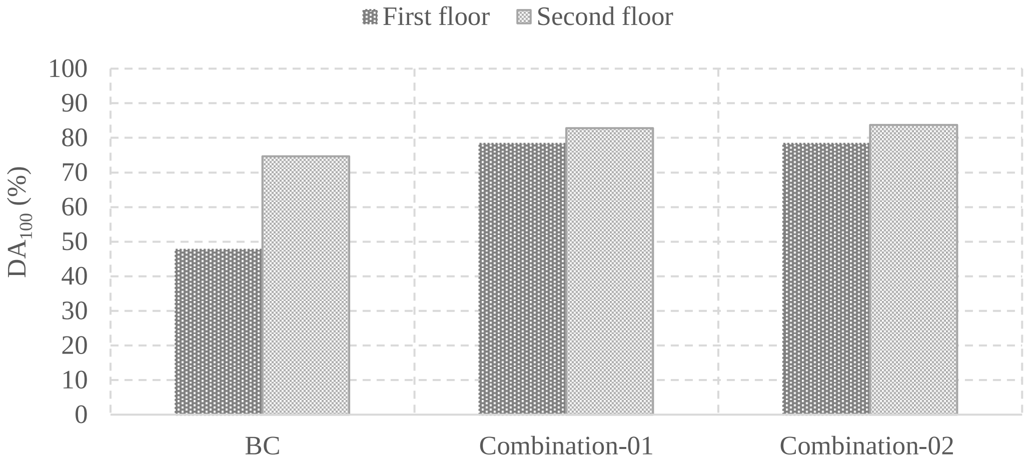


Figure 48: Effect of top-lighting system on the circulation area on the first and second floor.

6.1.5.2 Uniformity ratio of different internal functional zones

The uniformity of illuminance was verified for all the internal functional zones, see Table 13. The ratio between the minimum and average DF was used to calculate this metrics. The results were not satisfactory in the existing combination considering the recommendations from the standards. Even in two improved combinations it was not possible to reach the desired level of uniformity. Except the conference room, no other zones achieved a uniformity ratio of 0.3, which is the target minimum in BREEAM.

Table 13: Uniformity ratio in all functional zones.

Internal functions	**Existing combination**	**Combination-01**	**Combination-02**
Biblioteket	0.01	0.2	0.12
Silent Room	0.1	0.05	0.06
Computer Space	0.13	0.12	0.12
Mid study area	0	0	0
Cafe	0.07	0.02	0.03
L-shape study area	0	0	0
Staff Office-1	0.1	0.1	0.2
Staff Office-2	0	0	0
Conference	0.1	0.3	0.3
Book store	0	0.16	0.15
Small study area-1	0	0	0
Small study area-2	0.1	0	0

6.2 Parametric study for building's energy demand

6.2.1 Stage-1: Positions and glazing types for side-lit rooms

A total of 16 variations of side-lighting strategies were investigated in stage-1. These variations were divided into three basic shapes: 1) u-shape (four variations including the base case), 2) horizontal (eight variations), and 3) vertical (four variations). The variations took into account different parameters such as the type of clerestory, gap between side window and clerestory, the number of window pane, and position of the window sill. However, every other variation of the shape had the same glazing area, only the position of the window sill was different, i.e. the window sill of u-BC and u-01 was placed at 1.1 m and 0.9 m respectively. A comparison between the energy demand on both u-BC and u-01 is shown in Figure 49. The figure presents the energy demand for both options simulated with two different weather files that had solar and no-solar effects, also with two different glazing types (double and triple glazing window).

The glazing area of the two options did not change which resulted in constant WWR and WER. The energy demand for u-BC and u-01 remained the same for all conditions. Using the double glazing window, the energy demand was 180.6 kWh/m^2 with no sun and 150.1 kWh/m^2 with the sun. As the triple glazing window was used, the energy demand dropped to 165.5 kWh/m^2 and 143.8 kWh/m^2 respectively. It was deduced that different window sill positions did not affect the building's energy demand. Different glazing types and solar gains were the features which allowed changes towards the energy demand.

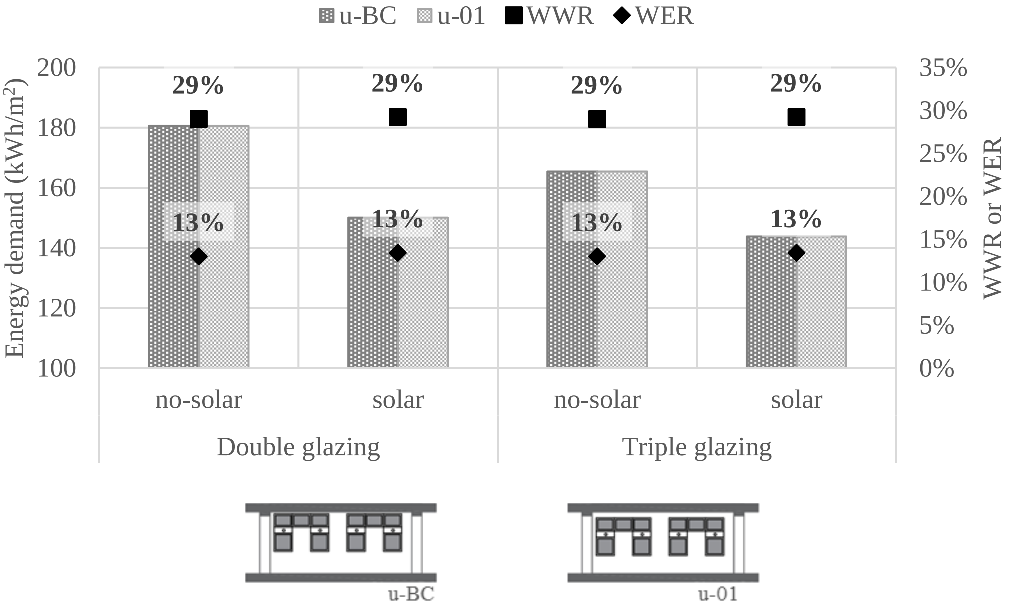


Figure 49: Building's energy demand (kWh/m^{2}yr) for different positions.

According to the results, different combinations that have the same glazing area were only simulated once, with the original position of the existing window sill (1.1 m). This resulted in a total of eight variations (Figure 50).

Figure 50: Side-lighting variations for stage-1 of energy simulations.

The results for energy intensity were analysed, see Figure 51. The WWR between each variations ranged from 29% to 37%. In the u-shape, u-01 had a larger WWR in comparison to u-BC as an effect of the continuous clerestory between two columns. By having more clerestory, the WWR increased from 29% in u-BC to 31% in u-01. The energy demand did not change for double glazing, resulting in 150.1 kWh/m^2 for both u-BC and u-01. However, with triple glazing, the energy demand was reduced from 143.8 kWh/m^2 for u-BC to 143.4 kWh/m^2 in u-01.

With the horizontal shape, the WWR varied according to both clerestory addition and the removal of the gap between the side-windows and clerestory. The h-02 and h-06 had a 0.3 m gap between the side-windows and clerestory while h-04 and h-08 did not have any gap. This resulted in an increase of WWR with 33% for h-02 to 36% for h-04, and 35% for h-06 to 37% for h-08. The energy demand for double glazing increased to 150.3 kWh/m^2, 150.5 kWh/m^2, 150.4 kWh/m^2, and 150.6 kWh/m^2 for h-02, h-04, h-06, and h-08 respectively. The differences between these cases are negligible. On the other hand, with triple glazing, the energy demand diminished from 142.8 kWh/m^2 for h-02 to 141.9 kWh/m^2 for h-04, to 142.5 kWh/m^2 for h-06, and to 141.6 kWh/m^2 for h-08.

In vertical shape analysis, the WWR varied with respect to the additional clerestory with v-04. The WWR had an increase, from 31% for v-02 to 32% for v-04. In relation to the energy demand, the results of double glazing increased with 150.1 kWh/m^2 and 150.2 kWh/m^2 as total energy use for v-02 and v-04 respectively. However, in the same manner as the other shapes, the triple glazing also produced a reduction, i.e. from 143.1 kWh/m^2 for v-02 to 142.8 kWh/m^2 for v-04.

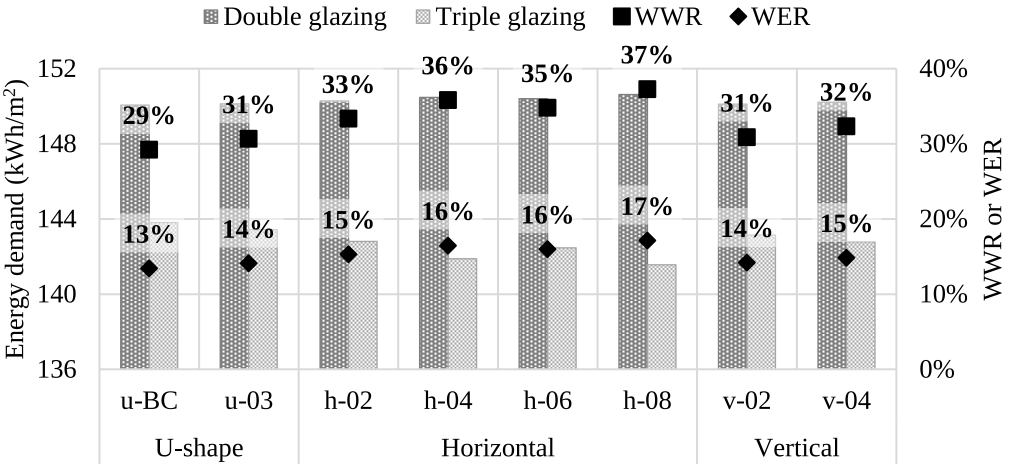


Figure 51: Building's energy demand (kWh/m^{2}yr) for different shapes.

As both the increase and reduction were not significant, it was suspected that instead of WWR, the window-to-envelope ratio (WER) should be examined. It was found that the WER of different variations varied between 13% and 17%. The largest WER increase can be found in h-08, which also had both the largest increase and reduction for double and triple glazing windows respectively.

To continue with the next stage, one best results for each window shape was selected for further examination. However, the selection was made according to the daylight results rather than the energy results since changes in the energy demand were not significant. The selected cases are: 1) u-03 for u-shape, 2) h-08 for horizontal, and 3) v-04 for vertical. It was also decided to only use double glazing window for the next stages onward as the triple glazing window had low visual transmittance that led to low daylight results.

6.2.2 Stage-2: Feasible shape for side-lighting

According to the results of stage-1, the change in window shape did not yield a significant increase in building energy use. Further simulations for a 240 m^2 room in four cardinal orientations were conducted for u-03, h-08, and v-04 in comparison to u-BC. These simulations were conducted using four different methods: 1) steady state calculations, 2) simulations with ParaSol, 3) simulations with EnergyPlus with no sun, and 4) EnergyPlus with sun.

6.2.2.1 Calculations without solar gains for first floor

Steady state calculations were compared in terms of heating demand to EnergyPlus simulations without sun, see Figure 52. It was assumed that different orientations would not give different results as no solar gains were taken into account in these simulations. However, the figure will still show results from different orientations for validating purpose.

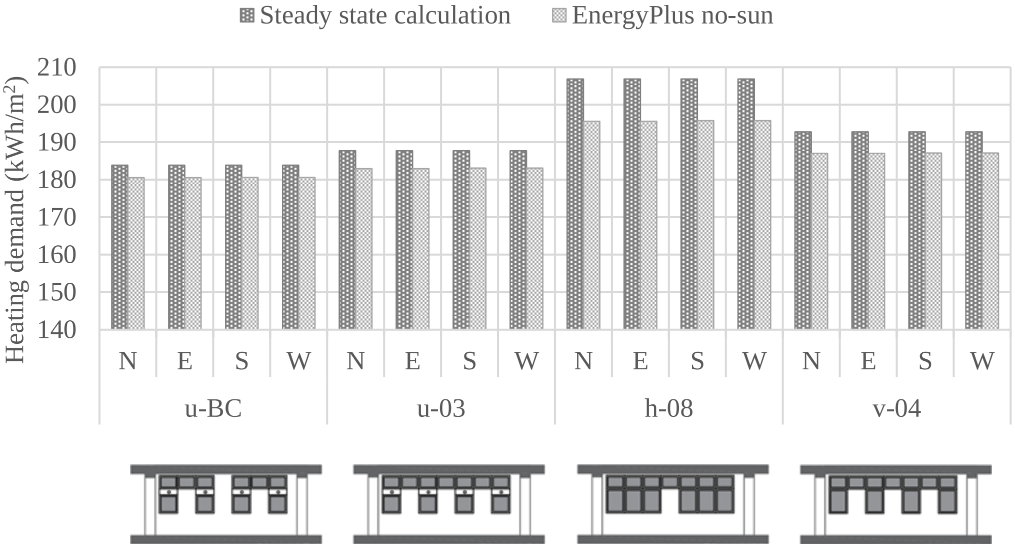


Figure 52: Heating demand (kWh/m^{2}yr) for no-solar based simulations.

In general, a relative difference of less than 10% is observed between steady state and energy simulations, which is a sign of reliability. The results of EnergyPlus were generally lower than a simple steady state calculation which can be explained by the difference in outdoor temperature used in each methods. The u-BC which had the smallest glazing area obtained the lowest heating demand, followed by u-03, v-04, and h-08. In u-BC where the smallest difference occurred, the steady state calculation resulted in 183.9 kWh/m^2 while EnergyPlus resulted in 180.6 kWh/m^2.

6.2.2.2 Calculations with solar gains for the first floor

A comparison of heating demand results between two different calculation methods was made using ParaSol and EnergyPlus with sun, see Figure 53. As both methods took solar radiation into account, the results of cooling demand can also be obtained (Figure 54). An obvious difference in comparison to the results without solar gains can be seen.

From the simulation results, it can be observed that both heating and cooling demand results were different for each orientation. In general, ParaSol obtained lower heating demand in comparison to EnergyPlus, except on the south orientation of h-08. On the contrary, for cooling demand results, ParaSol obtained much higher results from EnergyPlus, which can be explained by differences in the way solar radiation is calculated in each program.

The results of the heating demand in all orientations and shapes ranged from 126.3 kWh/m^2 to 158.2 kWh/m^2 for ParaSol. On the other hand, EnergyPlus results varied between 129.6 kWh/m^2 and 165.0 kWh/m^2. In all shapes, the heating demand showed the highest results in the room towards the north orientation and in contrast, the lowest heating demand was obtained in the room towards the south orientation. The highest heating demand for both methods can be seen in h-08, north direction. And the lowest heating demand was obtained in u-BC, south direction and h-08, south direction for ParaSol and EnergyPlus respectively.

Looking at the cooling demand, the difference between the results obtained from ParaSol and EnergyPlus were rather drastic. Note that the cooling demand in all shapes were considered low with the numbers ranging from 0 kWh/m^2 to 6 kWh/m^2. ParaSol showed more varied results ranging between 0.1 kWh/m^2 and 6 kWh/m^2. On the other hand, EnergyPlus obtained cooling demand ranged from 0 kWh/m^2 to 0.9 kWh/m^2.

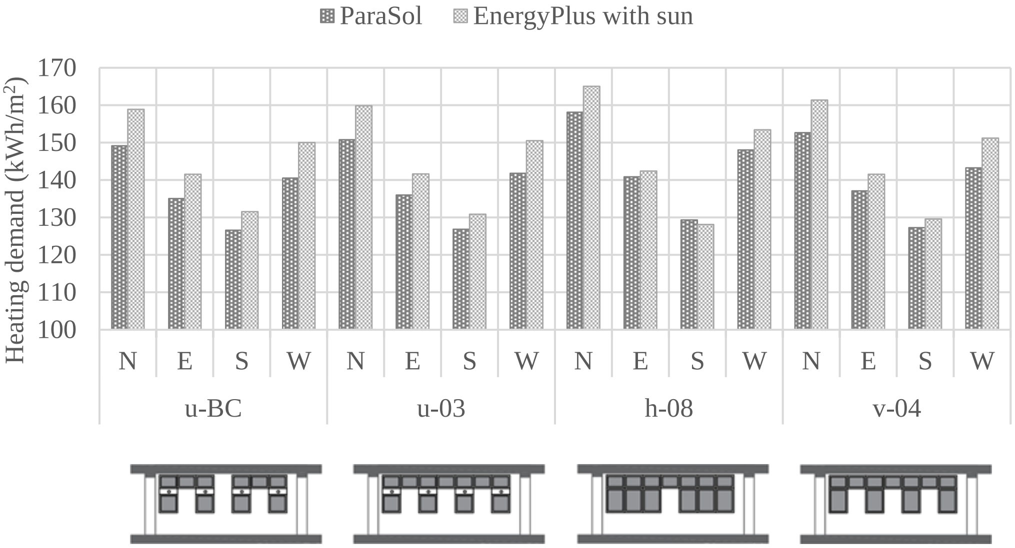


Figure 53: Heating demand (kWh/m^{2}yr) for solar based simulations.

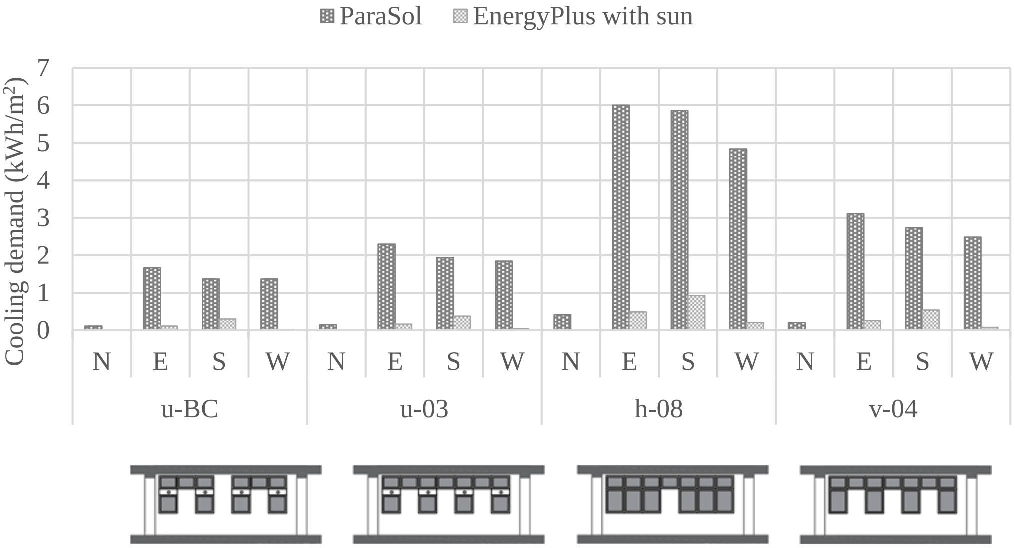


Figure 54: Cooling demand (kWh/m^{2}yr) for solar based simulations.

After seeing the results from both heating and cooling demand, the results for the energy demand were analyzed (Figure 55). The results obtained from EnergyPlus showed larger energy demand in comparison to the results from ParaSol simulations, except for the east and south orientation of h-08. The largest difference can be seen in u-BC north direction with 149.3 kWh/m^2 from ParaSol and 158.9 kWh/m^2 from EnergyPlus. On the other hand, the smallest difference were obtained with v-04 south direction (130 kWh/m^2 and 130.2 kWh/m^2 for the results obtained from ParaSol and EnergyPlus respectively).

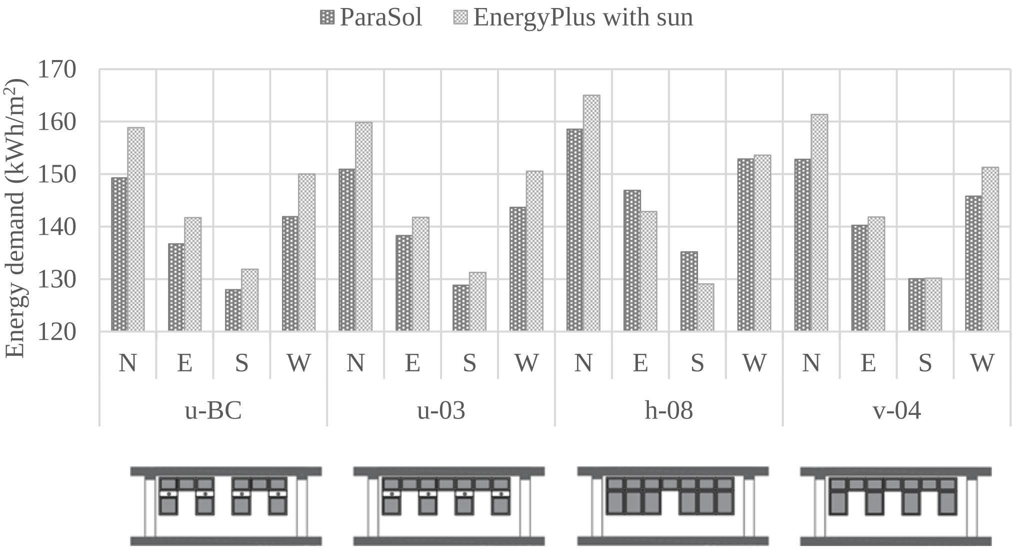


Figure 55: Energy demand (kWh/m^{2}yr) for solar based simulations.

From these results, it was deduced that both methods were comparable to each other, meaning that the model was sufficiently reliable to proceed with the next stage of the study.

6.2.2.3 Calculations with solar gains for both floors

Different effects on the heating and cooling demand can be seen according to each orientation (Figure 56). Four different shapes will be examined: 1) u-BC, 2) u-03, 3) h-08, and 4) v-04. Figure 56 shows the proportion of both heating and cooling demand for different shapes and orientations. The results are presented as total of heating and cooling demand on both floors.

On the north side, there was no cooling demand for any of the four shapes. In contrast, on the rooms towards the south orientation, a cooling demand occurred for all window shapes. Especially on v-04, where the cooling demand was actually larger than the heating demand. On both east and west orientations, the cooling demand increased and reduced in proportion to the glazing area.

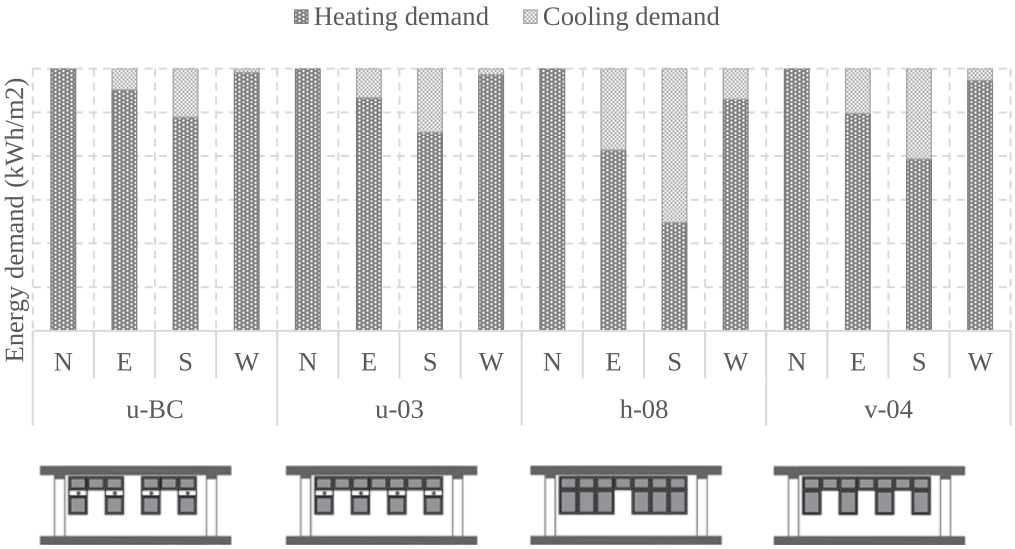


Figure 56: Effect of heating and cooling energy demand (kWh/m^{2}yr) for different orientations.

The results for heating and cooling demands were then compared to the WWR, see Figure 57 and Figure 58, which show both heating and cooling demand on the first and second floor as a function of WWR.

On the first floor, both heating and cooling demands increased as the WWR increased. The heating demand ranged from 144.9 kWh/m^2 to 145.7 kWh/m^2, and the cooling demand did not exhibit a significant variation. However, on the second floor, as the WWR increased, the heating demand was rather constant i.e. between 155.1 kWh/m^2 and 155.3 kWh/m^2 while the cooling demand increased from 0.05 kWh/m^2 with the smallest WWR to 0.2 kWh/m^2 with the largest one. Clearly, there was a distinct difference for both heating and cooling demand between the first and second floor. On the first floor, the heating and cooling demand were lower in comparison to the demand on the second floor. This happened because the second floor had more envelope area (external wall and roof) in comparison to the first floor (only external wall).

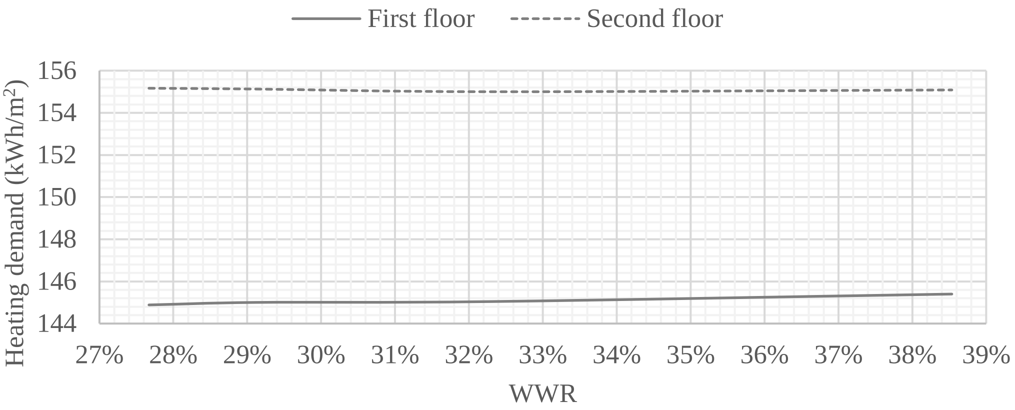


Figure 57: Heating demand (kWh/m^{2}yr) based on WWR.

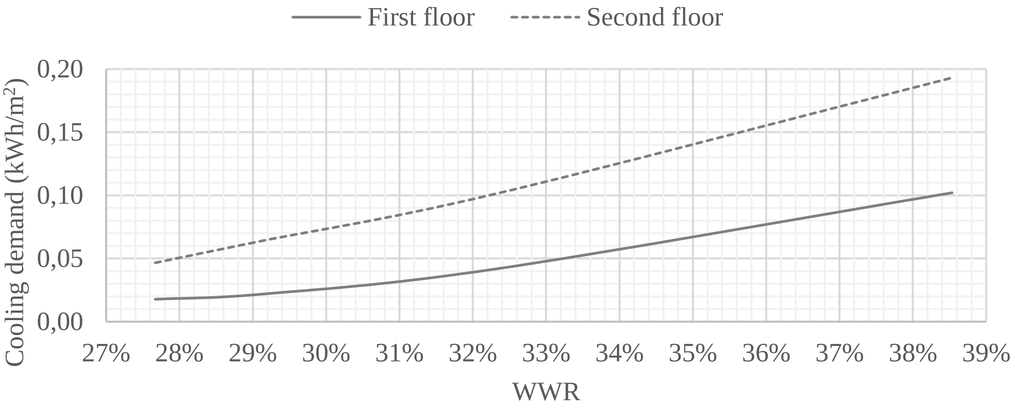


Figure 58: Cooling demand (kWh/m^{2}yr) based on WWR.

6.2.2.4 Calculations with solar gains for the whole building

To determine which shape would be further examined, u-BC, u-03, h-08, and v-04 were compared to each other (Figure 59). Information about variations of the WWR and WER on each shape was also included. u-03, h-08, and v-04 experienced a slight increase in energy use compared to u-BC. However, separation of the heating and cooling demand showed a different trend between all shapes. The heating demand between all shapes increased in the same manner with respect to the total energy consumption, which were: 1) 155.1 kWh/m^2 heating demand and 0.1 kWh/m^2 cooling demand in u-03, 2) 155.3 kWh/m^2 heating demand and 0.2 kWh/m^2 cooling demand in h-08, and 3) 155.1 kWh/m^2 heating demand and 0.1 kWh/m^2 cooling demand in v-04. h-08 experienced the highest rise in the building's total energy consumption. However, as the daylight study showed the best result in h-08, it was decided to use this shape for further examination.

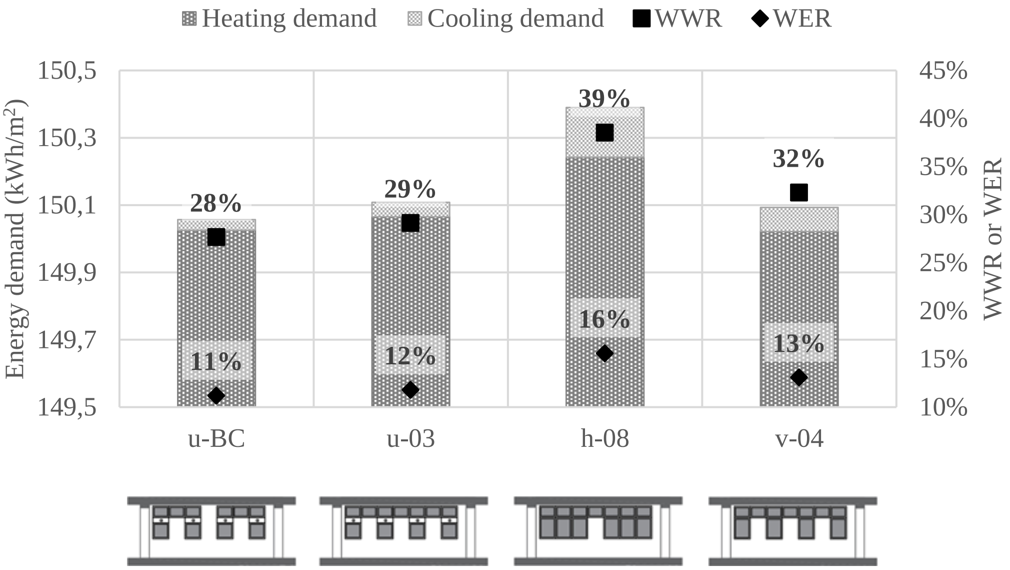


Figure 59: Total energy demand (kWh/m^{2}yr) for different shapes.

6.2.3 Stage-3: Reasonable width for side-lighting

From stage-2, the total width of h-08 (which will be referred as w-BC) was altered. The width for w-BC was 2.7 m and the total height to the clerestory sill was 2 m. Four variations were examined. The first variation (width-01) had the same width as w-BC; the difference was only on the height where the window sill was moved to 0.9 m instead of being kept constant at 1.1 m, resulted in a total height (until the clerestory sill) of 2.2 m. The width variations were then determined as: 1) width-01 (w-01) with 2.7 m, 2) width-02 (w-2) with 2.85 m, 3) width-03 (w-03) with 3 m, and 4) width-04 (w-04) with 3.15 m. The height kept constant at 2.2 m.

6.2.3.1 Calculations without solar gains for the first floor

Figure 60 shows the heating demand obtained from calculations that did not take solar radiation into account. Just like the results of stage-1, the orientation had no effects on the heating demand. Starting from w-01 to w-04, the glazing area increased with an increment of 2%. The heating demand increased accordingly. In all width variations, steady state calculations always obtained higher values in comparison to EnergyPlus simulations since each methods had a specific way to handle the outdoor temperature in the calculations.

The smallest difference obtained in w-BC east orientation, with a heating demand of 206.9 kWh/m^2 and 195.5 kWh/m^2 for steady state and EnergyPlus calculations respectively. On the other hand, the largest difference was obtained with w-04 north orientation (223.5 kWh/m^2 for steady state and 202.7 kWh/m^2 for EnergyPlus calculations respectively). It was deduced that with the larger glazing area, the difference between two methods was also logically larger but similar in proportion.

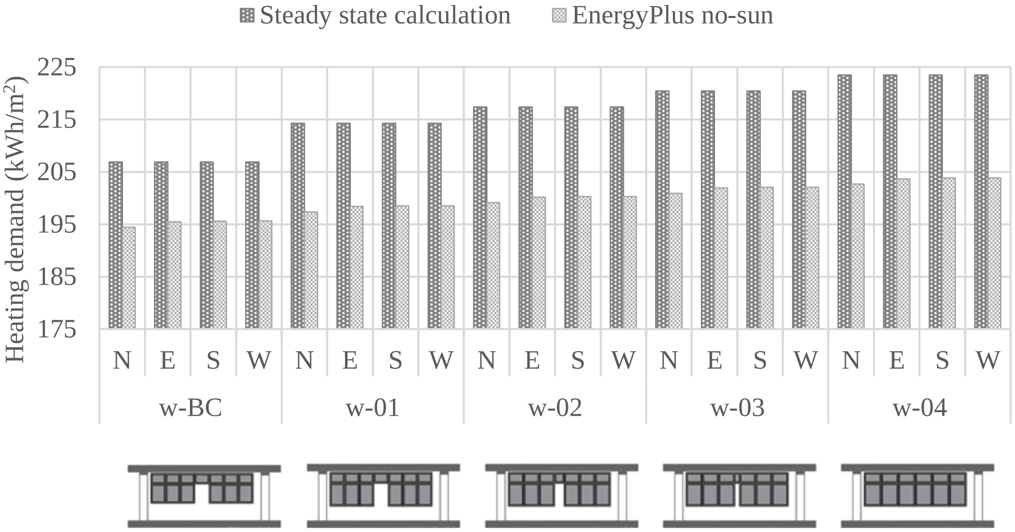


Figure 60: Heating demand (kWh/m²yr) for no-solar based simulations.

6.2.3.2 Calculations with solar gains for the first floor

In the same manner as in the previous section, both heating (Figure 61) and cooling demands (Figure 62) with sun exhibited a gradual increase with the increase in glazing area. This was observed for results obtained from ParaSol and EnergyPlus. However, a difference between the two methods was visible. As the glazing area increased, the difference between the two calculation methods became smaller.

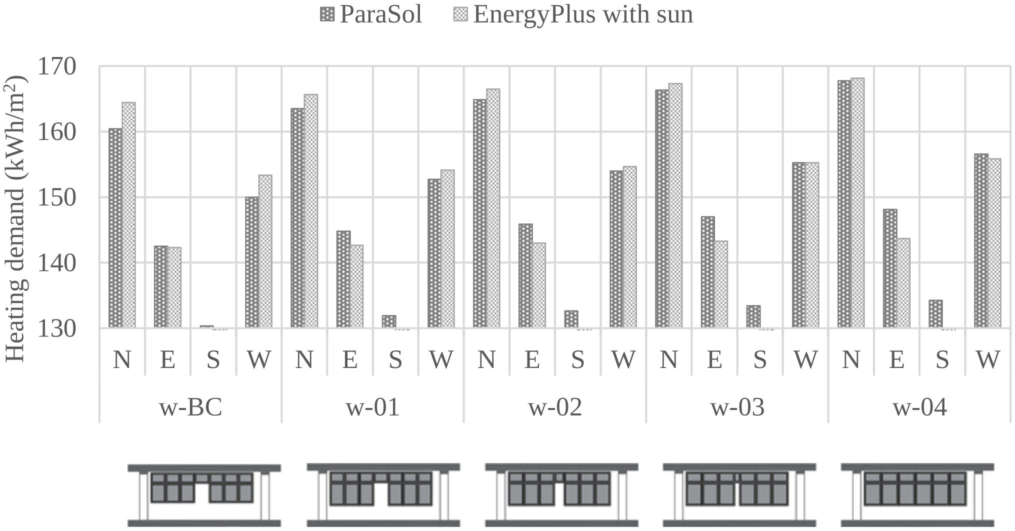


Figure 61: Heating demand (kWh/m²yr) for solar based simulations.

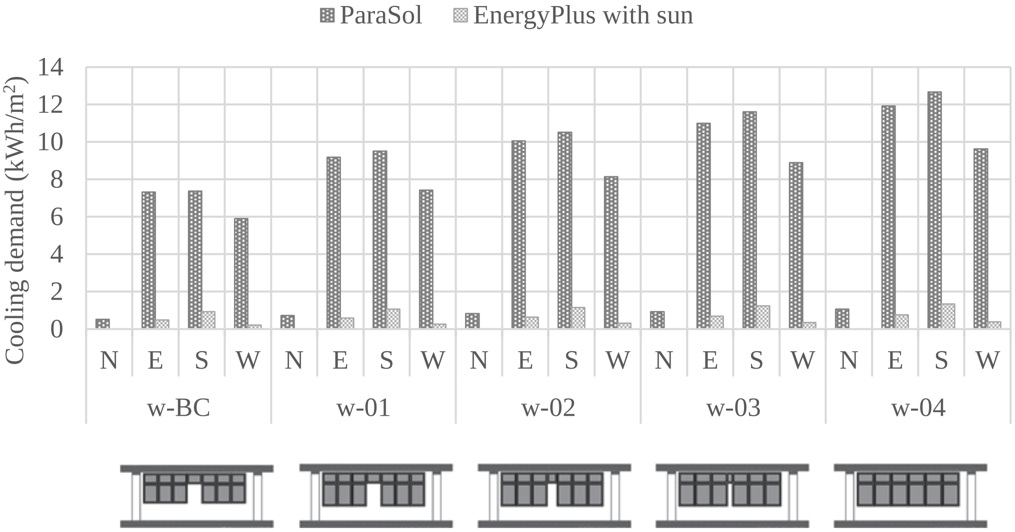


Figure 62: Cooling demand (kWh/m^{2}yr) for solar based simulations.

For the heating demand, the largest difference was obtained with w-04, south orientation with 134.3 kWh/m^2 for ParaSol and 127.5 kWh/m^2 for EnergyPlus. On the other hand, the smallest difference was obtained with w-03, west orientation with 155.3 kWh/m^2 for both methods.

For the cooling demand, the two methods yielded a large differences. The largest difference was ten times higher in ParaSol compared to EnergyPlus. ParaSol hangles solar gains in a more detailed way compared to EnergyPlus[1]. However, note that the cooling demand was relatively small ranging from 0 kWh/m^2 to 12.7 kWh/m^2. ParaSol returned higher cooling totals in comparison to EnergyPlus for all width variations.

The results for the energy demand were also examined, see Figure 63. The north direction resulted in the lowest difference of energy demand between the two methods, which could be due to the near absence of sun on this facade. In contrast, the south orientation returned the highest difference, most probably because of the difference in calculation of solar gains. It was also observed that at this stage, the total energy demand increased linearly as a function of glazing area.

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[1] *the sun position is calculated more often and angle-dependent solar transmission properties are calculated in detail.*

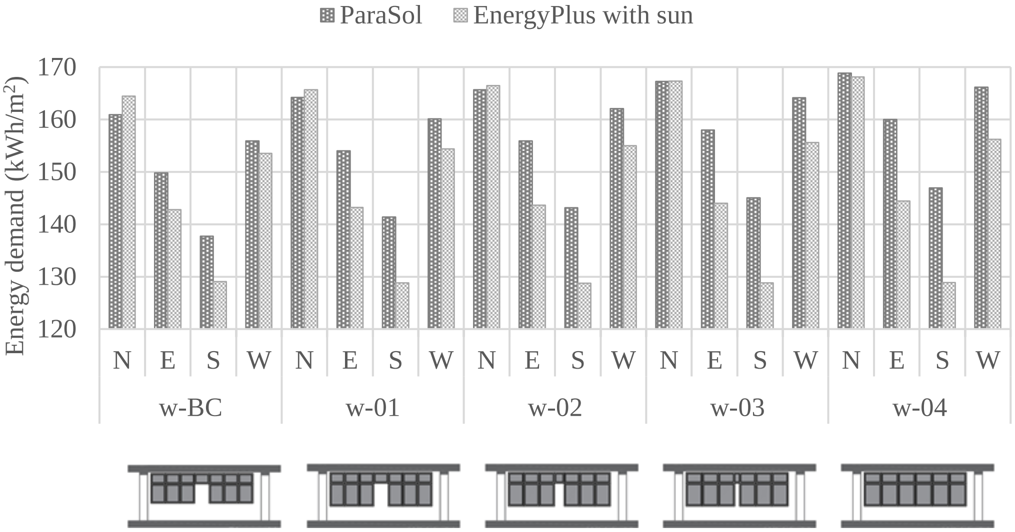

Figure 63: Energy demand (kWh/m^{2}yr) for solar based simulations.

However, from the results, we concluded that both returned relatively close results, which gave confidence in the methodology.

6.2.3.3 Calculations with internal solar gain for both floors

In the same manner as the previous stage, a 240 m^2 room was oriented towards four cardinal directions. The results can be seen in Figure 64. Similarly as before, the windows facing the north direction did not have any cooling demand. In contrast, the rooms towards the south orientation had the highest cooling demand. The windows placed on the east orientation showed a larger proportion of cooling demand in comparison to the windows towards the west. As the width increased, the proportion of the heating demand reduced and the cooling demand increased.

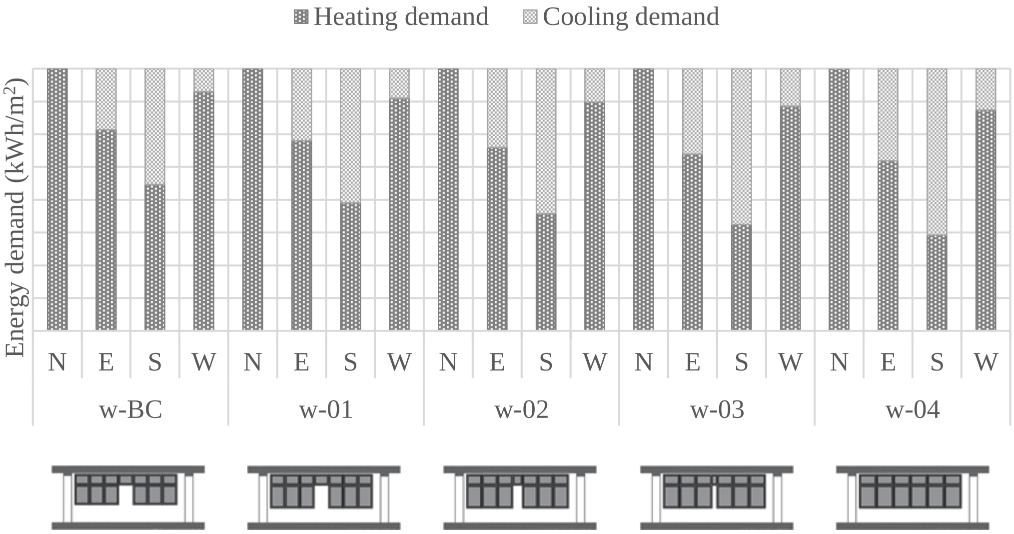

Figure 64: Effect of window width on heating and cooling energy demand (kWh/m^{2}yr) for different orientations.

The results for heating and cooling demands with respect to WWR can be seen in Figure 65 and Figure 66. On the first floor, the heating demand increased slightly as the WWR increased . However, on the second floor, the heating demand was rather constant although the WWR increased. On the other hand, the cooling demand showed a parallel increase on both the first and second floor along with the increase in WWR. For both heating and cooling demand, the second floor had higher demand in comparison to the first floor.

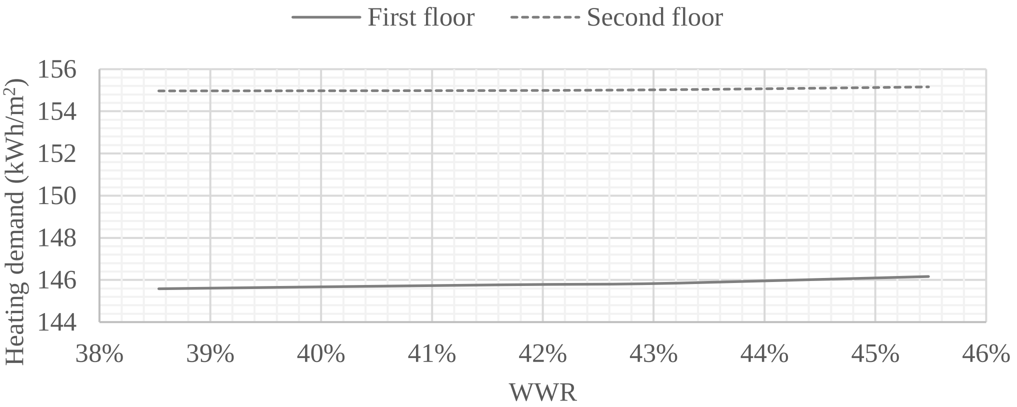

Figure 65: Heating energy demand (kWh/m^{2}yr) as a function of WWR.

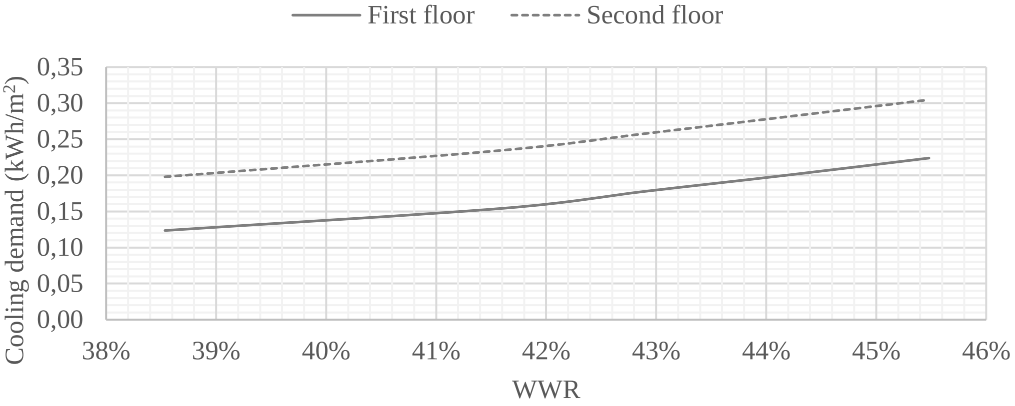

Figure 66: Cooling energy demand (kWh/m^{2}yr) as a function of WWR.

6.2.3.4 Calculations with internal solar gain for the whole building

A comparison of w-BC with w-01, w-02, w-03, and w-04 were conducted and the results are presented in Figure 67. The difference between the increase of the WWR and WER was visible. The figure showed a parallel increase in the total energy demand in relation to the increase of both WWR and WER.

Examining the building's energy demand, in comparison to w-BC that had 150.4 kWh/m^2, the energy demand increased to: 1) 150.6 kWh/m^2 for w-01, 2) 150.6 kWh/m^2 for w-02, 3) 150.8 kWh/m^2 for w-03, and 4) 150.9 kWh/m^2 for w-04. As the energy demand did not increase significantly in all width variations, it was decided to pick the width with both the least and the most increase for the combination with the top-lighting option in stage-5. According to that, w-01 and w-04 were used for the examination in stage-5.

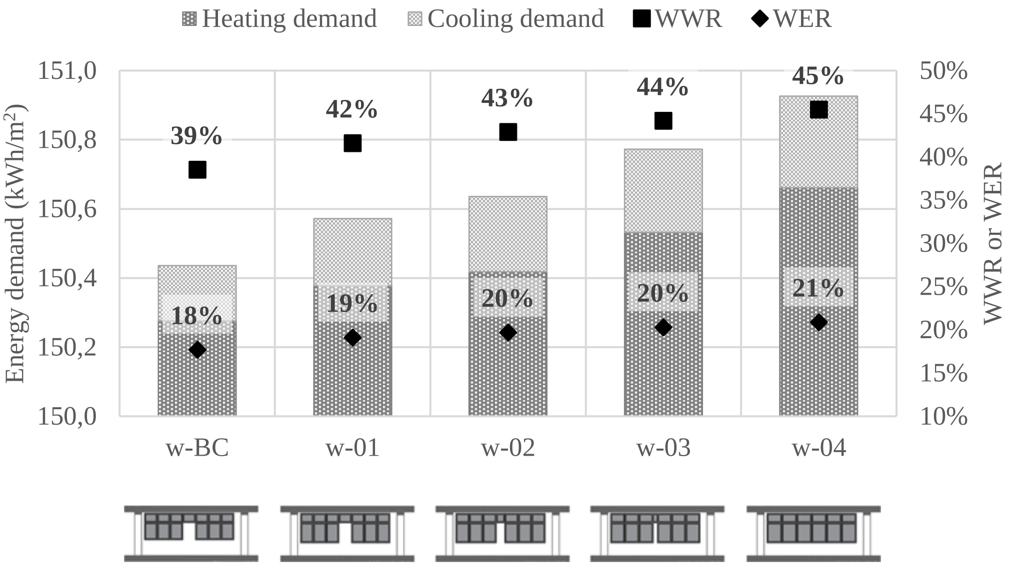

Figure 67: Total energy demand (kWh/m^{2}yr) for different widths.

6.2.4 Stage-4: Top-lighting

Regarding top-lighting, a total of 13 combinations taking into account different skylight shapes, orientations, tilt angles, and SFR were investigated. As stated previously in the methodology chapter, the SFR did not differ for most of the cases, except for t-12 (sloped-S, 15°). This case was created by extending the hole of the skylight in the floor slab, so that the edge of the hole reached the wall in line with the HVAC system area. The results for the building's energy demand with different types of skylights can be seen in Figure 68. Note that this figure shows the results of energy demand in the whole building without any side-lighting; the cooling demand is so small in comparison to the heating demand that it is hardly visible on the graph.

Looking at the results for different orientations and tilts in sloped skylight, it can be seen that sloped skylight towards the south orientation experienced the largest reduction in comparison to other types of skylight. However, only the 15° tilt were examined for larger SFR for aesthetic reasons. While changing the SFR from 4% to 6%, the energy demand for sloped-S, 15° decreased from 245.2 kWh/m^2 to 241.4 kWh/m^2.

With different types of skylights and orientations, the energy demand diminished in comparison to t-BC. The largest reduction occurred with t-BC yielding 247.7 kWh/m^2, which decreased to 241.4 kWh/m^2 with t-12. However, the cooling demand, which was low (0 kWh/m^2 to 0.1 kWh/m^2), remained unchanged between different types of skylights. From this result, t-12 was selected as best alternative to be combined with w-01 and w-04 in stage-5.

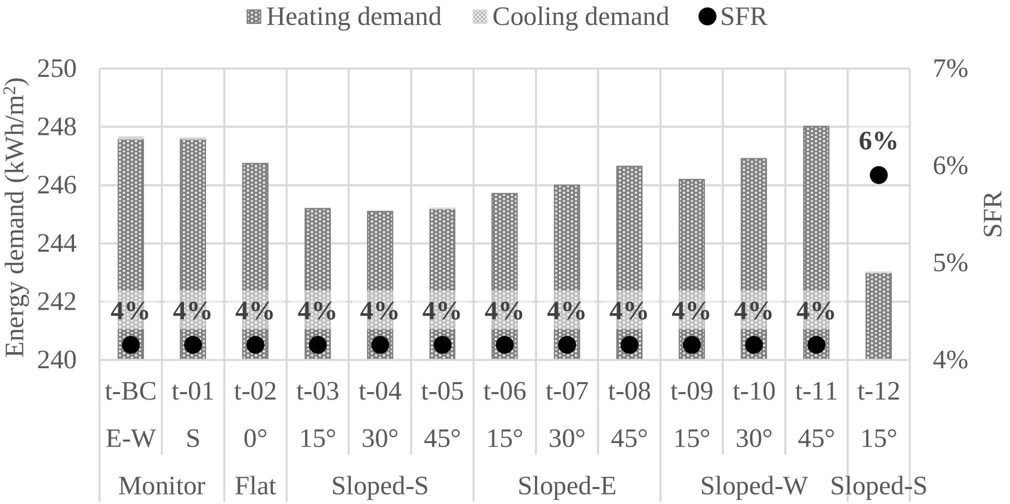

Figure 68: Total energy demand (kWh/m^{2}yr) for different skylights.

6.2.5 Stage-5: Combination of side-lighting and top-lighting

From previous stages, several simulations to determine the best performing side-lighting and top-lighting strategies were performed. Cases w-01 and w-04 were combined with toplight-12. An additional insulation layer was added to the external wall and roof to compensate for extra heat losses of larger glazing areas. The results for energy demand of the base case (BC), combination-01 (w-01 and t-12), and combination-02 (w-04 and t-12) can be seen in Figure 69. Note that, although the previous stages had no internal gains, the simulations conducted in stage-5 took into account the internal gains such as equipments, lighting load, people, and ventilation rates. Initially, a proper temperature schedule based on the building's occupancy hours and real conditions were also applied to the simulation model. In general, this resulted in a significantly lower energy demand.

Increasing the WWR, WER, and SFR of the building created an increase in the energy demand. In comparison to BC, the heating demand increased from 39.6 kWh/m^2 to 43.1 kWh/m^2 for combination-01 and to 43.9 kWh/m^2 for combination-02. The cooling demand also exhibited an increase from 13.2 kWh/m^2 for BC to 16 kWh/m^2 and 16.1 kWh/m^2 for combination-01 and 02 respectively.

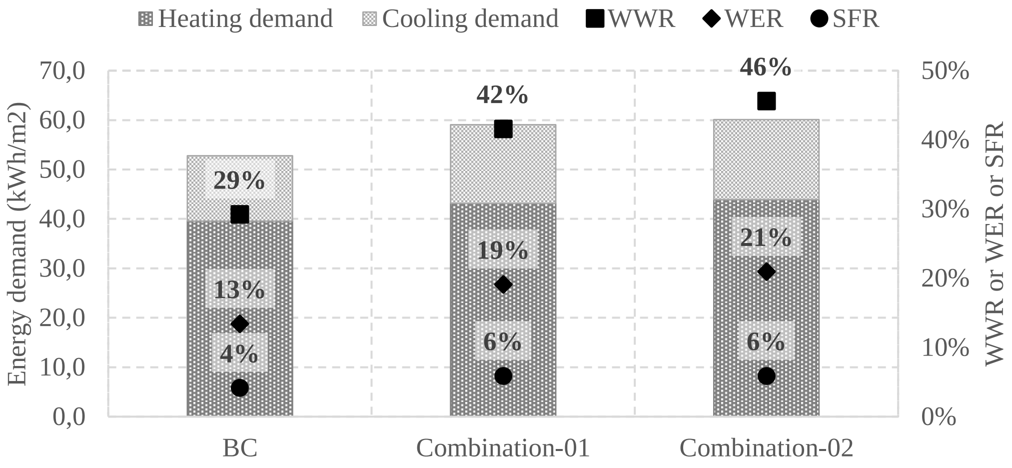

Figure 69: Total energy demand (kWh/m^{2}yr) for different combinations of side-lighting and top-lighting.

To compensate the increase in energy demand, one more insulation layer was added to the external walls and roof. The results are presented in Figure 70.

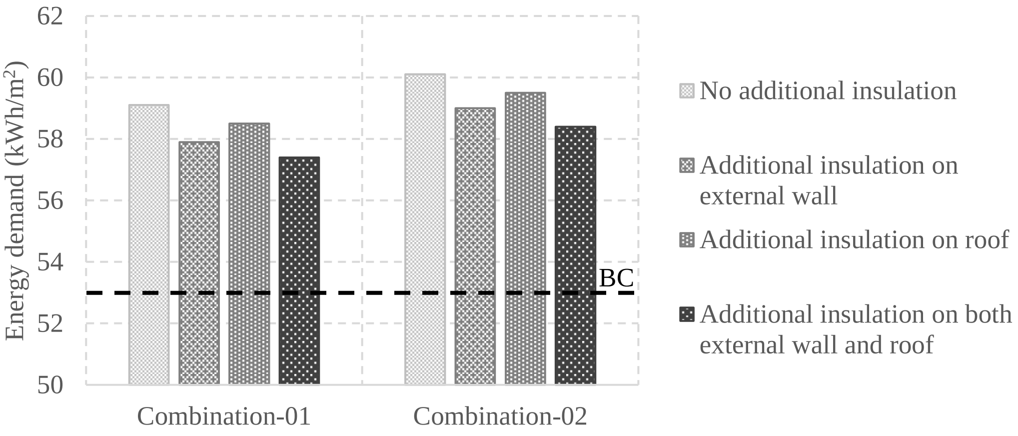

Figure 70: Total energy demand (kWh/m^{2}yr) for different combinations with additional insulation.

The addition of one more insulation layer to the external walls in combination-01 reduced the energy demand from 59.1 kWh/m^2 to 57.9 kWh/m^2, and to 58.5 kWh/m^2 for added insulation to the roof. The reduction occurred in combination-02 in the same manner as combination-01. It was then deduced that adding one more insulation layer on the external walls was more efficient than adding it on the roof due to lower U-value on the external walls (0.13 W/m^{2}K) than the roof (0.2 W/m^{2}K). However, the largest reduction can be seen when the insulation layer was installed on both external walls and roof. The energy demand was reduced to 57.4 kWh/m^2 and 58.4 kWh/m^2 in combination-01 and 02 respectively. It needs to be mentioned that even with added insulation on both external walls and roof, the energy demand was still higher in comparison to BC. Perhaps a more efficient solution would be to use a three-pane glass assembly with a higher visual transmittance. This would limit the added energy use due to increased glazing that was obtained here with the double glazing.

6.3 Electrical lighting dependency

As mentioned in the methodology chapter, electrical lighting dependency was calculated using UDI$_{100-2000}$ for the whole floor area of the selected combinations. Nonetheless, the core of the building was not illuminated by daylight. It can be seen in Figure 71 for combination-01 and Figure 72 for combination-02, that the daylight only reached the area located at around 4 m to 8 m from the periphery for both first and second floors and both combinations. Thus, limited area in the periphery of both floors was excluded from the use of electrical lighting.

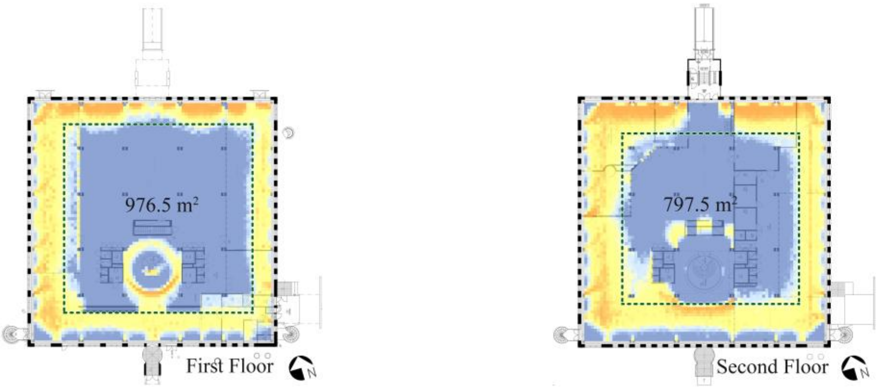

Figure 71: UDI$_{100-2000}$ for combination-01.

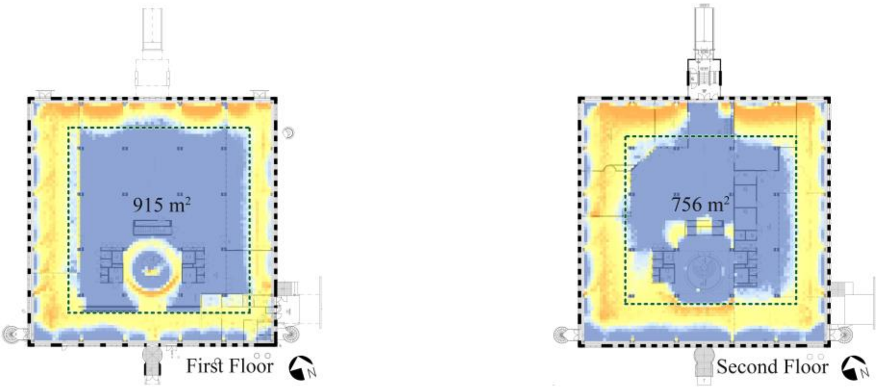

Figure 72: UDI$_{100-2000}$ for combination-02.

The results of $UDI_{100-2000}$ and the details about the building's occupancy hours and electrical lighting dependency from the existing lighting condition can be seen in Table 14. Based on the existing electrical lighting load of 8.5 W/m^2 and the fact that the electrical lighting considered on all the time during the operating hours, the annual lighting demand for the existing building was 78 336 kWh (24.5 kWh/m^2).

Table 14: $UDI_{100-2000}$, operational hours, and electrical lighting load.

	Combination-01	**Combination-02**
$UDI_{100-2000}$ in first floor	42%	43.5%
$UDI_{100-2000}$ in second floor	48%	49%
Annual operational hours	2880 hours	2880 hours
Electrical lighting load	8.5 W/m^2	8.5 W/m^2
The core area that needs to be lit for all the operational hours:		
● First floor	976.5 m^2	915 m^2
● Second floor	797.5 m^2	756 m^2
The peripheral area that needs to be lit for the remaining time of UDI percentage:		
● First floor	623.5 m^2	685 m^2
● Second floor	802.5 m^2	844 m^2

6.3.1 Combination-01

The $UDI_{100-2000}$ of combination-01 reached 42% on the first floor, meaning that the periphery on the first floor was illuminated within 100 – 2000 lux by daylight during 42% of the building's operational hours. Similarly, on the second floor, the daylight provided illuminance between 100 – 2000 lux for 48% of the annual occupancy hours for the peripheral area. The higher elevation favoured the second floor to fetch more daylight and higher UDI.

The results of calculation for the lighting demand for both first and second floor in combination-01 can be seen in Table 15. Based on the lighting calculation for the first and second floor, combination-01 still needed 19.5 kWh/m^2 annually for electrical lighting.

Table 15: Lighting demand calculation for combination-01.

Combination-01	**First floor**	**Second floor**	**Total energy demand**	**Total energy demand/floor area**
Lighting demand to be fulfilled in a year	32757 kWh	29738 kWh	62495 kWh	19.5 kWh/m²

6.3.2 Combination-02

The results for combination-02 showed $UDI_{100-2000}$ of 43.5% and 49% on the first and second floor respectively. This means that for the mentioned percentage and operating hours, areas in the building's periphery were illuminated with 100 – 2000 lux by daylight 43.5% and 49% for the time. According to the calculation in Table 16, combination-02 will need 19 kWh/m^2 of electrical lighting in one year. In comparison to the existing building, the electrical dependency of combination-02 was diminished.

Table 16: Lighting demand calculation for combination-02.

Combination-02	**First floor**	**Second floor**	**Total energy demand**	**Total energy demand/floor area**
Lighting demand to be fulfilled in a year	31874 kWh	29044 kWh	60918 kWh	19 kWh/m²

6.4 Combination of daylighting and building's energy consumption results

According to daylight level, energy use, and electrical lighting dependency, the differences between combination-01 and combination-02 were negligible. From combination-01 to combination-02, $sDA_{300,\,50\%}$ value increased from 32% to 35% and from 46% to 50% on the first and second floor respectively. The electrical lighting dependency of combination-02 decreased from 19.5 kWh/m^2 to 19 kWh/m^2 in comparison to combination-01, which is a negligible difference. On the contrary, the energy consumption increased from 59.1 kWh/m^2 to 60.1 kWh/m^2 in combination-02 with respect to combination-01, which is also a small difference. Nonetheless, combination-02 provided more continuous and better view out in comparison to combination-01. Therefore, considering all aspects, despite very small increase of energy consumption, combination-02 was evaluated as a generally better architectural solution providing much improved interior conditions and view out compared to the existing building. The authors believe that the small increase in energy demand could be compensated by other improvements in the mechanical system, with additional passive design measures or by adding an active solar system on the roof of the building. It is also worth to mention that the current building is clearly unsatisfactory in terms of view out and daylighting.

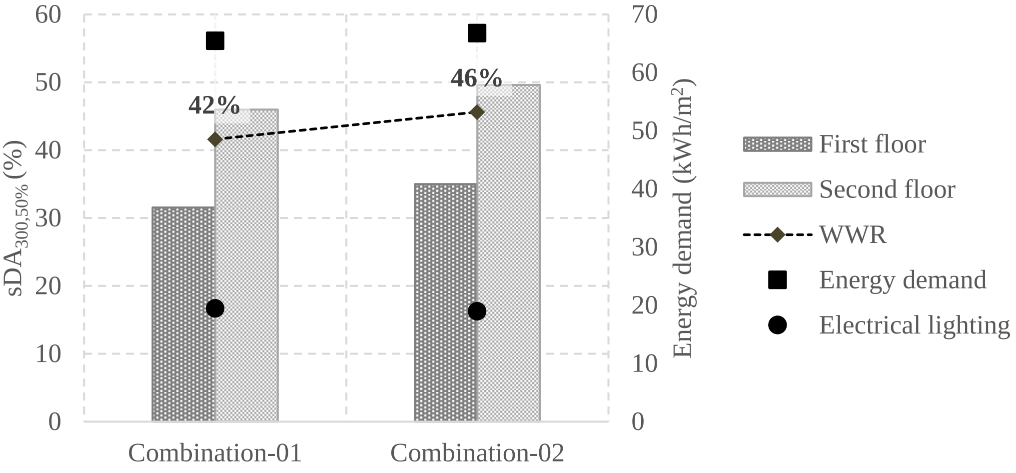

Figure 73: Daylight quantity sDA$_{300,\ 50\%}$ (%), total energy demand (kWh/m²) and electrical lighting dependency (kWh/m²) of combination-01 and combination-02.

7 Discussion

7.1 Daylight

7.1.1 Stage-1: Positions and glazing types for side-lit rooms

Among all 16 variations of double glazing windows studied, we found that continuous glazing solutions created a more significant impact on daylight level. To reach good daylighting levels, alterations such as- extra window pane was added, while gaps between windows and clerestories were removed and extra clerestories were added, which increased the WWR of the variations. Note that, along with the WWR, the position of the openings had an important effect on daylight level. For example, in stage-1, both h-05 and h-06 were modelled with a WWR of 35%. Yet, h-05 had an ADF of 0.37% whereas h-06 had an ADF of 0.42%, which was positioned 0.2 m higher than h-05. Therefore, the result indicates that a higher position helped to fetch more daylight and penetrate deeper towards the building core even with the same opening area, this finding is going in line with a study by Dubois et al. (2019). This feature was constant for all the simulation results.

7.1.2 Stage-2 & 3: Feasible shape and width for side-lighting

Looking at a 240 m² room, the shape and width variations presented similar effect with respect to the four cardinal orientations. For DDM results, climatic effect can be observed. The south facade provided the best results as the south was the most accessible orientation for sunlight naturally. However, low solar angle during the longer occupancy hours in the afternoon favored the west direction with increased sunlight in comparison to the east direction. On the north, the values were the lowest as this orientation received mostly skylight. In addition to climatic effect, the surrounding contextual elements, such as- adjacent buildings, sloped terrains, trees etc. created an impact which were clearly observed in SDM results. On the east orientation, the volume of the Computer Science Building along with the trees next to the facade reduced daylighting markedly. On the north orientation, obstructions were provided by higher sloped terrains. The south and the west facades were more open towards the sky in comparison to the north and east facades. Note that, on the second floor due to higher elevation the effects of the surrounding obstructions were slightly reduced, and a better level of daylight was achieved in comparison to the first floor.

On the first floor towards south orientation, type-3 windows with an area of 5.5 m² were replaced with type-1 windows of u-03 , h-08 and v-04 with the area of 3.4 m², 5 m² and 4 m² respectively. Surprisingly, the last two variations resulted in higher sDA and ADF values only by being positioned at 0.55 m higher. In short, to raise the amount of daylight quantity inside the building, larger windows were not necessarily needed on the south direction.

The view out provided by the proposed variations were providing more comfortable visual field with less obstructions as perceived from the sitting position studied. Note that all the shapes including the existing one allowed the view of at least two layers, namely- the sky and landscape in the visual field, which complied with the medium requirement for view out of Swedish Standard SS-EN 17037.

7.1.3 Stage-4: Different type, orientation and slope for top lighting

For the given building, sloped skylight towards south orientation undoubtedly outperformed the existing roof monitor towards east-west orientation as it helped to fetch daylight from the zenith and from lower angled sun. However, changing the tilt angle of the sloped skylight generated similar results due to similar glazing size, hole size and reflector area. The results also showed that by increasing SFR, it was possible to raise the daylight level proportionally. As shown in result chapter, except the circulation, this toplighting strategy could not make a considerable impact within the building. Yet, it is also important to provide sufficient daylighting in the circulation area. The toplight, t-12 resulted in $UDI_{100-2000}$ of 60% on the first floor circulation area which lessened the necessity for electrical lighting to a great extent on that zone. On the contrary, on the second floor, the circulation area appeared to be overlit as 75% of the time it was illuminated by more than 2000 lux, this might create an uncomfortable visual condition for the users.

7.1.4 Combination of side-lighting and top-lighting

Even with the best performing windows and skylight, daylight level was only increased close to the fenestration area but it was not possible to obtain deep daylight penetration where some of the critical zones were located. The three poorly lit zones resulted in very poor average DA_{90} which created a gloomy appearance and a continuous need for electrical lighting in these zones. Penetration of daylight to these darker areas could be possible by adding more top-lighting systems over the middle core of the building at the right position and in the right proportion. However, it was not possible due to the placement of existing HVAC service room on top of the roof. One suggestion would be to move the HVAC service room to the basement where half of the area is currently unused, so that there will be available spaces to install skylights. However, further research needs to be carried out first to ensure the feasibility of moving the HVAC room and to determine the ideal position and proportion of the skylights. Another possible solution can be a reorganization of the internal functions within the building. For instance, the mid study area can be replaced with the existing cafeteria and kitchen at the periphery of the building, as both functions occupy almost the same area (around 310 m²). The cafeteria and kitchen can be shifted to the basement as well. In addition, the computer space in the north periphery of the first floor can be moved to the middle zone and replaced with some part of the study areas, as diffused daylight is more preferable for reading and writing tasks compared to VDU works. In a similar manner, the conference room on the second floor can be replaced with the two underlit small study zones. Moving the conference room to the middle core area might still work as it is preferable to have darker ambiance there for projection. Appendix C shows an illustration of daylight level (DA_{300}) for the functions mentioned above.

Although daylight level improved by these two proposed combinations, uniformity could not reach to the satisfactory level within the functional zones in this research. Even with a good sDA or ADF value, uniformity could not be achieved due to the steep difference of daylight level between the area next to the fenestration and the area close to the core. This problem can also be solved by installing several smaller conical skylights at an appropriate distance, which is a popularly used method for libraries as mentioned in Chapter-2. To implement that method in the given building, further research is needed.

7.2 Energy consumption

7.2.1 Stage-1: Positions and glazing types for side-lit rooms

Based on the presented results, it was observed that the glazing position on the facade did not affect the building's energy demand. The energy demand was only affected by different glazing types, in this case double and triple glazing windows, and the glazing area (WWR in this case). Note that, this has a strong connection with the process the software calculate solar heat gains.

Although the WWR between each shape and position changed by approximately 6.1%, the increase in the building's energy consumption was considerably low, which was less than 0.5%. As the WER was calculated, it was found that the WER only increased by approximately 3.7%. It was then concluded that in this case, as the building envelope had more area in comparison to the external wall, WER should be used as the varying parameter when increasing the glazing area of the building instead of WWR. The results for the energy demand indicate that the energy demand follows the increase in WER very closely in fact.

Regarding the different window glazing types, changing the window from double to triple glazing resulted in a reduction between 4.2% – 6%. This might be the effect of the small difference in the WER between each shape and position. Another aspect that might have affected the condition was- the triple glazed window had lower SGHC in comparison to the double glazed window. This might have resulted in increased heating demand as the building received less solar heat gain.

7.2.2 Stage-2: Feasible shape for side-lighting

For simulations that did not take solar radiation into account, steady state calculations always returned lower results in comparison to EnergyPlus with no sun. This can be explained by the fact that steady state calculation used an average of outdoor temperature in one year. On the other hand, EnergyPlus used the hourly outdoor temperature that was generated by the weather file (8760 hourly values annually).

For the solar-based simulations, ParaSol simulated glazing area as one big area instead of following the windows' actual size as in EnergyPlus. This resulted in different way of calculating the periphery of the glazing area between both methods. Different periphery length will result in different thermal bridging which can give a significant effect towards the heating and cooling demand.

While looking at the effect of window shape on the heating and cooling demand in a smaller room, it was observed that both the heating and cooling demand reacted differently in each orientation although the same window shape and position were used. It was found that on the north orientation, the heating demand was the highest with no cooling demand regardless of the window shape. In the room that was facing towards the east, the heating demand dropped drastically, while the cooling demand went up with increased glazing area. The heating demand diminished the most on the south orientation and in contrast, the cooling demand had the largest increase with increased glazing area. On the west orientation, the heating demand was lower in comparison to the north, but higher in comparison to both the east and the south. In contrast, the cooling demand yielded as the heating demand diminished. Looking at these results, it was deduced that both the heating and cooling demand in each direction were complementing each other. This could explain why the energy consumption did not vary much in stage-1.

Comparing the WWR with both the heating and cooling demand, it was found that the energy consumption increased as a function of WWR. Also, the energy demand on the second floor was higher in comparison to the energy demand on the first floor. Looking at the building envelope, the first floor had less envelope, as it only had the external walls. Meanwhile, the second floor had both the external walls of the same size as the first floor, and the roof. This caused the second floor to have more thermal transmission towards outside, which leads to more energy demand both for heating and cooling. In reality, it would be like this since heat from the first floor would be lost towards the second floor, but this could not be observed here as adiabatic surfaces were used in the first floor model. This demonstration strengthened the finding in stage-1 that WER should be used instead of WWR as the varying parameter in this type of project.

Both findings in stage-2 were also applicable in stage-3. In that case, the discussion will move forward directly to stage-4.

7.2.3 Stage-4: Top-lighting

Regarding the different top-lighting strategies in stage-4, the results of the energy consumption were rather unexpected. The initial hypothesis was that larger top-light area should result in an increase in energy demand as more heat was lost towards the sky. However, the simulation results showed a reduction in the energy consumption as the glazing size increased depending on the skylight type and tilt. It was found that different tilt angles did not significantly affect the energy demand. From the obtained results, it was deduced that in this project, passive solar heat gains contributed significantly to the overall heating demand.

7.2.4 Stage-5: Combination of side-lighting and top-lighting

According to the results obtained from stage-5 simulations, both combination-01 and combination-02 resulted in an increase in energy demand. Adding one more insulation layer in both the external wall and the roof yielded the smallest increase in energy use compared to the base case. However, the difference between the added insulation and no additional insulation were lower than 4% for both combinations. Some LCC calculations might be needed to decide if it is worth to install an additional insulation layer. In addition, MAX IV in Lund has a lot of equipment that produces excess heat. The equipment is connected to a cooling system with both heat exchangers and heat pumps. With this system, it is planned that the excess heat will be transferred to the district heating system in Lund (MAX IV, 2019). This might make the issue of heating relatively less important than i.e the issue of electric lighting in the future.

7.3 Electrical lighting dependency

The electrical lighting dependency results were quite predictable from the daylight results. Energy demand for lighting was reduced to around 5 kWh/m^2 in the improved combinations from the existing combination. Although daylight contributed to lessen the electrical lighting uses only in the peripheral areas, the overall annual decrease of energy demand for lighting can be considered as a significant advantage of improved daylighting.

8 Conclusions

This thesis investigated how WWR, WER, SFR, surrounding environment, and orientations will affect the daylight condition and energy demand in LTH Studiecentrum which is located in Lund, Sweden. This building is compact and considered too enclosed regarding outdoor view. The study was guided by three main questions: 1) The ideal position, shape, and width for the side-lighting strategy, 2) The effect of current top-lighting position and condition towards the overall daylight level, and 3) The increase on both heating and cooling demands after increasing WWR, WER, and SFR. It was predicted that increasing WWR and WER for the side windows would improve the daylight level inside the building. However, since the size of the toplight was increased only to a small extent, no significant effect were expected. Following the daylight level, both heating and cooling load were also predicted to increase as WWR, WER, and SFR increased. In addition, the research also showed that, by improving daylighting energy demand for electrical lighting can be reduced to a considerable extent.

Considering the questions and hypotheses mentioned above, it could be concluded that:

- In daylighting, different vertical position for windows; i.e. window sill placed at 1.1 m and 0.9 m; obtained different results. Windows placed on higher position obtained higher daylight level. This did not apply to energy simulation in our case (using EnergyPlus). However, this depends on how the energy softwares calculate the solar heat gains during the simulation.
- Adding more clerestory in between two columns proved to increase the daylight level in all shapes.
- Providing more continuous glazing area; i.e. by removing extra window pane from u-shape and by removing the gap between side-window and clerestory enhanced the daylighting level to a great extent. Moreover, with continuous glazing the quality of the view out improved significantly as well.
- By improving the side-lighting and top-lighting at the current position, the desired daylighting was not achieved in all the parts of the building. Only the functional zones near the fenestration areas achieved improved daylighting but not the core areas of the building.
- To improve the daylighting in all the parts further improvement would be needed for the top-lighting.
- Uniformity of light is an important factor to ensure visual comfort which was not possible to achieve in a desired level with the suggested improvements. Additional skylights and task lights might improve the condition. However, further research will need to be conducted for this part.
- While conduction energy simulations with different methods, it is important to know how the software calculates the inputs, i.e. average outdoor temperature, solar radiation, and perceived geometry based on the modelling.
- As WWR and WER increased, energy demand increased as well. This is true for both heating and cooling. However, in this case WER should be used as the varying

parameter because the building envelope had more area in comparison to the external wall.

- Changing the window from double to triple glazing allows reduction below 10% for energy demand. This occurred because of lower SGHC value in triple glazing windows that resulted in increased heating demand as the building received less solar heat gains.
- For both heating and cooling demands, different orientations had different effects. In this case, they were complementing each other that resulted in insignificant changes in the total energy demand.
- In this study, the results from top-lighting simulation did not go in line with the hypothesis. However, passive solar heat gains was found to bring a significant contribution to the overall heating demand.
- Adding more insulation on the building envelope only resulted in a small reduction in energy use. Some LCC calculation might be needed to decide if it is worth to install an additional insulation layer.
- As the daylight level increased, the energy demand increased as well. However, the electrical lighting dependency experienced a reduction. At a certain point, this could balance out the increased building energy use.
- Combination-02 (w-04 and t-12) was considered as the most reasonable solution in this study despite of the increased energy demand. However, both the daylight level and occupant’s access towards the view out experienced dramatic improvement.

This research made a more humane approach towards sustainability by creating more lively and healthy indoor environment and providing more connectivity with outdoor environment for the users. Reduction in energy demand actively leads a building towards sustainability, but this study showed a passive way to achieve sustainability by improving users productivity.

Limitations and future studies

This thesis project was focused on enhancing the daylight level of a compact building (LTH Studiecentrum) in Lund, Sweden. Although a thorough study was done on energy demand, selections were based on daylight results.

In the research, more concentration was given towards side-lighting strategies than top-lighting strategies. Due to the current position and condition, potential solutions of top-lighting strategy could not be explored. However, some practical considerations were missing in the methodology, such as available window size in the market.

For daylight results, as the building was considered compact, only side-lighting was not be sufficient to reach the desired daylighting level. Consequently, most of the zones managed to comply with the daylight requirement from Miljöbyggnad, BREEAM-SE, and Swedish Standard SS-EN 17037, but few could not at all. However, the daylight uniformity was nowhere near the requirement. To enhance daylight uniformity and overall daylight level in all zones, future studies focusing on the top-lighting strategies need to be conducted.

Regarding the energy investigation, triple glazing windows were not investigated further as the daylight level diminished significantly due to low visual transmittance (0.4). However, in the market nowadays, triple glazing windows with visual transmittance of 0.69 (spectrally selective) exists. Using double glazing, the increase on the energy demand as WWR and WER increased could not be compensated, even with adding one more insulation layer on the external walls and roof. If spectrally selective three-pane windows were used, the energy demand would not be as high. Triple glazing window could also enhance the thermal comfort inside the building which could result in higher satisfactory level for the occupants.

Summary

Daylight is known as a free source of light that has positive effects on health, increasing occupant’s productivity, bringing thermal and visual comfort within the indoor area, and increasing energy efficiency of buildings. Integration of daylighting in buildings can also reduce dependency on electric lighting which leads a higher resilience. This thesis concerned the daylighting strategy in LTH study center located in Lund, Sweden, a building with a very compact building shape. This building was first designed as a library, then from 2005 to 2006, it was renovated into a study hub. The current daylight level in the building is considered unsatisfactory while the view out is judged very poor. Due to the compact form, enhancement of daylighting is considered difficult but necessary.

Initially, a literature review was conducted to specify the daylighting methods and limitations of the study. Combination of side-lighting and top-lighting strategies were implemented for this study. For the side-lighting strategy, various choices of side window positions, quantities, and size; also additional clerestory were implemented. As for the top-lighting, three different shapes and slopes were tested keeping the current position and size. With these variations, the window-to-wall ratio (WWR) and skylight-to-floor ratio (SFR) of the building increased, which would increase the building’s energy demand as well. To check the significance of the increasing energy demand, energy simulations were also performed. As a comparison for the daylight study, various building certification system such as Miljöbyggnad, BREEAM-SE, and Swedish Standard SS-EN 17037 were considered. Additionally, a brief calculation and discussion regarding the electric lighting dependency was carried out.

The results showed, as expected, an increase in both the daylight level and building’s energy demand as the WWR was increased. However, the electric light dependency was reduced. As the energy demand increase was not significant although the WWR increased considerably, window-to-envelope ratio (WER) was found to be more suitable as significant indicator for this study. The top-lighting was found to produce a negligible effect on the daylight level in functional zones. But it improved daylighting in the circulation areas, which was considered a significant advantage. Although side-lighting succeeded to increase the daylight level inside the building, the daylight level was improved close to the building periphery. The core area was still considered dark, and this leads to a non-uniform daylight condition inside the building. To solve this problem, further study focusing on top-lighting needs to be conducted. Additionally, by providing continuous side windows, the view out improved remarkably.

Regarding building certifications, it was not possible to certify all functional zones using either static or dynamic daylight metrics since the rooms in the core area did not experience an increase in daylighting. Besides, conducting further study focusing on top-lighting strategies, simple reorganization of the internal functions within the building was suggested as a potential solution.

Adding more insulation layer in building envelope was also studied to see if it could suppress the increase on the building’s energy demand caused by an increase in WWR. It was found that the energy demand diminished with one more insulation layer on both the

external walls and roof. However, the reduction was small. To check if it would be necessary to add more insulation, an LCC study for longer time period is needed.

Lastly, energy demand for lighting was reduced in the improved combinations from the existing building. However, daylighting contributed to reduce the reliance on electrical lighting only in the peripheral areas. Thus, overall reduction of energy demand for lighting can be considered as a significant advantage of improved daylighting.

A higher daylight level, greater views out and reduced reliance on the use of electrical lighting was considered more important for the users and the building and well worth paying the ecological and economical price for an increase in energy use.

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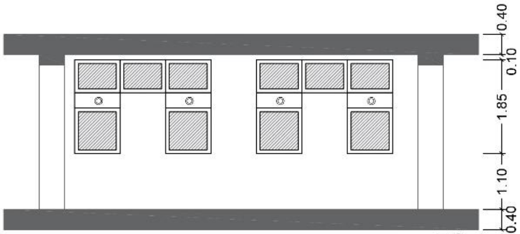
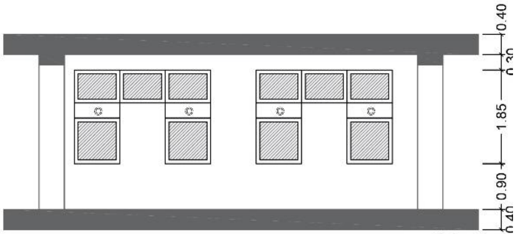
Appendix A

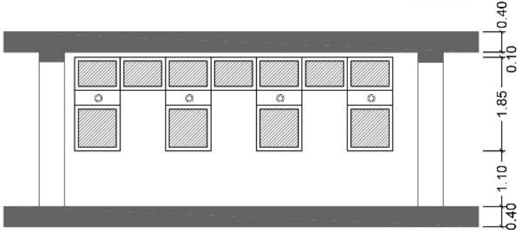
A1. U-shape window variations



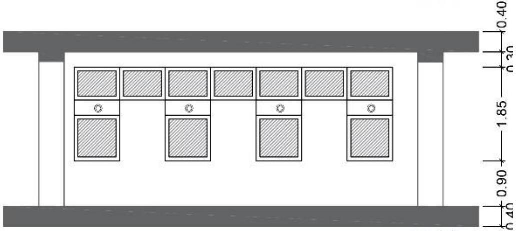
u-BC



u-01

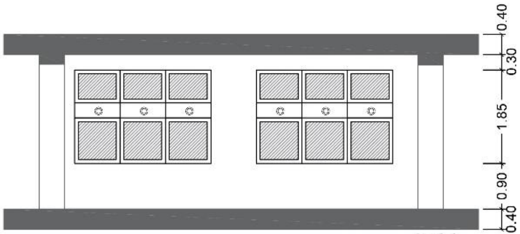


u-02

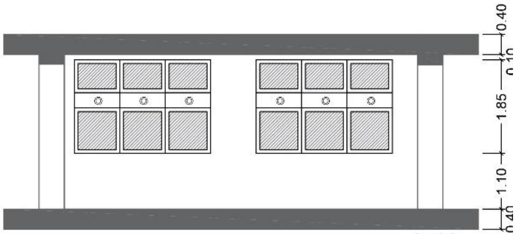


u-03

A2. Horizontal window without additional clerestory variations



h-01



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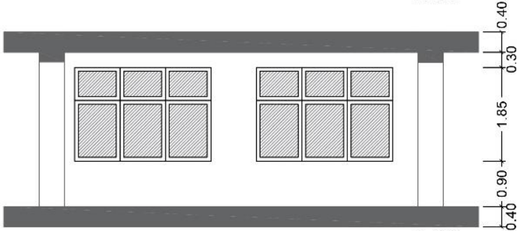

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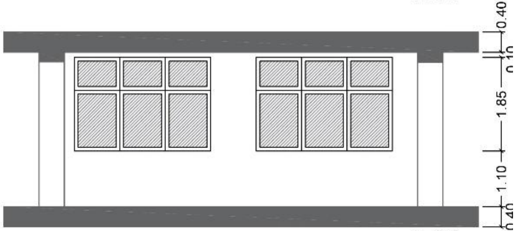
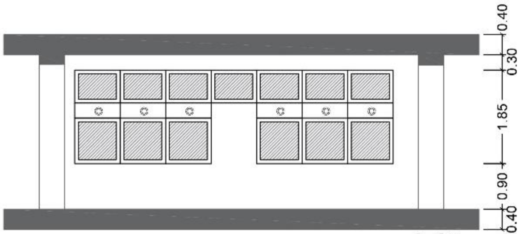


h-04

A3. Horizontal window with additional clerestory variations



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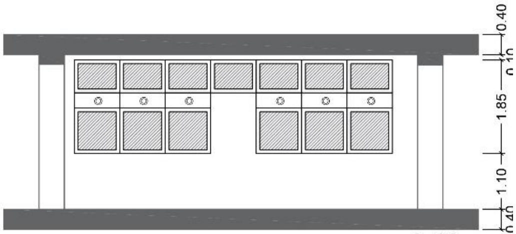
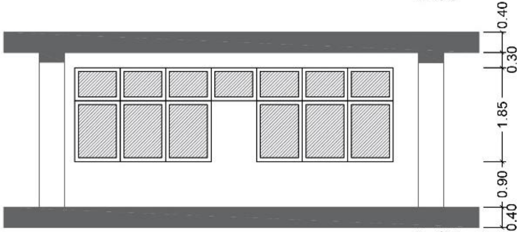
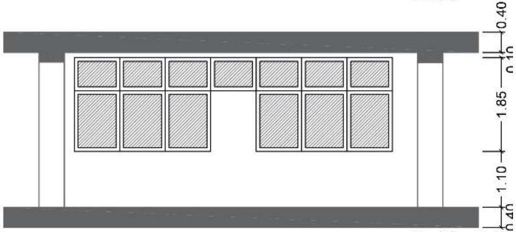


h-06

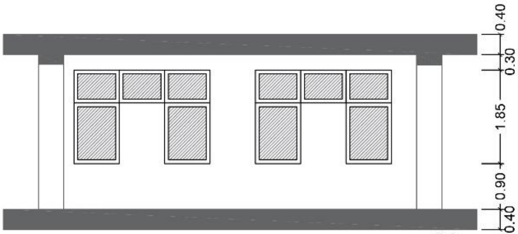


h-07

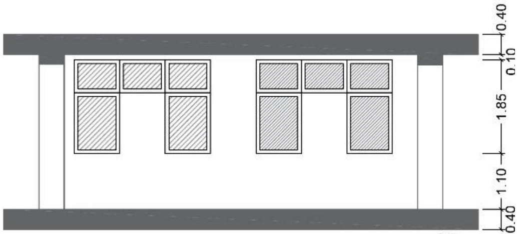


h-08

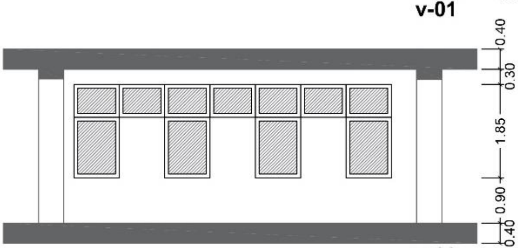
A4. Vertical window variations



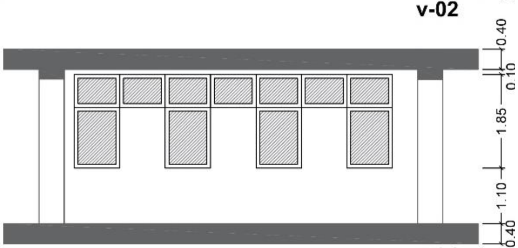
v-01



v-02



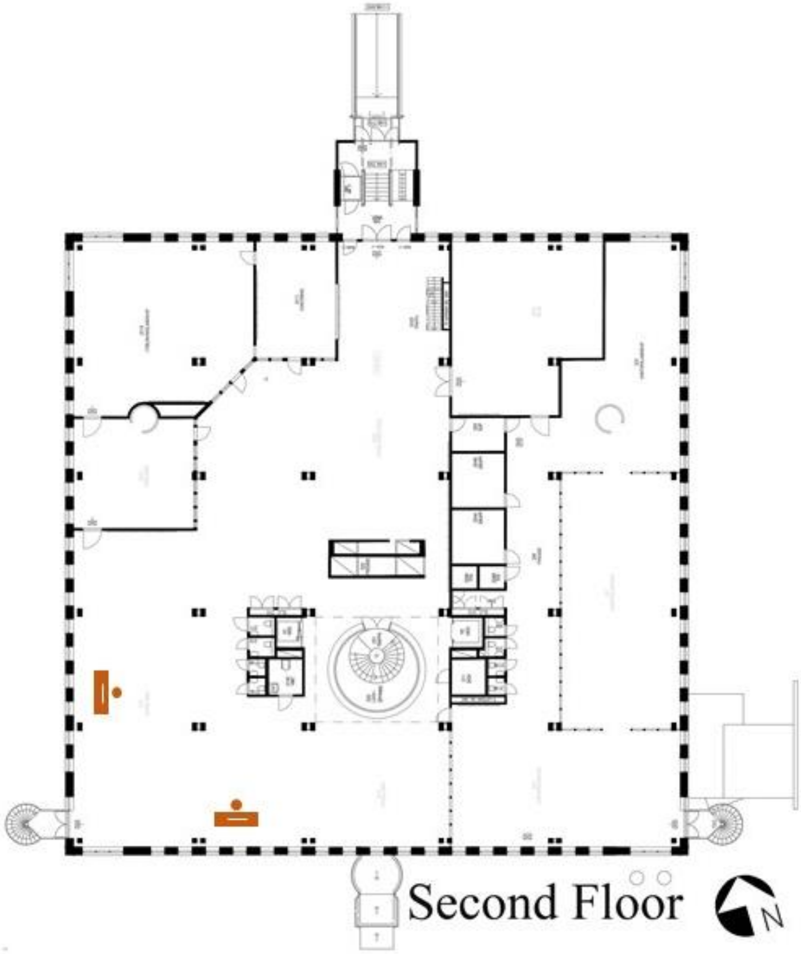
v-03



v-04

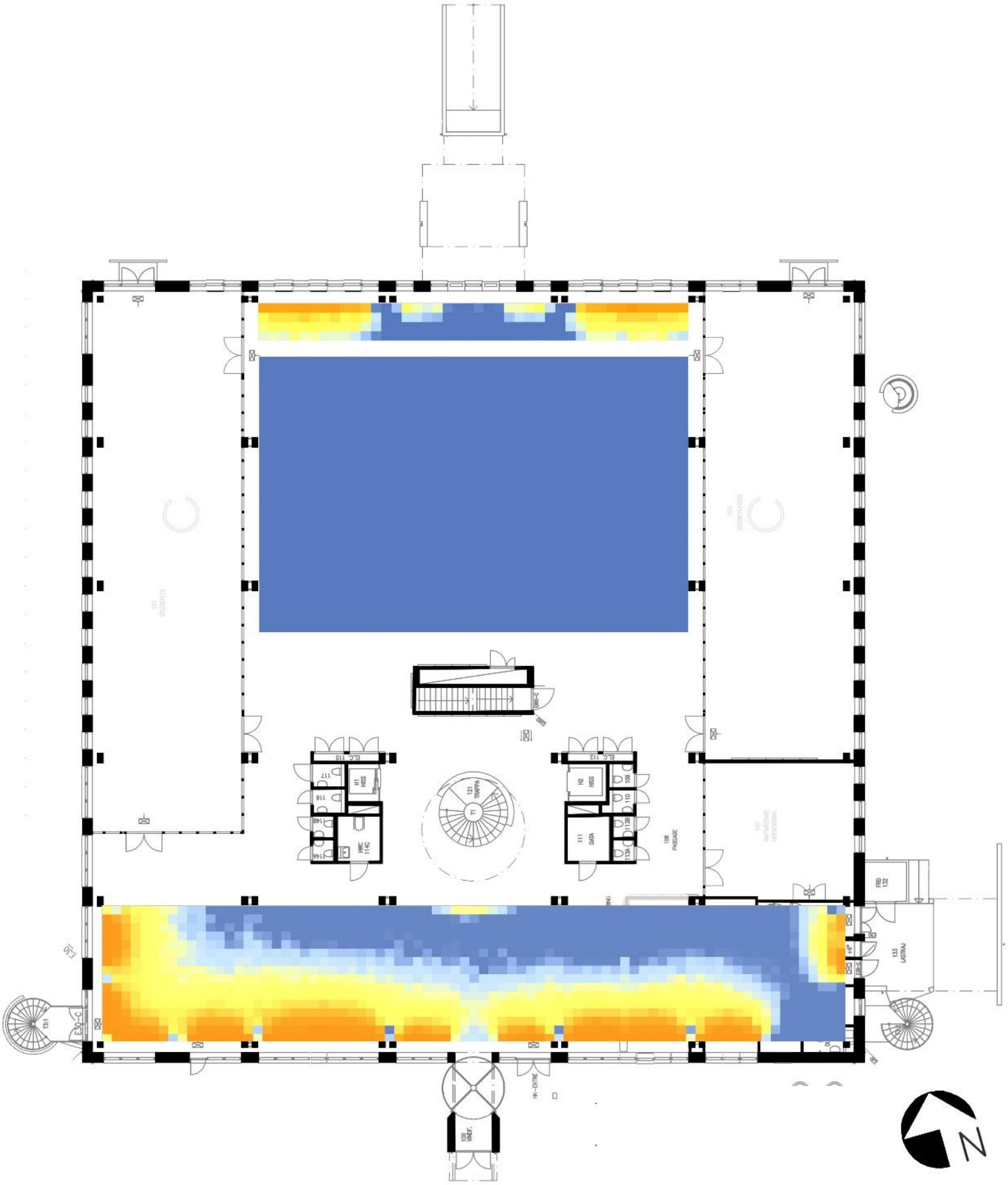
Appendix B

B1. Position of workstation to evaluate DGP

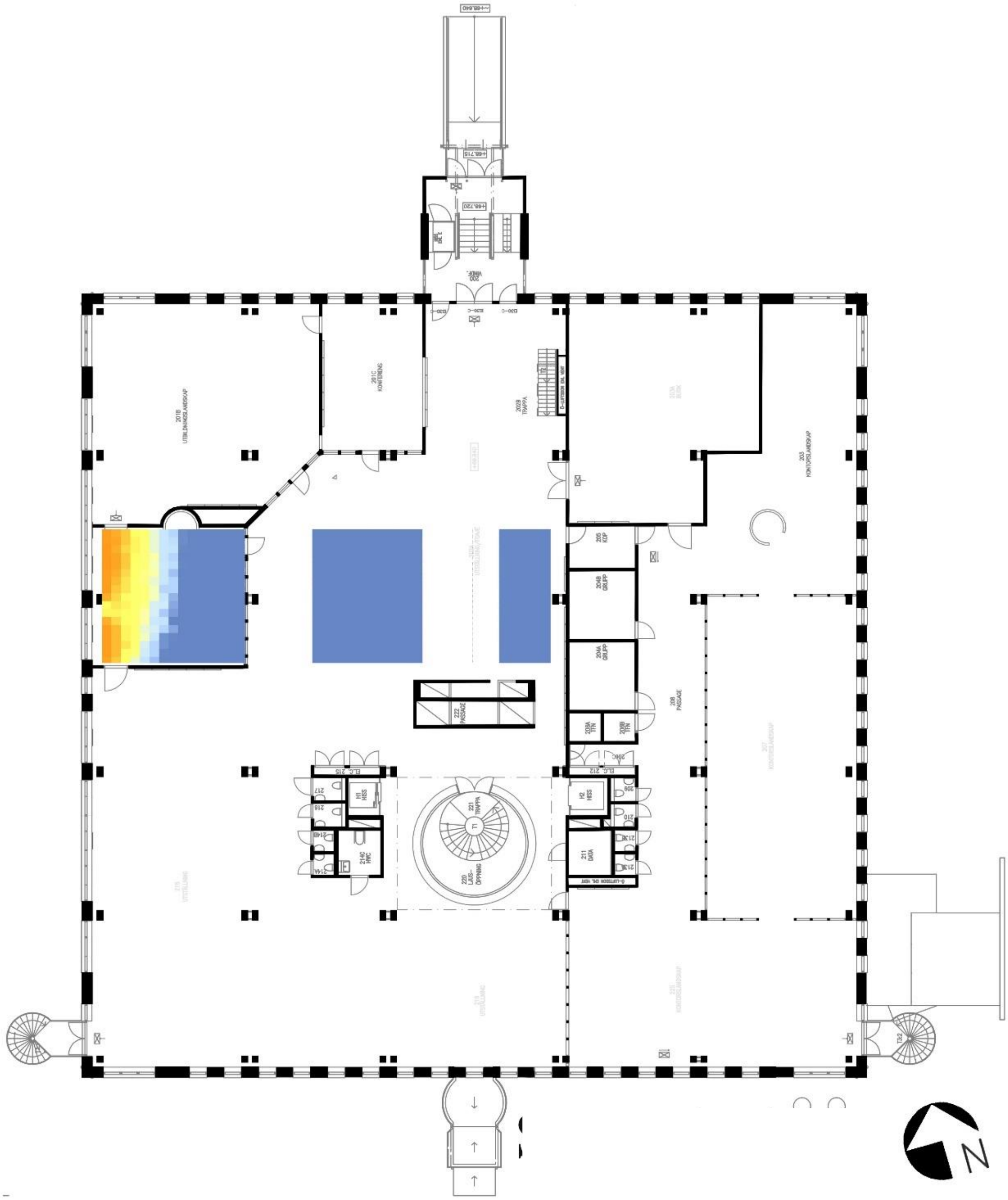


Appendix C

C1. DA$_{300}$ for the proposal on the first floor for combination-02



C2. DA$_{300}$ for the proposal on the second floor for combination-02



LUND UNIVERSITY

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Stage-01 (Daylight Reasults)

Sidelighting

No.	Name	Form	"View" window					Clerestory				Glazing	Daylight Result (grid 0.5 @ 0.85 m elevation)					
			Height (m) of the window pane	Width (m) of the window pane	Window pane no.	Height from the floor (m)	Gap towards clerestory (m)	Height (m)	Width (m)	Window pane no.	Distance from ceiling (m)	VT	WWR (%)	Increase of WWR from base case	WFR (%)	DF	Increase of DF from base case	DF Median
DOUBLE-GLAZED WINDOWS																		
without skylight																		
1	**u-01**	**"U-shape"**	0,9	0,9	2	0,9	0,3	0,65	0,9	On top of "view" windows only	0,4	0,692	29,23	0%	10	0,31	-9%	0,06
2	**u-BC**		**0,9**	**0,9**	**2**	**1,1**	**0,3**	**0,65**	**0,9**		**0,1**	**0,692**	**29,23**	**0%**	**10**	**0,34**	0%	**0,07**
3	**u-02**		0,9	0,9	2	0,9	0,3	0,65	0,9	Continous between two columns	0,4	0,692	30,68	5%	10	0,33	-3%	0,06
4	**u-03**		0,9	0,9	2	1,1	0,3	0,65	0,9		0,1	0,692	30,68	5%	10	0,36	6%	0,08
5	**h-01**	**"Horizontal"**	0,9	0,9	3	0,9	0,3	0,65	0,9	On top of "view" windows only	0,4	0,692	33,36	14%	11	0,34	0%	0,06
6	**h-02**		0,9	0,9	3	1,1	0,3	0,65	0,9		0,1	0,692	33,36	14%	11	0,39	15%	0,08
7	**h-03**		1,2	0,9	3	0,9	0	0,65	0,9		0,4	0,692	35,84	23%	12	0,45	32%	0,08
8	**h-04**		1,2	0,9	3	1,1	0	0,65	0,9		0,1	0,692	35,84	23%	12	0,51	50%	0,11
9	**h-05**		0,9	0,9	3	0,9	0,3	0,65	0,9	Continous between two columns	0,4	0,692	34,81	19%	11	0,37	9%	0,07
10	**h-06**		0,9	0,9	3	1,1	0,3	0,65	0,9		0,1	0,692	34,81	19%	11	0,42	24%	0,09
11	**h-07**		1,2	0,9	3	0,9	0	0,65	0,9		0,4	0,692	37,29	28%	12	0,47	38%	0,9
12	**h-08**		1,2	0,9	3	1,1	0	0,65	0,9		0,1	0,692	37,29	28%	12	0,54	59%	0,12
13	**v-01**	**"Vertical"**	1,2	0,9	2	0,9	0	0,65	0,9	On top of "view" windows only	0,4	0,692	30,88	6%	10	0,37	9%	0,7
14	**v-02**		1,2	0,9	2	1,1	0	0,65	0,9		0,1	0,692	30,88	6%	10	0,4	18%	0,09
15	**v-03**		1,2	0,9	2	0,9	0	0,65	0,9	Continous between two columns	0,4	0,692	32,33	11%	11	0,39	15%	0,08
16	**v-04**		1,2	0,9	2	1,1	0	0,65	0,9		0,1	0,692	32,33	11%	11	0,42	24%	0,1
TRIPLE-GLAZED WINDOWS																		
without skylight																		
1	**u-01**	**"U-shape"**	0,9	0,9	2	0,9	0,3	0,65	0,9	On top of "view" windows only	0,4	0,415	29,23	0%	10	0,17	-50%	0,03
2	**u-BC**		**0,9**	**0,9**	**2**	**1,2**	**0,3**	**0,65**	**0,9**		**0,1**	**0,415**	**29,23**	**0%**	**10**	**0,18**	-47%	**0,04**
3	**u-02**		0,9	0,9	2	0,9	0,3	0,65	0,9	Continous between two columns	0,4	0,415	30,68	5%	10	0,18	-47%	0,03
4	**u-03**		0,9	0,9	2	1,2	0,3	0,65	0,9		0,1	0,415	30,68	5%	10	0,19	-44%	0,04
5	**h-01**	**"Horizontal" / "Square"**	0,9	0,9	3	0,9	0,3	0,65	0,9	On top of "view" windows only	0,4	0,415	33,36	14%	11	0,19	-44%	0,03
6	**h-02**		0,9	0,9	3	1,2	0,3	0,65	0,9		0,1	0,415	33,36	14%	11	0,21	-38%	0,04
7	**h-03**		1,2	0,9	3	0,9	0	0,65	0,9		0,4	0,415	35,84	23%	12	0,24	-29%	0,05
8	**h-04**		1,2	0,9	3	1,2	0	0,65	0,9		0,1	0,415	35,84	23%	12	0,28	-18%	0,06
9	**h-05**		0,9	0,9	3	0,9	0,3	0,65	0,9	Continous between two columns	0,4	0,415	34,81	19%	11	0,2	-41%	0,04
10	**h-06**		0,9	0,9	3	1,2	0,3	0,65	0,9		0,1	0,415	34,81	19%	11	0,23	-32%	0,05
11	**h-07**		1,2	0,9	3	0,9	0	0,65	0,9		0,4	0,415	37,29	28%	12	0,26	-24%	0,05
12	**h-08**		1,2	0,9	3	1,2	0	0,65	0,9		0,1	0,415	37,29	28%	12	0,29	-15%	0,07
13	**v-01**	**"Vertical"**	1,2	0,9	2	0,9	0	0,6	0,9	On top of "view" windows only	0,4	0,415	30,88	6%	10	0,2	-41%	0,04
14	**v-02**		1,2	0,9	2	1,2	0	0,6	0,9		0,1	0,415	30,88	6%	10	0,22	-35%	0,05
15	**v-03**		1,2	0,9	2	0,9	0	0,6	0,9	Continous between two columns	0,4	0,415	32,33	11%	11	0,21	-38%	0,04
16	**v-04**		1,2	0,9	2	1,2	0	0,6	0,9		0,1	0,415	32,33	11%	11	0,23	-32%	0,05

Stage-01 (Energy Reasults)

Sidelighting

No.	Name	Window type			Windows area					Energy Result (Rhino; CPH sun)										
						Total				1st Floor				2nd Floor				Total		
		U-Value (W/m2 K)	SGHC	VT	Total sidelighting area	WWR	*WWR increase/decrease*	WER	*WER increase/decreas*	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/	*Total Energy Need (kWh)*	*Total Energy Load (kWh/m2)*	*Increase/reduction*
DOUBLE-GLAZED WINDOWS																				
without skylight																				
1	**u-01**	2,88	0,768	0,692																
2	**u-BC**	**2,88**	**0,768**	**0,692**	**317,97**	**29,23%**		**13,43%**		**231816,0**	**144,9**	**28,4**	**0,0**	**248265,4**	**155,2**	**74,6**	**0,0**	***480184,4***	***150,1***	
3	**u-02**	2,88	0,768	0,692																
4	**u-03**	2,88	0,768	0,692	**333,765**	**30,68%**	***1,45%***	**14,09%**	***0,67%***	232049,6	**145,0**	38,5	**0,0**	248224,4	**155,1**	104,0	**0,1**	***480416,5***	***150,1***	***0,05%***
5	**h-01**	2,88	0,768	0,692																
6	**h-02**	2,88	0,768	0,692	**362,97**	**33,36%**	***4,14%***	**15,33%**	***1,90%***	232328,8	**145,2**	59,1	**0,0**	248350,5	**155,2**	160,6	**0,1**	***480899,0***	***150,3***	***0,15%***
7	**h-03**	2,88	0,768	0,692																
8	**h-04**	2,88	0,768	0,692	**389,97**	**35,84%**	***6,62%***	**16,47%**	***3,04%***	232752,7	**145,5**	100,6	**0,1**	248399,8	**155,2**	258,1	**0,2**	***481511,2***	***150,5***	***0,28%***
9	**h-05**	2,88	0,768	0,692																
10	**h-06**	2,88	0,768	0,692	**378,765**	**34,81%**	***5,59%***	**16,00%**	***2,57%***	232620,5	**145,4**	74,0	**0,0**	248397,4	**155,2**	195,6	**0,1**	***481287,5***	***150,4***	***0,23%***
11	**h-07**	2,88	0,768	0,692																
12	**h-08**	2,88	0,768	0,692	**405,765**	**37,29%**	***8,07%***	**17,14%**	***3,71%***	233082,8	**145,7**	119,6	**0,1**	248518,2	**155,3**	297,9	**0,2**	***482018,5***	***150,6***	***0,38%***
13	**v-01**	2,88	0,768	0,692																
14	**v-02**	2,88	0,768	0,692	**335,97**	**30,88%**	***1,65%***	**14,19%**	***0,76%***	232028,0	**145,0**	46,3	**0,0**	248135,6	**155,1**	126,4	**0,1**	***480336,3***	***150,1***	***0,03%***
15	**v-03**	2,88	0,768	0,692																
16	**v-04**	2,88	0,768	0,692	**351,765**	**32,33%**	***3,11%***	**14,85%**	***1,43%***	232306,0	**145,2**	59,7	**0,0**	248152,2	**155,1**	159,4	**0,1**	***480677,3***	***150,2***	***0,10%***
TRIPLE-GLAZED WINDOWS																				
without skylight																				
1	**u-01**	1	0,539	0,415																
2	**u-BC**	**1**	**0,539**	**0,415**	**0,585**	**0,05%**		**0,02%**		**221833,7**	**138,6**	**0,0**	**0,0**	**238337,4**	**149,0**	**1,9**	**0,0**	***460173,0***	***143,8***	***-4,17%***
3	**u-02**	1	0,539	0,415																
4	**u-03**	1	0,539	0,415	**333,765**	**30,68%**	***1,45%***	**14,09%**	***0,67%***	221429,4	**138,4**	0,1	**0,0**	237532,3	**148,5**	4,8	**0,0**	***458966,6***	***143,4***	***-4,42%***
5	**h-01**	1	0,539	0,415																
6	**h-02**	1	0,539	0,415	**362,97**	**33,36%**	***4,14%***	**15,33%**	***1,90%***	220722,2	**138,0**	0,9	**0,0**	236238,0	**147,6**	10,8	**0,0**	***456971,9***	***142,8***	***-4,83%***
7	**h-03**	1	0,539	0,415																
8	**h-04**	1	0,539	0,415	**389,97**	**35,84%**	***6,62%***	**16,47%**	***3,04%***	219679,0	**137,3**	3,7	**0,0**	234309,5	**146,4**	23,5	**0,0**	***454015,7***	***141,9***	***-5,45%***
9	**h-05**	1	0,539	0,415																
10	**h-06**	1	0,539	0,415	**378,765**	**34,81%**	***5,59%***	**16,00%**	***2,57%***	220350,2	**137,7**	1,7	**0,0**	235523,2	**147,2**	14,9	**0,0**	***455890,0***	***142,5***	***-5,06%***
11	**h-07**	1	0,539	0,415																
12	**h-08**	1	0,539	0,415	**405,765**	**37,29%**	***8,07%***	**17,14%**	***3,71%***	219323,2	**137,1**	5,3	**0,0**	233632,5	**146,0**	31,4	**0,0**	***452992,4***	***141,6***	***-5,66%***
13	**v-01**	1	0,539	0,415																
14	**v-02**	1	0,539	0,415	**335,97**	**30,88%**	***1,65%***	**14,19%**	***0,76%***	221094,8	**138,2**	0,3	**0,0**	236941,1	**148,1**	7,2	**0,0**	***458043,4***	***143,1***	***-4,61%***
15	**v-03**	1	0,539	0,415																
16	**v-04**	1	0,539	0,415	**351,765**	**32,33%**	***3,11%***	**14,85%**	***1,43%***	220718,2	**137,9**	0,9	**0,0**	236212,7	**147,6**	10,7	**0,0**	***456942,5***	***142,8***	***-4,84%***

Stage-02

Sidelighting ; Window Shape

No.	Name	Form	Windows area				Daylight Result								Energy Result (Rhino; CPH sun)														
							1st Floor				2nd Floor				1st Floor						2nd Floor						*Total*		
			WWR	*WWR increase/decrease*	WER	*WER increase/decreas*	DF average	DA	sDA	CDA	DF average	DA	sDA	CDA	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Difference with base case (heating)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	Difference with base case (cooling)	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Difference with base case (heating)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	Difference with base case (cooling)	*Total Energy Need (kWh)*	*Total Energy Load (kWh/m2)*	*Difference with base case*
DOUBLE-GLAZED WINDOWS																													
NORTH 240 m2 ; without skylight																													
2	**u-BC**	**U shape**	**30,18%**		**9,00%**		**0,60**	**6,10%**	**4,20%**	**25,20%**	**0,7**	**9,30%**	**9,02%**	**30,50%**	**38132,1**	**158,9**		**0,0**	**0,00**		**42257,8**	**176,1**		**0,0**	**0,00**		***80389,9***	***167,5***	
4	**u-03**	U shape	**30,18%**	***0,00%***	**9,00%**	***0,00%***	0,70	6,80%	4,80%	27,00%	0,8	10,02%	9,84%	31,76%	38366,0	**159,9**	0,61%	0,0	**0,00**	#DIV/0!	42477,7	**177,0**	0,52%	0,0	**0,00**	#DIV/0!	***80843,7***	***168,4***	***0,56%***
12	**h-08**	Square	**43,59%**	***13,41%***	**13,00%**	***4,00%***	1,50	19,30%	21,00%	43,70%	1,6	22,21%	25,41%	46,12%	39602,0	**165,0**	3,85%	0,0	**0,00**	#DIV/0!	43642,3	**181,8**	3,28%	0,0	**0,00**	#DIV/0!	***83244,3***	***173,4***	***3,55%***
16	**v-04**	Vertical	**34,41%**	***4,24%***	**10,26%**	***1,26%***	1,00	11,20%	2,20%	33,70%	1,0	14,41%	15,68%	37,38%	38731,0	**161,4**	1,57%	0,0	**0,00**	#DIV/0!	42820,6	**178,4**	1,33%	0,0	**0,00**	#DIV/0!	***81551,6***	***169,9***	***1,45%***
EAST 240 m2 ; without skylight																													
2	**u-BC**	**U shape**	**30,18%**		**9,00%**		**0,60**	**14,30%**	**9,80%**	**33,00%**	**0,7**	**18,23%**	**16,39%**	**38,06%**	**33980,6**	**141,6**		**26,0**	**0,11**		**37668,0**	**157,0**		**43,6**	**0,18**		***71718,2***	***149,4***	
4	**u-03**	U shape	**30,18%**	***0,00%***	**9,00%**	***0,00%***	0,70	16,00%	11,60%	35,10%	0,8	20,13%	18,58%	40,51%	33988,3	**141,6**	0,02%	37,4	**0,16**	0,4	37650,3	**156,9**	-0,05%	57,6	**0,24**	32,11%	***71733,6***	***149,4***	***0,02%***
12	**h-08**	Square	**43,59%**	***13,41%***	**13,00%**	***4,00%***	1,20	26,20%	28,00%	46,30%	1,6	33,23%	37,05%	53,52%	34167,3	**142,4**	0,55%	117,1	**0,49**	3,5	37736,2	**157,2**	0,18%	151,6	**0,63**	247,71%	***72172,2***	***150,4***	***0,63%***
16	**v-04**	Vertical	**34,41%**	***4,24%***	**10,26%**	***1,26%***	0,90	20,40%	20,00%	40,80%	1,0	25,23%	27,65%	45,45%	33973,8	**141,6**	-0,02%	60,5	**0,25**	1,3	37606,4	**156,7**	-0,16%	85,9	**0,36**	97,02%	***71726,6***	***149,4***	***0,01%***
SOUTH 240 m2 ; without skylight																													
2	**u-BC**	**U shape**	**30,18%**		**9,00%**		**1,30**	**37,30%**	**38,00%**	**56,70%**	**1,0**	**32,70%**	**31,80%**	**54,00%**	**31408,2**	**130,9**		**62,9**	**0,26**		**34911,5**	**145,5**		**84,6**	**0,35**		***66467,2***	***138,5***	
4	**u-03**	U shape	**30,18%**	***0,00%***	**9,00%**	***0,00%***	1,00	31,70%	31,00%	52,80%	1,0	35,43%	36,58%	56,56%	31417,0	**130,9**	0,03%	89,9	**0,37**	0,4	34703,6	**144,6**	-0,60%	103,6	**0,43**	22,46%	***66314,1***	***138,2***	***-0,23%***
12	**h-08**	Square	**43,59%**	***13,41%***	**13,00%**	***4,00%***	2,00	48,70%	52,20%	66,50%	2,1	54,39%	61,48%	70,95%	30761,0	**128,2**	-2,06%	221,2	**0,92**	2,5	33810,2	**140,9**	-3,15%	237,0	**0,99**	180,14%	***65029,4***	***135,5***	***-2,16%***
16	**v-04**	Vertical	**34,41%**	***4,24%***	**10,26%**	***1,26%***	1,30	38,60%	40,30%	58,80%	1,4	43,20%	45,59%	63,23%	31109,0	**129,6**	-0,95%	128,9	**0,54**	1,0	34320,7	**143,0**	-1,69%	142,0	**0,59**	67,85%	***65700,6***	***136,9***	***-1,15%***
WEST 240 m2 ; without skylight																													
2	**u-BC**	**U shape**	**30,18%**		**9,00%**		**1,30**	**25,80%**	**38,00%**	**48,70%**	**1,0**	**20,97%**	**20,00%**	**43,97%**	**36002,7**	**150,0**		**4,4**	**0,02**		**39943,3**	**166,4**		**8,3**	**0,03**		***75958,7***	***158,2***	
4	**u-03**	U shape	**30,18%**	***0,00%***	**9,00%**	***0,00%***	1,30	22,50%	21,30%	46,00%	1,1	23,32%	23,61%	46,85%	36118,7	**150,5**	0,32%	8,1	**0,03**	0,8	40046,7	**166,9**	0,26%	13,1	**0,05**	57,83%	***76186,6***	***158,7***	***0,30%***
12	**h-08**	Square	**43,59%**	***13,41%***	**13,00%**	***4,00%***	2,30	41,10%	45,50%	63,00%	2,2	42,42%	48,42%	64,08%	36816,8	**153,4**	2,26%	49,5	**0,21**	10,3	40694,6	**169,6**	1,88%	59,6	**0,25**	618,07%	***77620,5***	***161,7***	***2,19%***
16	**v-04**	Vertical	**34,41%**	***4,24%***	**10,26%**	***1,26%***	1,50	30,70%	32,30%	55,20%	1,4	30,23%	33,11%	53,71%	36288,6	**151,2**	0,79%	17,5	**0,07**	3,0	40198,4	**167,5**	0,64%	24,1	**0,10**	190,36%	***76528,6***	***159,4***	***0,75%***
WHOLE BUILDING ; without skylight																													
2	**u-BC**	**U shape**	**27,67%**		**11,20%**		**0,34**								**231816,0**	**144,9**		**28,4**	**0,0**		**248265,4**	**155,2**		**74,6**	**0,0**		***480184,4***	***150,1***	
4	**u-03**	U shape	**29,12%**	***1,45%***	**11,79%**	***0,59%***	0,36								232007,0	**145,0**	0,08%	34,9	**0,0**	0,2	248204,0	**155,1**	-0,02%	102,3	**0,1**	37,13%	***480348,2***	***150,1***	***0,03%***
12	**h-08**	Square	**38,54%**	***10,87%***	**15,60%**	***4,40%***	0,54								232641,2	**145,4**	0,36%	163,3	**0,1**	4,8	248135,3	**155,1**	-0,05%	309,0	**0,2**	314,21%	***481248,8***	***150,4***	***0,22%***
16	**v-04**	Vertical	**32,30%**	***4,63%***	**13,07%**	***1,87%***	0,42								232070,5	**145,0**	0,11%	66,6	**0,0**	1,3	248000,2	**155,0**	-0,11%	161,7	**0,1**	116,76%	***480299,0***	***150,1***	***0,02%***

Stage-03

Sidelighting ; Window Width

No.	Name	Form	Windows area				Daylight Result								Energy Result (Rhino; CPH sun)									
							1st Floor				2nd Floor				1st Floor				2nd Floor				*Total*	
			WWR	*WWR increase/decrease*	WER	*WER increase/decrease*	DF average	DA	sDA	CDA	DF average	DA	sDA	CDA	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	*Total Energy Load (kWh/m2)*	*Increase/reduction*
DOUBLE-GLAZED WINDOWS																								
without skylight																								
NORTH																								
1	w-BC	Square	43,59%		13,00%		1,50	19,30%	21,10%	43,70%	1,50	22,38%	25,31%	46,14%	39464,7	164,4	0,0	0,0	42160,1	175,7	0,0	0,0	*170,1*	
2	w-01		47,82%	*4,24%*	14,26%	*1,26%*	1,50	20,10%	21,70%	44,40%	1,70	24,68%	28,18%	49,05%	39755,7	165,6	0,0	0,0	42433,0	176,8	0,0	0,0	*171,2*	*0,69%*
3	w-02		49,78%	*6,19%*	14,85%	*1,85%*	1,60	21,00%	22,40%	45,50%	1,80	25,84%	29,20%	50,43%	39956,4	166,5	0,0	0,0	42624,2	177,6	0,0	0,0	*172,0*	*1,17%*
4	w-03		51,74%	*8,15%*	15,43%	*2,43%*	1,70	22,70%	23,90%	47,10%	1,90	27,27%	30,94%	51,78%	40154,1	167,3	0,0	0,0	42811,3	178,4	0,0	0,0	*172,8*	*1,64%*
5	w-04		53,69%	*10,10%*	16,01%	*3,01%*	1,80	24,00%	26,00%	48,70%	2,00	28,46%	32,99%	52,90%	40352,7	168,1	0,0	0,0	43000,5	179,2	0,1	0,0	*173,7*	*2,12%*
EAST																								
1	w-BC	Square	43,59%		13,00%		1,20	26,20%	38,00%	46,30%	1,20	33,18%	38,03%	53,46%	34157,9	142,3	117,0	0,5	37706,0	157,1	151,3	0,6	*150,3*	
2	w-01		47,82%	*4,24%*	14,26%	*1,26%*	1,20	26,70%	28,00%	47,00%	1,70	35,02%	38,69%	55,52%	34238,9	142,7	139,8	0,6	37761,0	157,3	178,4	0,7	*150,7*	*0,26%*
3	w-02		49,78%	*6,19%*	14,85%	*1,85%*	1,20	27,60%	29,20%	47,00%	1,80	35,85%	39,45%	56,27%	34320,0	143,0	153,3	0,6	37823,4	157,6	194,0	0,8	*151,0*	*0,50%*
4	w-03		51,74%	*8,15%*	15,43%	*2,43%*	1,30	28,60%	29,50%	49,00%	1,90	37,37%	41,97%	57,57%	34395,2	143,3	167,6	0,7	37882,2	157,8	210,6	0,9	*151,4*	*0,73%*
5	w-04		53,69%	*10,10%*	16,01%	*3,01%*	1,40	29,00%	31,10%	50,20%	2,00	38,77%	43,06%	58,84%	34483,1	143,7	181,8	0,8	37952,9	158,1	227,1	0,9	*151,8*	*0,99%*
SOUTH																								
1	w-BC	Square	43,59%		13,00%		2,00	48,70%	52,20%	66,50%	2,00	53,96%	60,76%	70,63%	30747,4	128,1	221,2	0,9	33750,3	140,6	237,2	1,0	*135,3*	
2	w-01		47,82%	*4,24%*	14,26%	*1,26%*	2,00	50,30%	55,20%	67,80%	2,30	56,42%	64,24%	72,14%	30653,3	127,7	256,8	1,1	33597,8	140,0	273,4	1,1	*135,0*	*-0,27%*
3	w-02		49,78%	*6,19%*	14,85%	*1,85%*	2,10	51,40%	56,70%	68,50%	2,40	57,38%	65,27%	72,81%	30629,6	127,6	277,8	1,2	33538,1	139,7	294,5	1,2	*134,9*	*-0,33%*
4	w-03		51,74%	*8,15%*	15,43%	*2,43%*	2,20	52,70%	59,00%	69,40%	2,60	59,55%	69,47%	74,17%	30614,6	127,6	299,0	1,2	33487,9	139,5	315,7	1,3	*134,8*	*-0,37%*
5	w-04		53,69%	*10,10%*	16,01%	*3,01%*	2,30	53,80%	61,00%	79,30%	2,70	60,97%	71,31%	75,02%	30608,9	127,5	320,2	1,3	33446,8	139,4	336,9	1,4	*134,8*	*-0,37%*
WEST																								
1	w-BC	Square	43,59%		13,00%		2,30	41,10%	45,50%	63,00%	2,30	42,39%	47,76%	64,16%	36803,0	153,3	49,5	0,2	40670,6	169,5	59,6	0,2	*161,6*	
2	w-01		47,82%	*4,24%*	14,26%	*1,26%*	2,40	43,70%	48,30%	65,00%	2,40	45,50%	51,37%	66,42%	36989,8	154,1	64,4	0,3	40849,3	170,2	75,3	0,3	*162,5*	*0,51%*
3	w-02		49,78%	*6,19%*	14,85%	*1,85%*	2,50	45,00%	50,30%	66,00%	2,60	46,90%	52,79%	57,53%	37123,6	154,7	73,6	0,3	40976,8	170,7	85,3	0,4	*163,0*	*0,87%*
4	w-03		51,74%	*8,15%*	15,43%	*2,43%*	2,60	47,00%	51,80%	67,50%	2,70	49,10%	56,07%	68,96%	37262,0	155,3	83,1	0,3	41107,7	171,3	95,7	0,4	*163,6*	*1,24%*
5	w-04		53,69%	*10,10%*	16,01%	*3,01%*	2,80	49,00%	55,10%	68,80%	2,90	50,91%	58,36%	70,22%	37405,3	155,9	92,8	0,4	41243,0	171,8	106,3	0,4	*164,3*	*1,63%*
WHOLE BUILDING																								
1	w-BC	Square	38,54%		17,71%										232931,0	145,6	197,7	0,1	247950,3	155,0	316,7	0,2	*150,4*	
2	w-01		41,61%	*3,08%*	19,12%	*1,41%*									233229,2	145,8	247,0	0,2	247979,3	155,0	375,7	0,2	*150,6*	*0,09%*
3	w-02		42,90%	*4,37%*	19,71%	*2,01%*									233310,0	145,8	284,6	0,2	248027,2	155,0	412,6	0,3	*150,6*	*0,13%*
4	w-03		44,19%	*5,66%*	20,30%	*2,60%*									233572,3	146,0	320,4	0,2	248130,7	155,1	450,0	0,3	*150,8*	*0,22%*
5	w-04		45,48%	*6,94%*	20,90%	*3,19%*									233862,3	146,2	358,3	0,2	248255,8	155,2	487,5	0,3	*150,9*	*0,33%*

Stage-04

Toplighting

No.	Name	Type	"View" window		Window type			Window Area		Daylight Result			Energy Result (Rhino; CPH sun)														
										1st Floor			1st Floor				2nd Floor				Skylight				*Total*		
			Orientation	Slope	U-Value (W/m2 K)	SGHC	VT	Total toplighting area	SFR	DA average	sDA	CDA	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	*Total Energy Need (kWh)*	*Total Energy Load (kWh/m2)*	*Increase/reduction*
DOUBLE-GLAZED WINDOWS																											
0	**t-BC**	**Monitor**	**east-west**	**90**	**2,88**	**0,768**	**0,692**	**66,5**	**4,16%**	**1,20%**	**0,82%**	**2,80%**	**391103,5**	**254,0**	**0,0**	**0,0**	**391674,5**	**255,2**	**0,0**	**0,0**	**25983,9**	**134,6**	**213,2**	**1,1**	***808975,1***	***247,7***	
1	**t-01**	Monitor	south	90	**2,88**	**0,768**	**0,692**	66,5	4,16%	1,90%	1,30%	3,10%	391103,1	**254,0**	0,0	**0,0**	391665,8	**255,2**	0,0	**0,0**	25983,7	**134,6**	108,9	**0,6**	***808861,5***	***247,6***	***-0,01%***
2	**t-02**	Open skylight	none	0				66,5	4,16%	2,70%	3,00%	5,20%	383401,8	**249,0**	0,0	**0,0**	391664,2	**255,2**	0,0	**0,0**	30905,7	**160,1**	0,0	**0,0**	***805971,7***	***246,7***	***-0,37%***
3	**t-03**		south	15				66,5	4,16%	4,20%	4,30%	8,00%	380709,1	**247,2**	0,0	**0,0**	391379,1	**255,0**	0,0	**0,0**	28854,5	**149,5**	0,0	**0,0**	***800942,7***	***245,2***	***-0,99%***
4	**t-04**			30				66,5	4,16%	4,10%	4,20%	7,90%	379121,4	**246,2**	0,0	**0,0**	391365,2	**255,0**	0,0	**0,0**	30123,1	**156,1**	0,0	**0,0**	***800609,7***	***245,1***	***-1,03%***
5	**t-05**			45				66,5	4,16%	4,10%	4,20%	7,90%	376635,5	**244,6**	0,0	**0,0**	391359,2	**255,0**	0,0	**0,0**	32951,5	**170,7**	15,9	**0,1**	***800962,1***	***245,2***	***-0,99%***
6	**t-06**		east	15				66,5	4,16%	3,90%	4,00%	7,40%	381956,5	**248,0**	0,0	**0,0**	391372,5	**255,0**	0,0	**0,0**	29281,7	**151,7**	0,0	**0,0**	***802610,7***	***245,7***	***-0,79%***
7	**t-07**			30				66,5	4,16%	3,80%	4,00%	7,30%	381285,5	**247,6**	0,0	**0,0**	391366,9	**255,0**	0,0	**0,0**	30883	**160,0**	0,0	**0,0**	***803535,4***	***246,0***	***-0,67%***
8	**t-08**			45				66,5	4,16%	3,70%	4,00%	7,20%	380127,7	**246,8**	0,0	**0,0**	391363,5	**255,0**	0,0	**0,0**	34182,8	**177,1**	0,0	**0,0**	***805674,0***	***246,6***	***-0,41%***
9	**t-09**		west	15				66,5	4,16%	3,80%	4,00%	7,30%	383069,7	**248,7**	0,0	**0,0**	391369,7	**255,0**	0,0	**0,0**	29737,1	**154,1**	0,0	**0,0**	***804176,5***	***246,2***	***-0,59%***
10	**t-10**			30				66,5	4,16%	3,70%	4,00%	7,20%	383420	**249,0**	0,0	**0,0**	391365,9	**255,0**	0,0	**0,0**	31720	**164,4**	0,0	**0,0**	***806505,9***	***246,9***	***-0,31%***
11	**t-11**			45				66,5	4,16%	3,60%	4,00%	7,20%	383297	**248,9**	0,0	**0,0**	391384,3	**255,0**	0,0	**0,0**	35446,4	**183,7**	0,0	**0,0**	***810127,7***	***248,0***	***0,14%***
12	**t-12**		south	15				94,5	5,91%	4,70%	4,70%	9,00%	369710,5	**245,6**	0,0	**0,0**	384931,2	**254,6**	0,0	**0,0**	39102,9	**144,6**	18,6	**0,1**	***793763,2***	***241,4***	***-2,52%***

Stage-05

Combined

No.	Name	Sidelighting ratio		Skylight					Glazing type			Daylight Result						Energy Result (Rhino; DNK_Copenhagen)					
												1st Floor			2nd Floor			Heating and Cooling				*Total*	
		WWR	WER	Skylight Type	Orientation	Slope	Total toplighting area	SFR	U-Value (W/m2 K)	SGHC	VT	DA average	sDA	CDA	DA average	sDA	CDA	Annual Heating Need (kWh)	Annual Heating Load (kWh/m2)	Annual Cooling Need (kWh)	Annual Cooling Load (kWh/m2)	*Total Energy Load (kWh/m2)*	*Increase/reduction*
DOUBLE-GLAZED WINDOWS																							
0	**Existing_building (u-BC + t-BC)**	**29,23%**	**13,43%**	**Monitor skylight**	**east-west**	**90**	**66,5**	**4,16%**	**2,88**	**0,768**	**0,692**							**202532,8**	**39,6**	**67820,2**	**13,2**	***52,8***	
1	**w-01 + t-12 (combination-01)**	**41,61%**	**19,12%**	Open skylight + HVAC corridor	south	15	94,5	5,91%	2,88	0,768	0,692	28,17%	31,56%	43,35%	38,79%	45,98%	54,03%	220784,1	**43,1**	81814,9	**16,0**	***59,1***	***11,93%***
2	**w-01 + t-12 + Wall insulation**																	215086,4	**42,0**	81601,4	**15,9**	***57,9***	***9,74%***
3	**w-01 + t-12 + Roof insulation**																	218089,7	**42,6**	81517,4	**15,9**	***58,5***	***10,82%***
4	**w-01 + t-12 + Wall and roof insulation**																	212348,1	**41,5**	81510,8	**15,9**	***57,4***	***8,69%***
5	**w-04 + t-12 (combination-02)**	**45,62%**	**20,96%**									30,70%	35,00%	45,50%	41,70%	49,60%	56,40%	224965	**43,9**	82638,2	**16,1**	***60,1***	***13,78%***
6	**w-04 + t-12 + Wall insulation**																	219455,5	**42,9**	82424,4	**16,1**	***59,0***	***11,66%***
7	**w-04 + t-12 + Roof insulation**																	222270,9	**43,4**	82341,4	**16,1**	***59,5***	***12,67%***
8	**w-04 + t-12 + Wall and roof insulation**																	216717,2	**42,3**	82333,8	**16,1**	***58,4***	***10,62%***